Md Ibrahim Khalil Ullah

A design methodology of a product: bicycle frame for simultaneous improvement of mechanical and environmental performance

Graduate thesis in Masters in Sustainable Manufacturing
Supervisor: Stergios Goutianos
Co-supervisor: Angela Daniela La Rosa; Shifteh Mihanyar
October 2022

Graduate thesis

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Abstract

At present, advanced materials is mostly a combination of high mechanical properties with additional properties, e.g., lightweight, recyclability or other features. In many industries, the use of lightweight materials such as composites offers significant advantages over traditional materials. A typical example is transportation, where lightweight materials lead to significant fuel savings. However, considering sustainability and circularity, most composite materials are not recyclable and reusable. This has a negative environmental impact. On the other hand, with modern manufacturing methods, for example additive manufacturing, it is possible to produce highly optimized, lightweight metallic structures, which may directly compete with composites. These structures have the advantage of being recyclable at the end of their lifetime. As a result, sometimes designers and developers fall into a dilemma to decide which material should be selected for a particular structure where end-of-life scenarios of the product or materials are considered. Therefore, a demand arises to develop a product design methodology where, (i) composite or metallic structures can be designed with unique features, (ii) mechanical performance and environmental impact are considered throughout its lifetime, (iii) end-of-life alternatives are counted. With the proposed methodology, it may be possible to answer the multi-objectives optimization problem. So, In this project, it will be attempted to develop such a methodology considering as an example a bicycle frame. Three materials will be considered for the frame: a) aluminum, b) conventional composite such as carbon/epoxy and c) a composite material based on natural fibers which is flax fiber in this study. The different parametric models will be developed, and life cycle assessment will be conducted for different materials to optimize the design of the product.

Sammendrag

For tiden kan avanserte materialer kombinere høye mekaniske egenskaper med tilleggsegenskaper, for eksempel lettvekt, resirkulerbarhet eller andre funksjoner. I mange bransjer gir bruken av lette materialer som kompositter betydelige fordeler i forhold til tradisjonelle materialer. Et typisk eksempel er transport, der lette materialer fører til betydelige drivstoffbesparelser. Men når det gjelder bærekraft og sirkularitet, er de fleste komposittmaterialer ikke resirkulerbare og gjenbrukbare. Dette har en negativ miljøpåvirkning. På den annen side, med moderne produksjonsmetoder, for eksempel additiv produksjon, er det mulig å produsere svært optimaliserte lette metallkonstruksjoner, som direkte kan konkurrere med kompositter. Disse strukturene har fordelen av å være resirkulerbare ved slutten av levetiden. Som et resultat faller designere og utviklere noen ganger inn i et dilemma for å bestemme hvilket materiale som skal velges for en bestemt struktur der end-of-life-scenarier for produktet eller materialene vurderes. Derfor oppstår det behov for å utvikle en produktdesignmetodikk der (i) kompositt- eller metallkonstruksjoner kan utformes med unike egenskaper, (ii) mekanisk ytelse og miljøpåvirkning vurderes gjennom hele levetiden, (iii) alternativer for slutten av levetiden telles. Med den foreslåtte metoden kan det være mulig å svare på multi-objectives optimaliseringsproblemet. Så i dette prosjektet vil det bli forsøkt å utvikle en slik metodikk med tanke på et eksempel på en sykkelramme. Tre materialer vil bli vurdert for rammen: a) aluminium, b) konvensjonell kompositt som karbon / epoksy og c) et komposittmateriale basert på naturlige fibre som er linfiber i denne studien. De forskjellige parametriske modellene vil bli utviklet, og livssyklusvurdering vil bli utført for forskjellige materialer for å optimalisere utformingen av produktet.

Preface

This paper is the summary work of the master's thesis as the completion of the master's study program from the Sustainable Manufacturing, Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology (NTNU). This work has carried out from January'22 to Octaber'22.

The work presented here was done solely by me under the direct supervision of Stergios Goutianos, Professor, Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology. And my co-supervisors were Angela Daniela La Rosa, Associate Professor, and Shifteh Mihanyar, Associate Professor from the Department of Manufacturing and Civil Engineering, NTNU. I am very grateful to all of them. Especially my main supervisor, Stergios Goutianos, for all his support and kind attitude to me during this journey. We started from scratch; I am very grateful to him for guiding me throughout this tenure.

I am also grateful to my parents and other family members to support me mentally during this time.

The aim of this work was to develop an optimization methodology for product development where the product will be optimized in the areas of design, manufacturing, and environmental impact etc. As an initial step and within time limitations, the outcome is great. We implemented the proposed methodology to the product bicycle frame for selecting the best suitable material. Within the work progression of this thesis, I learned, how to use Abaqus and the Optimization software Isight. My supervisor, help me a lot in this learning period. It was a nice experience to learn from the beginning and applied it to my thesis work.

Finally, we hope this proposed methodology will contribute to developing a highly optimized product that can sustain a for long run without having any negative impact to different factors.

Md Ibrahim Khalil Ullah

Gjøvik, Octaber 2022

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List of Abbreviations (or Symbols)

FEA	Finite Element Analysis
LCA	Life Cycle Assessment
ISO	International Organization for Standardization
DfE	Design for Environment
GHG	Green House Gas
ResCoM	Resource Conservative Manufacturing
PLM	Product Lifecycle Management
SPSD	Sustainable Product and Service Development
MLP	Multiple Lifecycle Products
DfU	Design for Upgradability
CAE	Computer Aided Engineering

CAD	Computer Aided Design
GUI	Graphical User Interface
TKM	Ton multiplying with kilometer
AlF_2	Aluminum difluoride
VOC	Volatile Organic Compound

1 Introduction

Designing a product requires multiple considerations to meet end-use objectives. Earlier in product development, the design consideration was only limited to one or two parameters. For example, when making tools for hunting from hard rock in the early human age, sharp edge or angle was the only consideration to beat the animal. However, as the critical and analytical capacity of human increased with time, continuous efforts have been always carried out to cross the previous success. At present the majority of design optimization issues in real-world products or structures involve several design variables. Therefore, the designer must frequently take into account a number of objectives. These objectives typically contradict rather than reinforce one another. Although the design may not always be optimum, a single-objective optimization formulation performs well with respect to a single objective. Considering a hypothetical instance, a structure is produced using the fewest amount of construction materials if it is optimized for the least weight while taking into account restrictions such as allowable stresses, displacements, buckling loads, frequencies etc. However, this type of structure may not perform well in terms of dynamic response under seismic loadings [2]. The goal of a product engineer is now to create a product that is both safe and effective. The scale and complexity of a project or product can vary and may require a significant number of resources as well as high construction and maintenance expenditures. A cost-effective design is therefore one of the main goals for engineers [3]. As a result, product design optimization and development processes have also improved from earlier methods and approaches. In every industrial revolution, the considerations and equipment used for designing a product and further development processes had updated noticeably. Among all the industrial revolutions, the transition from third to fourth is significant for human life. It is that time when researchers or engineers started to think more deeply while developing a product. Environmental and other issues were also started to be under consideration. Thereafter, the product development and the designing process got both critical but at the same time holistic approaches due to environmental and sustainability considerations. And now developing a product is not only meeting one or two requirements rather it is a process to build more functional and meeting multi-objective and environmental requirements. Considering the automotive industry as an example, in the early days, the focus was given to manufacturing different body parts with high accuracy and their own specifications. With the advancement of science, now in addition to the highly accurate design specification of different body parts, light weight is also considered to outweigh previous benefits where complex design parts were possible to produce through various additive manufacturing processes. Additionally, environmental factors are being taken into account throughout the design phase to alleviate the load on the industry. As a result, material selection for different automobile body parts has become highly important while developing a new product within this industry. These examples are almost the same for all products that have been developed or are being developed. Lightweight product development is now considered one of the most holistic approaches since it can benefit in many ways. Like, when lightweight, environment, environment and structural, etc. factors are considered, a design approach not only reduces the weight of whole-body parts but at the same time, makes the parts be manufactured with less effort and complexity by reducing their energy consumption both in the material and manufacturing stage. In addition, emission to environment from the newly produced product will bear less consequence than traditional approach. Apart from the reduction of weight through this new designing approach, product performances are verified in early stage. So, highest quality and service of the product is possible to achieve.

However, to achieve this goal there are several design and development approaches, which have been proposed and applied for product development over the last few decades. They all have some advantages and limitations. In general, dealing with numerous design variables and restrictions in the form of constraints makes engineering tasks complex [3]. Therefore, some method has proposed how a product can be structurally optimized during manufacturing. While other methods considered optimizing a product in the design stage. Some approaches include optimization restrictions that only apply to one or two target functions. On the other hand, in some product optimization processes, they consider environmental performance only for a product's when designing and producing. As a result, the product leaves a smaller carbon footprint throughout production, use, and disposal. For such optimization, several methodologies have taken into consideration various instruments and techniques.

Furthermore, present time is very competitive and sustainability consideration is one of the mandatory considerations for a product development. There should be multi-objective while designing a product that can consider both sustainability issues and meet product functionalities. Key purpose of this study is to propose and demonstrate an optimization methodology where the optimization of a product design includes the reduction of environmental impact of a product. Inclusion of the environmental impacts in structural optimization differentiates this study from most earlier optimization studies. From a literature review, it was found that there is only a limited published work where the environmental assessment was considered during design optimization of a product. Furthermore, the cross validation of those methodologies for real life cases is very rear in most cases. This will also overcome in this study by applying the proposed optimization method on a product. For design optimization, the Finite Element Analysis (FEA) method is applied on the design model. For environmental optimization Life Cycle Assessment (LCA) method is used. LCA's primary potential for influencing environmental decisions is its ability to offer a quantitative foundation for evaluating prospective advancements in a system's environmental performance over the course of its life cycle [4].

Over the time, several tools have been used to optimize a product during development process. In recent years, on all these designing and development processes, usage of digital tools plays a significant role. Whereas initially researcher and developer put very hard work to implement those optimization processes through plethora of mathematical terms and rules because of manual calculation process. But now with the help of digital tools i.e., different software's, mathematical problem can be solved, and solutions can get in less time, effort and more efficiently. However sometimes, a component-based technique is used to perform structural optimization of mechanical system components, which means that interactions between the optimized component and its surroundings (system) are frequently ignored [5]. For such optimization processes, there is no assurance that an optimum design can be achieved, and which can be also costly and time-consuming. Therefore, in this study, different software's and cross validation of different mathematical principles in those software's tried to establish in order to find the best solution rationally and eliminate the arbitrary element of trial-and-error methods in the design process. Additionally, analysis capabilities have improved concurrently with the development of numerical tools, which led to an improvement in analysis capabilities for establishing a optimize product design.

2 Background

Numerous studies have been conducted in the past to identify qualities or factors that should be taken into account while designing or fabricating a product. Materials, shapes, production processes, and manufacturers play a key part in the development of products, [6]. This means each of these parameters individually or collectively can be the primary objective goal to during a product optimization. In the broadest definition, the term "product optimization" refers to a methodical strategy for product creation in which the analyst repeatedly modifies the formula and processing parameters [7]. And during this optimization, analysts may consider distinct factors or parameters for particular product development. For example, the goal of the research study of [6] was to minimize the number of parts and create a simpler version of a product without sacrificing quality in order to increase the production rate and lower costs. On the other side, a propeller's process efficiency was taken into account in design optimization by [8]. And in [9], optimization procedures are used for the arrangement of different materials in order to carry the load and boundary condition of the bus roof with less weight. Also, in many cases, analysts tried to optimize a product structurally. Like, [10] claim that the main goal of optimization should be structural optimization and it could be used to minimize the product's mass while satisfying all restrictions. Additionally, it was indicated that this process can lead to increased energy efficiency. However, in some cases, the development of products with longer lives was the main emphasis of [11] research. They recommended that a product's life cycle be optimized by maximizing material efficiency, life extension, and product recycling. [12] put emphasis to apply modular structure in designing for remanufacturing. So that the product can be recycled or reused at a later time to lessen its impact on the environment. In [13], analysts thought material strength should be a crucial factor for product structural optimization. Additionally, they thought that a product with improved structural integrity may satisfy customers and be more long-lasting. It seems, different researchers have considered different parameters or factors for product optimization. However, it is not only one parameter that can make a product fully optimized. Since there are several factors that need to consider while developing a product. In the following writings, it is tried to understand what can be the best possible factors and options that can help to optimize a product.

2.1 Material consideration in product development:

In the process of designing and developing a product, material choice always plays crucial role. Usually, a product can be made up from different materials that can all be substituted for one another. Most materials have different inherent qualities. The Ashby chart shows the density of various materials plotted against their Young's modulus and strength as [14] in figure 2.1. Here in this figure, on the top right corner metal belongs the maximum young modulus or strength and density. The lower it goes in both young's modulus and density; it will be softer materials. The strongest materials here are the silicon base materials, diamond etc on this figure. Besides these silicon and diamond, different types of steel, and titanium alloys also show high strength, but they have a bit higher density than diamond or silicon base materials. However, in real life application, it is not high strength material that can be suitable for end uses. Considering ceramics as an example, which have excellent strength but is noticeably brittle. Therefore, it cannot be used for all

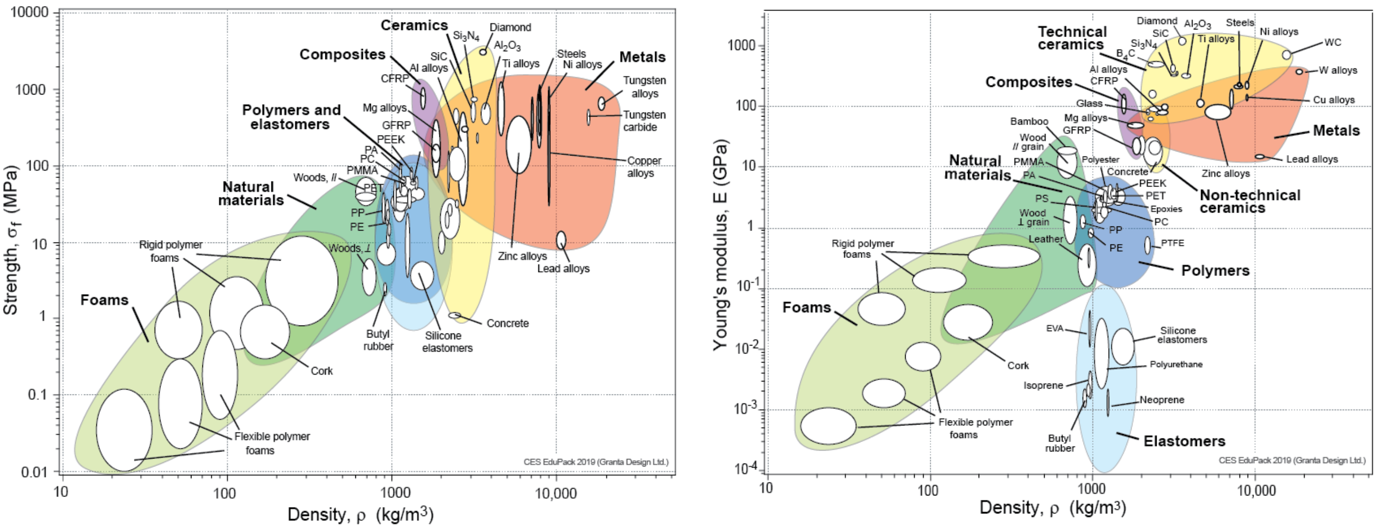


Figure 2.1: Ashby chart

applications requiring high strength. On the other side of low density region in the figure, different types of fiber composite materials, especially carbon fibre polymer composites show very high strength. This means that carbon fibre polymer composites show strength close to various metal alloys but with less weight than metals. This is a significant characteristic for many applications. Based on this result, product developers and engineers are now trying to replace many traditional materials of different products with much more lightweight composite materials that can provide similar properties.

Apart from the lightweight property, every material has some intrinsic properties for which they are being used in different products or in the same product in different parts. Considering the bicycle industry as an example, a bicycle frame can be produced with various types of materials e.g., aluminium, steel, different types of metal alloys, composites, etc. For the bicycle frame, strength is common and core properties that aluminium, steel, metal alloys, and composites material can meet no matter what are the intense of this strength. But in addition, they also have some intrinsic properties which make them distinct from each other. For example, all materials don't have similar material density, stiffness, resistance to deflection, etc. Rather all of these mentioned materials have different value of these properties. As a result, an aluminum bicycle frame performs differently than a bicycle frame built of another metal alloy or composite material. For example, while producing a bicycle tube, by changing the thickness of the tube, we may get the same strength for all different material frame models. But in that case, the other properties like stiffness or weight can be found different with that lower or high thickness value of the tube that later may create obstacle to achieve the optimization goal. Again, beside these properties, manufacturing processes also make each bicycle different from each other to perform. Because the way a metal frame is usually made, is not the same as a composite-made bicycle frame. And further to deep understanding, in each group, i.e., metal or composite manufacturing, there are plenty of alternatives for manufacturing. For metal structures, advanced additive manufacturing is one of the methods that show higher performance than traditional methods to produce highly accurate and complex structures. However, all these additive methods in many cases may not be suitable for composite manufacturing. So, it is necessary to follow different materials and manufacturing processes to produce high optimized products. Similarly, geometry of a product should also be defined precisely so that it can carry out the functionalities of it end uses. Like the example of material for tube frame, it may be possible to achieve same quality of tube by changing its radius, but similarly it may impact some other load or boundary condition of the frame. And this is also why there is need to apply constraint during optimization.

2.2 Geometry influence on functionality and quality of a product:

As mentioned above, various materials and production techniques might result in an optimized product. Similar to this, the shape or structure plays a crucial role in producing high-quality products that are highly functional. A product can be made using a wide variety of geometrical shapes. Perfectly crafted geometric forms are sometimes pleasing to the eye because of their distinctive symmetry. Likewise, a human face that is nearly flawlessly symmetrical and organically proportioned to follow the golden ratio is frequently thought to eye soothing. Consider the design of the well-known food item "Pringles chips," for instance. A chip can be made in a variety of shapes. But according to [15], it has been noted that the Pringles chips have the best crispness and texture, and their curved shape makes them easy to eat with the tongue. Like that chips structure, there are numerous features, i.e., height, thickness, volume, angle, density, size, etc. characterize the structure of a products. But it is always not true that a perfect symmetrical geometrical shape will be best in quality as well. Therefore, developer have been trying to find out the optimum geometrical shape of a product. Following the example of the human face and pringles chips, there is another notable example of geometrical optimization is the structural evaluation of “Bridge”. The structural difference of the supporting beam and column of a bridge has changed from early to present days [16] figure 2.2. Also, the position of those supporting beams has been updated overtimes for better suspension, load bearing capacity, vibration, etc. So, considering these and many other requirements, it is very significant to optimize a product geometrically while designing.

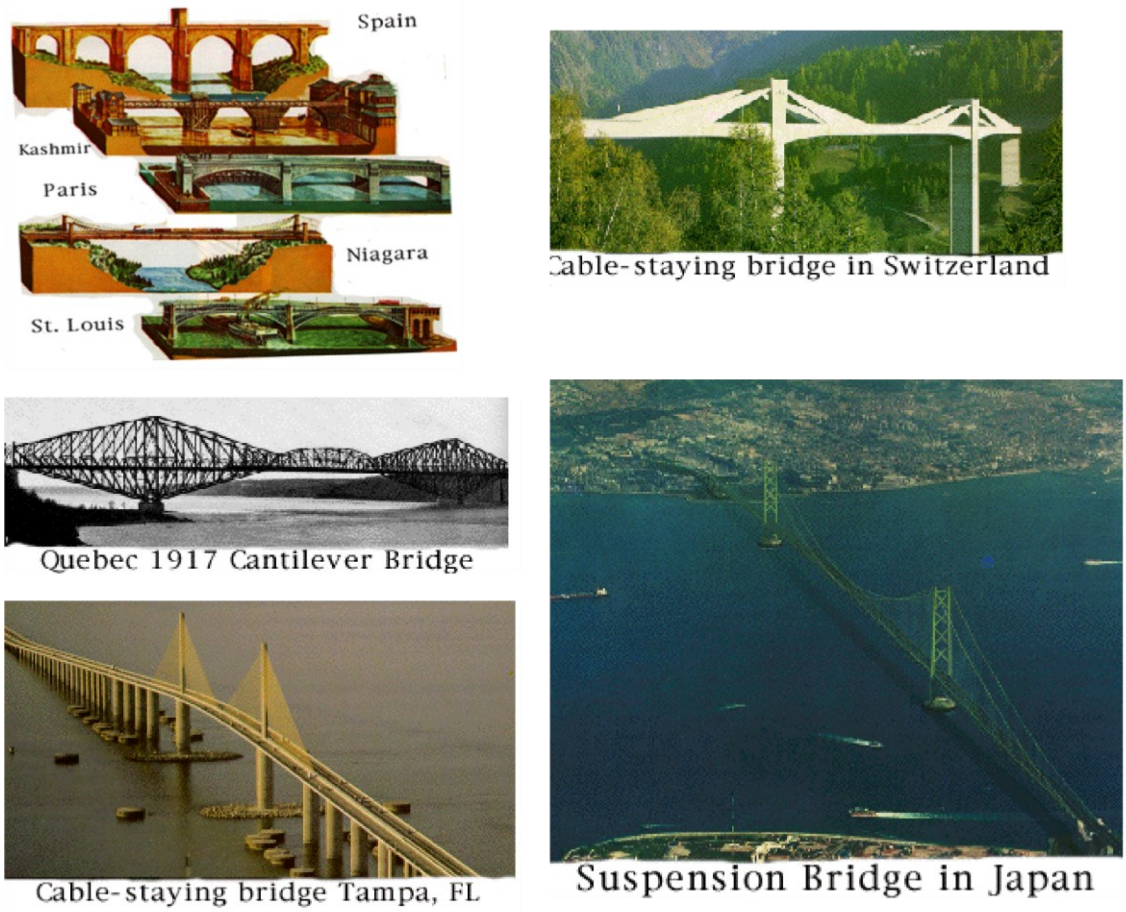


Figure 2.2: Geometrical changes in bridge design over time.

2.3 Manufacturing methods, Recyclability and biodegradability for material selection:

Both metals and plastics are used more frequently and have more success than other materials in the fabrication of products for complex geometries. However, metals have been used for product creation since the early stage of human history. Additionally, the focus had dedicated more to metals than to other materials due to their good service in tools, equipment, and high strength product development. In contrast, composite manufacturing techniques and equipment had not adapted to various high strength product development as same pace as metal. This is due to late discovery of polymers that used to reinforce the fiber in composite material. As a result, the procedure for creating complex structures in composite material is still somewhat complex. And the use of composite materials in the heavy automotive industry still has a lower success rate than metals. Although, researchers are trying to develop new methods and technologies to produce more complex composite structure but still metal shows better performance in many cases in terms of strength, durability and for other properties. And after the evolution of different additive manufacturing processes, especially 3D printing and other fabrication technologies and also other advance subtractive and formative manufacturing processes, the use of metals on product development rises up in different industry like, aerospace, automotive and others. As a result, it may become possible for engineers to produce a product in more convenient way e.g., in low cost, time, and effort to get an optimum product.

On the other side, the recyclability option has been explored from the 20th century, precisely from 1960s decade, while curious people had begun to think narratively about new design and development strategy [17]. Already manufactured products have significant negative effects on the environment, So, developer must consider the entire life span of the product in order to reduce its environmental impact. Since a product's designing stage has been proven to have the greatest influence on a product's ability to lessen its environmental impact, a product's ability to be recycled after use also depends on its design and development. Composite material recycling is a more difficult process than recycling metals and plastics. This is owing to the homogenous nature of metal and plastic, which makes it comparatively simple to separate and process the basic materials. But because fiber reinforcement and polymer resin have heterogenic properties, it is difficult to separate them in composite products [18] [19].

Additionally, since there can two types of composite material from degradability perspective. One is non bio-composites, and the other one is bio-composite materials. Bio-composite material is formed with biobased material. And it has been found that the natural degradation of bio-composite material is higher than metals when comparing the total life duration of metal and composite products. As a result, despite sustainability and environmental concerns, the composite material has great potential. But when developing a product, there are a number of factors like manufacturing processes, recyclability, biodegradability, etc. to take into account when choosing the material.

2.4 Methods to overcome environmental impacts:

It has been advised in several research studies that the environment should be taken into account when creating a product [20]. In [20] the environmental friendliness of two modern manufacturing methods, additive and subtractive, was assessed and it was suggested which one to use. [21] mentioned, reuse, recycling, or degradation compensation to environmental impact is greatly influenced by the early design stages. Therefore, it is essential to identify the crucial environmental aspects of a product’s life cycle at the design phase. Along with structural and material optimization, taking the environment into account is one of the essential criteria for producing the best possible product. As a result, numerous attempts have been made to incorporate or build a procedure for evaluating a product's social, economic, and environmental impact. According to [22], Life Cycle Assessment (LCA) and Ecodesign, often known as Design for Environment (DfE), are the two main methods or techniques that have been developed to assess the environmental effects. In order to assess these implications on environment for a product accounting environmental, social, and economic factor, LCA has been used extensively over the years. This is a noble strategy that was devised in the early 1960s to select the superior product between two options in terms of the influence on the environment [23]. LCA analysis is used to measure the environmental effects of a process or product over the course of its life cycle, according to ISO 14040 series. Additionally, every step, including material extraction, recycling, and disposal at the end of product life, is taken into account while making this assessment. There might be two objective methods used in LCA analysis as an environmental effect assessment tool [4]. One goal is to identify and assess a product or process' environmental performance from birth to disposal, which contributes to the decision of whether to choose the product or not. Another objective of LCA is considered, it is a tool to assess the potentiality of environmental improvement for the product system. A decision to select environmentally friendly products can be made following the evaluation of LCA in terms of performance indicators, such as global warming or GHG emission, acidification, eutrophication, and ozone depletion. By taking into consideration those LCA results, it is feasible to gain insight and take the necessary steps to build an environmentally sustainable process or product. As a result, when those two goals are taken into account simultaneously, LCA aids in the early stages of product design optimization.

2.5 Optimization; a path to solve or address product development issues:

It is unquestionable that there are many aspects and difficulties to take into account while creating a product. The more problems that are taken into account and resolved throughout the design phase, the better the final product will be. From the figure 2.3, it is tried to illustrate that how different factors have been considered over the times for a product development. It's shows, material, geometry and manufacturing had been considered in

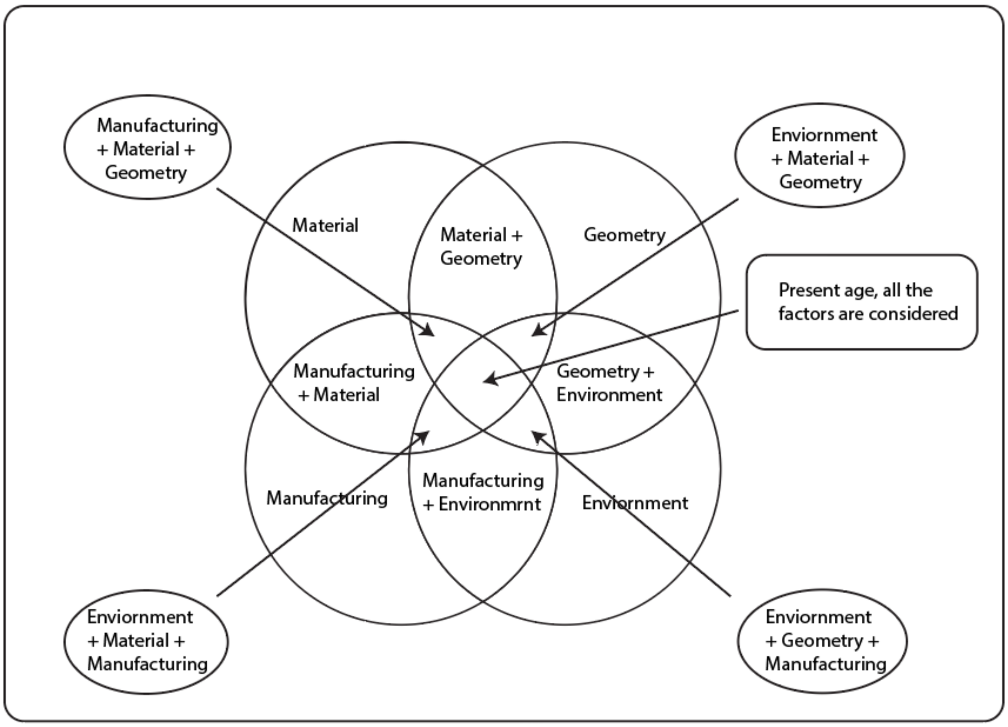


Figure 2.3: Factors considered over the times for product developments

many development processes where these were sometimes considered individually and sometimes combining each other. After the environmental awareness arises product developer tried to take consideration of different environmental indicators, like global warming, water consumption, temperature increase etc., individually, or rarely as a whole. Due of the time and manual labor constraints in past, there weren't many factors that could be taken into consideration. It got simpler to solve those problems and take into account additional factors after the advancement of various statistical and mathematical principles, especially after the computational device discovery. Therefore, various problems can be solved with less effort now and create more optimal products. It is different digital tools now and efficient use of these tools that make the development process more accurate, cost effective and time saving. For instance, reducing material from minor areas allows a structurally optimized product significantly reduced weight while improving product's quality. Additionally, reduction of material from a product accelerates the processes of development and production. Similar to this, when a product is environmentally optimized at the outset of its development, it lessens the pressure on environment more than a product that is not

	Environmental consideration		
Literature ref.	Yes	No	Partially
[13]		x	
[12]	x		
[24]	x		
[11]			x
[8]			x
[9]		x	
[10]			x
[25]	x		
[26]	x	x	
[27]	x	x	
[22]	x		

Yes=	Decision made on Sustainable environment consideration
No=	Decision made on Structural or manufacturing consideration
Partially=	Decision doesn't influence by environmental consideration fully rather other consideration

Table 2.1: Literatures summery of the optimization methodology that consider environmental issues

Various optimization strategies are available and used depending on the product category or optimization goal. To develop low-volume, aesthetically pleasing, structurally optimized products in [13], researchers used the morphological indicators (MI) hypothesis. The Computational Fluid Dynamics approach is frequently used in [8] for optimizing products that deal with or carry the fluid. The topology optimization method is commonly used for material placement to design parameters within certain loads and boundary conditions. Multi-Material topology optimization method has been using for structural optimization on many product development processes as an example in [9]. Resource Conservative Manufacturing (ResCoM), a new moniker for Product Lifecycle Management (PLM), has been proposed to make decisions for Multiple Lifecycle Products (MLP) in [12]. To close the manufacturing loop using the standard MLP strategy and produce a sustainable product, numerous factors must be taken into account. The ResCoM strategy puts those factors into consideration. Design for Upgradability (DfU) is another strategy that may be used to extend a product's lifetime by enhancing its usefulness, according to study by [28]. it was suggested the DfE technique followed by LCA in [22] for designing environmentally sustainable products. Investigators [24] with the assistance of industry experts recommended the Sustainable Product and Service Development (SPSD) technique. To make the product sustainable, SPSD methodology was taken into account at every stage of the life cycle. However, given the cost and time constraints, it might not be very useful in practice. In table 2.1 summery of the environmental consideration are given which have been observed in several literatures.

From above discussion, it is understandable that there is a noticeable gap remain in many optimization methodologies. And for a sustainable product development, it’s not only the structural or environmental issues should be consider. Rather, it is important to have the combination from both of these factors and include more and more factors for true optimized product. Therefore, to overcome this gap, this study has proposed an optimization methodology that described in the following methodology part. And later, this proposed method is implemented for optimizing the product that is a bicycle frame in this study. In the implementation phase it is tried to describe how a product can be optimized together both structurally and environmentally.

3 Methodology and tools

3.1 Proposed method:

Different investigations have already recommended numerous optimization approaches, which are compiled in the literature section of this work. However, a noble, independent strategy is developed in this study. The proposed approach is presented on the figure 3.1 in a methodical order. The designing stage is the initial phase that begins with the problem formulation. The problem might be defined based on the current issue or by assessing previous studies' findings. An in-depth examination of the problem formulation assists in the identification of design parameters, critical elements, loads, boundary conditions, etc. After identifying the issue and the design features that need to be optimized, the product model is built in the following stage. The optimization model can be created in both parametric and non-parametric approaches, according to experts but, the type of optimization model must be determined by the optimization goal whether it will be parametric or non-parametric [29]. The newly constructed model is then put through a Finite Element Analysis (FEA) simulation under pre-established boundary conditions, applied loads, and constraints to see if it structurally addresses the design challenge. The FEA is performed in this study by using the ABAQUS software. After the initial analysis, the developed design model will be further optimized in this study to reach the optimization goal or achieve continual improvement for the selected product. Therefore, the following stage involves reviewing the FEA simulation results, and important factors or properties that can be chosen as the objective functions for optimization. Stiffness, volume, energy, and other variables or qualities may be the important factors or parameters here for optimization. In this study, stiffness is considered the design parameter for structural optimization. From several research studies, it observed that stiffness is one of the mandatory properties that every material must have for a bicycle frame. By adjusting the variables while satisfying the constraints, the optimization process is carried out. Th operation is the repetitional process of 1000–1500 times, depending on the convergence rate, to get the optimum value.

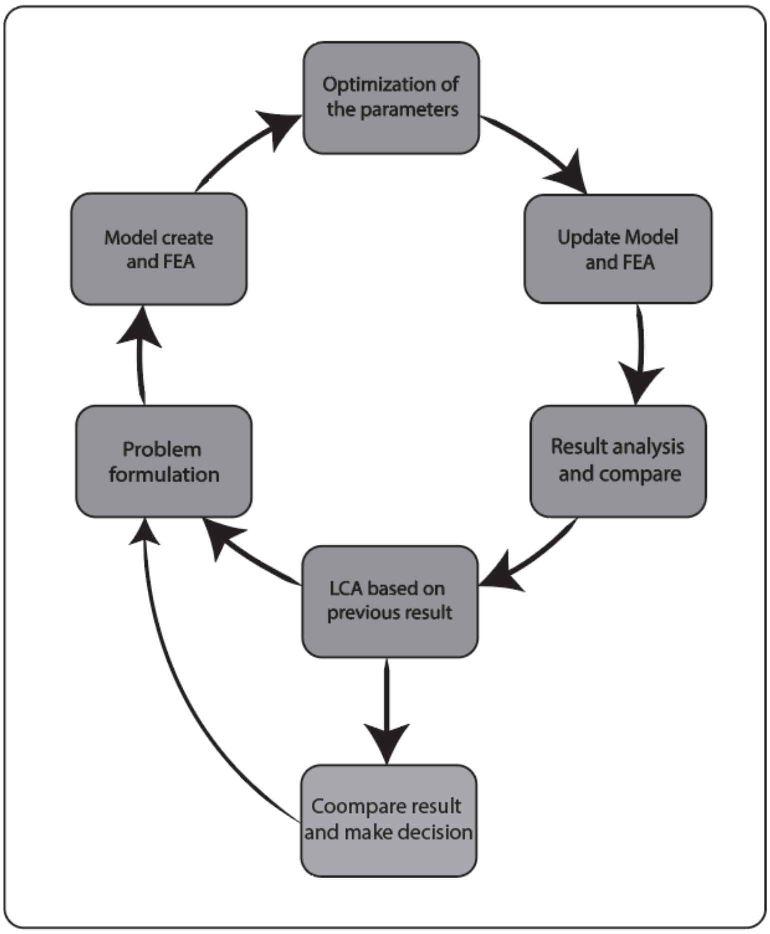


Figure 3.1: Proposed optimization framework

The Dassault Systèmes based ISIGHT software was employed in this study for optimization. After determining the best value for the predefined feature, the model is generated a second time using the updated optimized value, and FEA is used to support the optimization results. In the following stage, LCA is carried out based on the outcome of the simulation on the critical factor. In this step, the researcher or designer will be able to determine whether the product, which is composed of specified materials and features, will be ecologically beneficial. It will also be feasible to assess several solutions from an environmental standpoint and make a choice. In this study, this environmental impact evaluation is made from cradle to gate for the selected product bicycle frame.

3.1.1 Research Method:

In a general context, there are two sorts of research methods: qualitative and quantitative. This classification is based on how data are gathered and handled as proposed by [30]. In quantitative research, a significant amount of data analysis is used to do the research. Comparatively, qualitative research focuses on challenges that call for the interaction of in-depth analysis, human experimentation, and insight. This viewpoint enables us to define this study article as quantitative. Several digital platforms were used in this research to carry out the analysis. The name of the software and how it was applied in this study are described in the materials section.

3.1.2 Research strategy:

Yet again, [30] identify three categories for research strategies. Abductive, inductive, and deductive reasoning. The deductive method evaluates the theories that are in use, develops a hypothetical solution to the issue, and then attempts to resolve it. The inductive approach solely draws from actual perspective and observation, not current theories. Finally, abductive reasoning starts out inductively but ends with a solution to the dilemma. According to these categories, present research falls under the deductive category since it starts with the formulation of a problem based on a literature evaluation and proposes a framework for a solution.

3.1.3 Data collection:

Data for this research paper have been collected mostly from earlier literature paper. However, in some case e.g., in LCA few data are assumed based on the observation from the previous structural analysis.

3.1.4 Research Tools:

This research is performed inside the digital environment mainly. As a result, various CAD, modeling, and simulating software were employed throughout different stage of the optimization procedure. For instance, Solidworks was first utilized to create the product design model, but Abaqus CAE was eventually substituted. Isight software has been utilized to optimize the objective function. These two different categories softwares have allowed for structural optimization of the product designs. Finally, Simapro software has been used to carry out LCA in order to assess the environmental contribution in product manufacturing. The aim of using this software to make this optimization procedure more sustainable and efficient. A brief explanation of these software programs and how they were utilized for this project is described in the following section 3.2.

3.2 Abaqus software:

Parts name	Length in mm	Radius in mm
Head Tube	200	21.5
Top Tube	578	15
Bottom Tube	655	16
Seat Tube	296	15
Bottom Bracket	150	21.5
Seat Stays (around)	553	10
Chain Stays (around)	490	10

Table 3.1: Modified measurement table of bicycle frame

Abaqus is advanced software that conduct various analyses in material and structural stage for a product. Both linear and non-linear analysis can be performed with this software [31]. To build the geometry and analysis in Abaqus, the User manual [32] of this software has been followed in this paper. A Graphical User Interface (GUI) has been used to create the bicycle frame model. Python programming language is used to give commands or modifications to the model which is generated by GUI. Every command is usually passed to Abaqus CAE which translates the command and implements it. In several cases, to build the model, the Abaqus script is used to bypass the GUI. To build the bicycle frame, different diameters and lengths tube were considered. With the python command and GUI initially shell tubes of those different tubes of bicycle frame model are created as figure 3.4. All those tubes have known lengths and angles but no thickness. Every shell tube has given individual unique name that help them for identification and future usage. For the length and diameter reference paper were followed [33]. However, a few measurements have been changed to simplify the design and make it a parametric model e.g., seat and chain stays as shown in figure 3.2 which is taken from python script. However, this measurement modification is not significant that can impact to the goal of this study. The table 3.1 lists the updated measurement for reference. Also, to make the model parametric, different mathematical principles are used in the python script.

Stresses analysis for various materials is performed after the parametric model has been developed. In this study, the optimum design product is compared among three types of materials: aluminum, carbon fiber epoxy composite, and flax fiber epoxy composite. There

```
#seat_tube,
seat_tube_radius=15.0
seat_tube_length=296.0

#top_tube,
top_tube_radius=15.0
top_tube_length=578.0
angel_top_seat=100
distance_top_origin=35

#head_tube
head_tube_radius=21.50
head_tube_length=200.0
upward_distance_top_tube_join=50

#bottom__bracket
bottom__bracket_radius=21.50
bottom__bracket_length=150.0

#bottom_tube
distance_top_bottm_at_head=9
bottom_tube_radius=16.00
bottom_tube_length= 655

#chain_stays
chain_stays_long_length=400.0
chain_stays_small_length_y=88.0
chain_stays_small_length_z=60.0
chain_stays_small_radius=10.0
distance_chain_stays_mid_bracket=40

#seat_stays
ratio=(1.0-chain_stays_small_length_y/chain_stays_long_length)
seat_stays_length_total=math.sqrt((seat_tube_length-distance_top_origin)**2+(chain_stays_long_length+chain_stays_small_length_y)**2)
seat_stays_long_length=ratio * seat_stays_length_total
seat_stays_small_length=seat_stays_length_total-seat_stays_long_length

#stays_connector
stays_connector_length= 2*(chain_stays_small_length_z+distance_chain_stays_mid_bracket)
stays_connector_radius=5.0

#stays_edge_connector
stays_edge_connector_length=28.0
stays_edge_connector_radius=45.0
```

Figure 3.2: Tube section name and value of bicycle frame model in Abaqus script

are various procedures that must be taken in order to finish the Abaqus analysis, as illustrated in the figure 3.3. It has been observed that material properties for bicycle frames in Abaqus have been specified after creating parametric models of the chosen product. When establishing the material properties, two properties—density and elasticity—were taken into account. Following that, this material was allocated to various tube sections of the bicycle frame. Boundary conditions and loads were assigned for the stresses analysis in the following two steps. Corners of two sides joined by stays and the bottom of the head tube are regarded as fixed under a boundary condition. Additionally, loads of 650 N/m2, 60 N/m2, and 130 N/m2 are applied as concentric forces to the upper portions of the head tube, bottom brackets, and the seat tube (figure 3.5). All of these boundary conditions and loads are based on literature research, which is cited in the appendix. The entire bicycle frame is viewed as figure (4.1a) a single part in the job analysis.

3.3 Isight software:

Isight is a simulation software package that analyzes the design and automation of any component's process [34]. The current API for Isight is compatible with numerous additional house-brand or other branded applications. Any internal files, such as CAE, ODB, excel spreadsheets, text files, etc. from different commercial CAE/CAD software, such as Solidworks, Abaqus, Ansys, Catia, etc., can be integrated into this program for a variety of analyses. Digital analysis can be completed using the Isight software for optimization, design of experiments, Taguchi, etc. [35]. In this study, optimization analysis is used to optimize a bicycle product design frame. Various constraints are used in design

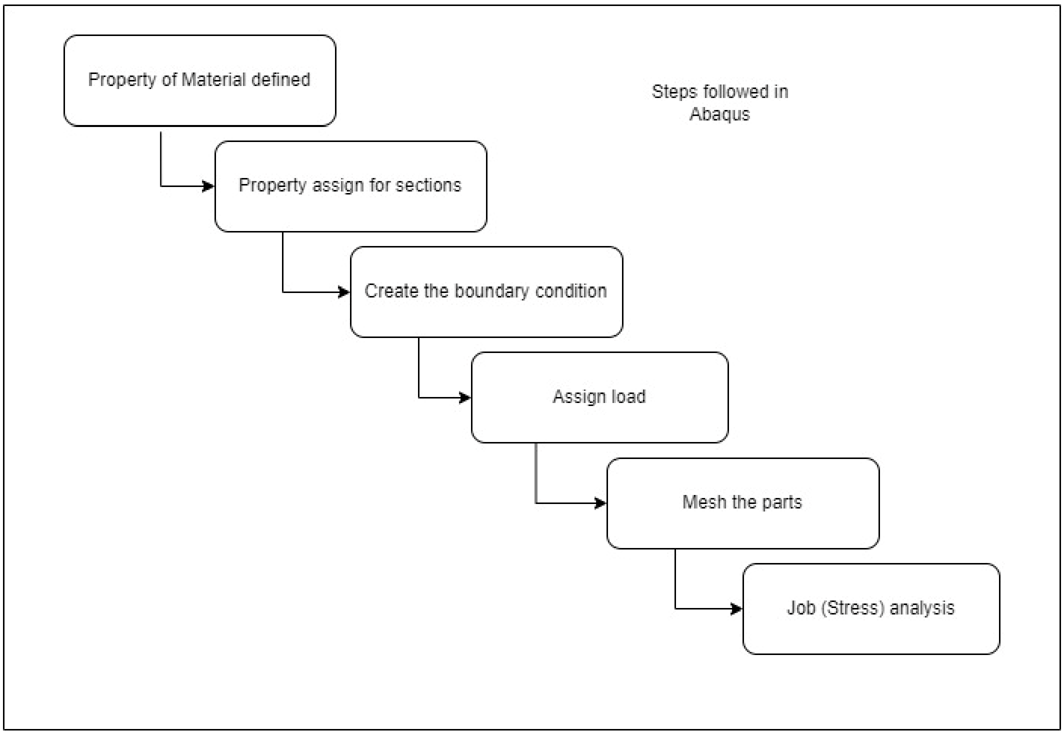


Figure 3.3: Steps followed in Abaqus for FEA

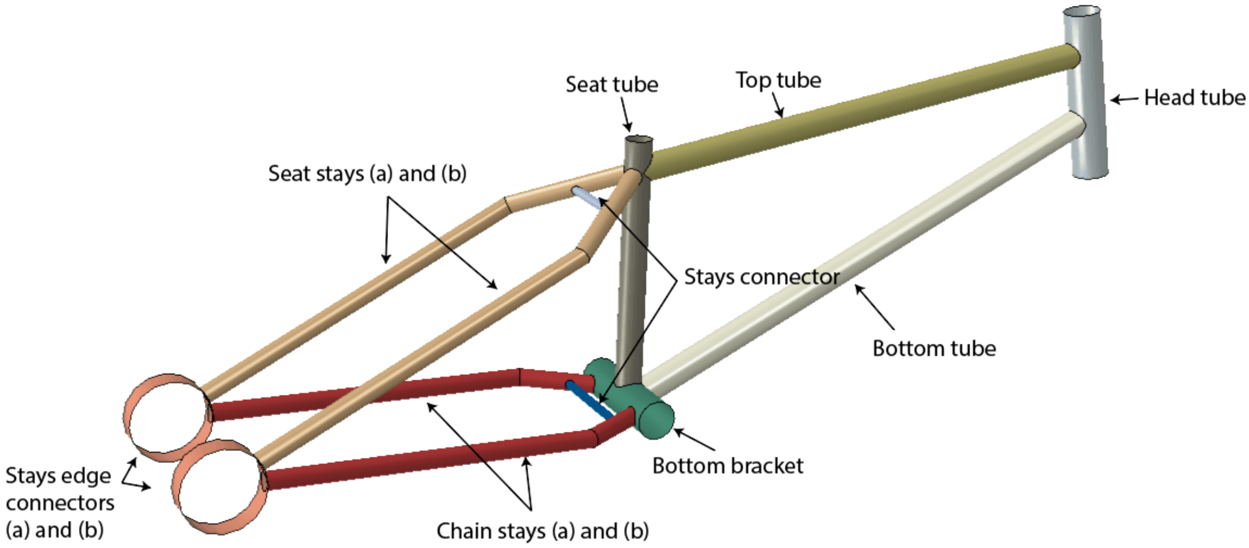


Figure 3.5: Different tube sections in created bicycle frame model on Abaqus

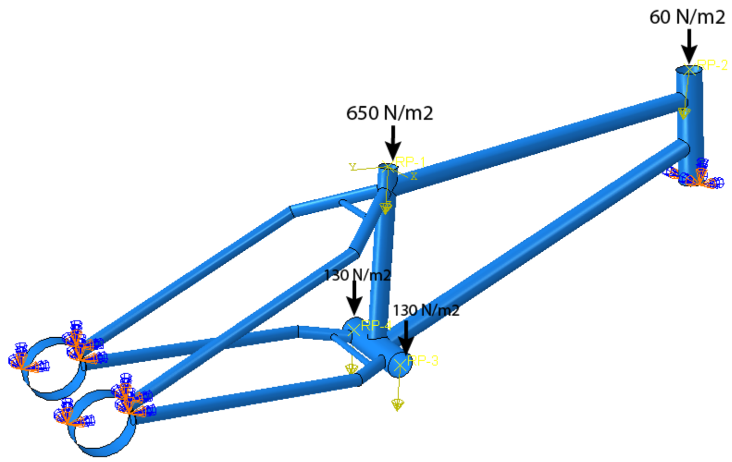


Figure 3.4: Bicycle frame model with applied load for FEA

optimization to achieve the realistic result in the optimization. These constraints are mathematically enforced by the optimization method [36].

This study uses the Abaqus software's CAE or text file for stresses and displacements analysis of a parametric bicycle frame design model to carry out the optimization procedure. The thickness of various tubes on the bicycle frame, the maximum displacements, and the maximum stresses limit are taken into consideration as constraints. On the other end, strain energy minimization or maximization is regarded as an objective function. Figure 3.6 summarizes Isight's entire process and figure 3.7 shows how data are usually flow between Isight and Abaqus software. Isight required the deployment of two programs for optimization. Our model includes Abaqus by default, thus one program was written in Abaqus and the other in an optimization program. First, the Isight Abaqus application runs the CAE file from the Abaqus task analysis. Available input parameters become apparent after the file has been read. The thickness of each tube was chosen for this study. Total strain energy, maximum stresses, and maximum displacements are chosen as output parameters. The Isight optimizing program is configured to execute optimization in the next section. For this, the Hooke-Jeeves technique was chosen as the

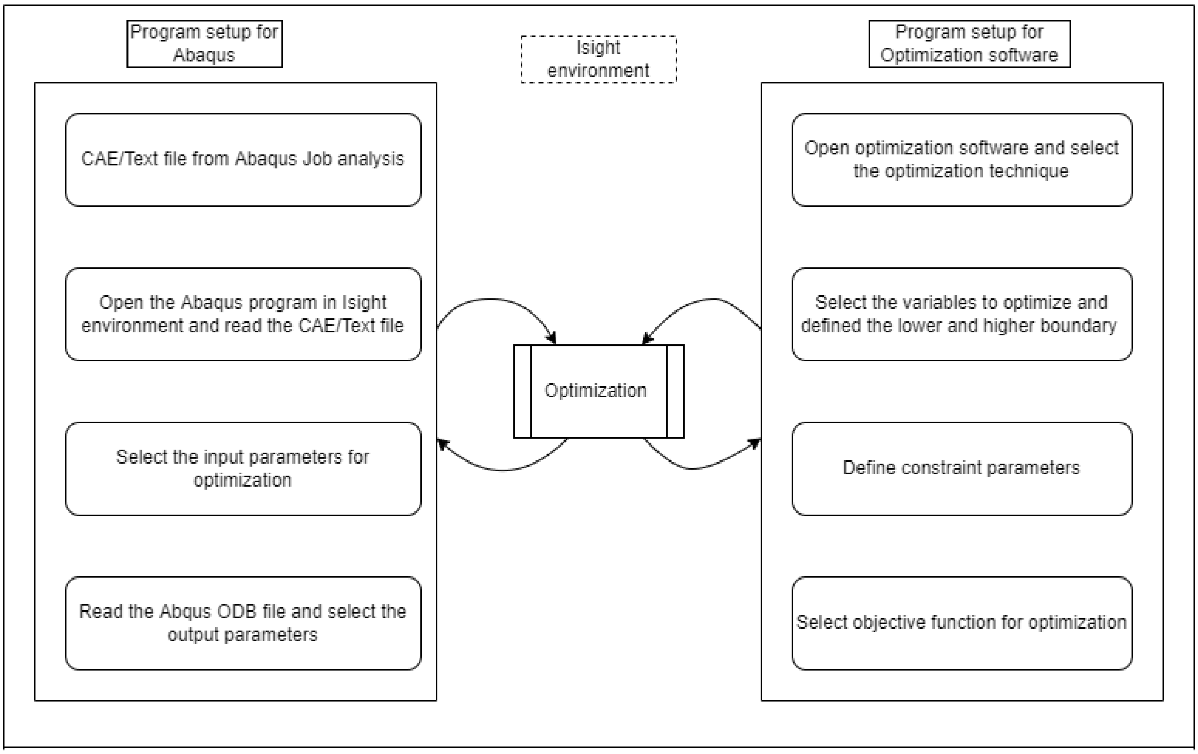


Figure 3.6: Isight optimization process

initial optimization technique. Both linear and non-linear design procedures are suitable for this technique. Additionally, this strategy works for long time simulations in order to produce good results. Maximum evaluations, relative step size, and maximum fail running were set up after choosing the optimization approach. These ranges usually stay at 1000–1500, 0.20–0.5, and 100–200, respectively. To get the ideal thickness value, input variables from the Abaqus are later limited with a lower and higher limit. This limit has been kept from 0.1mm to 3.0mm based on the materials. Next the highest limit of

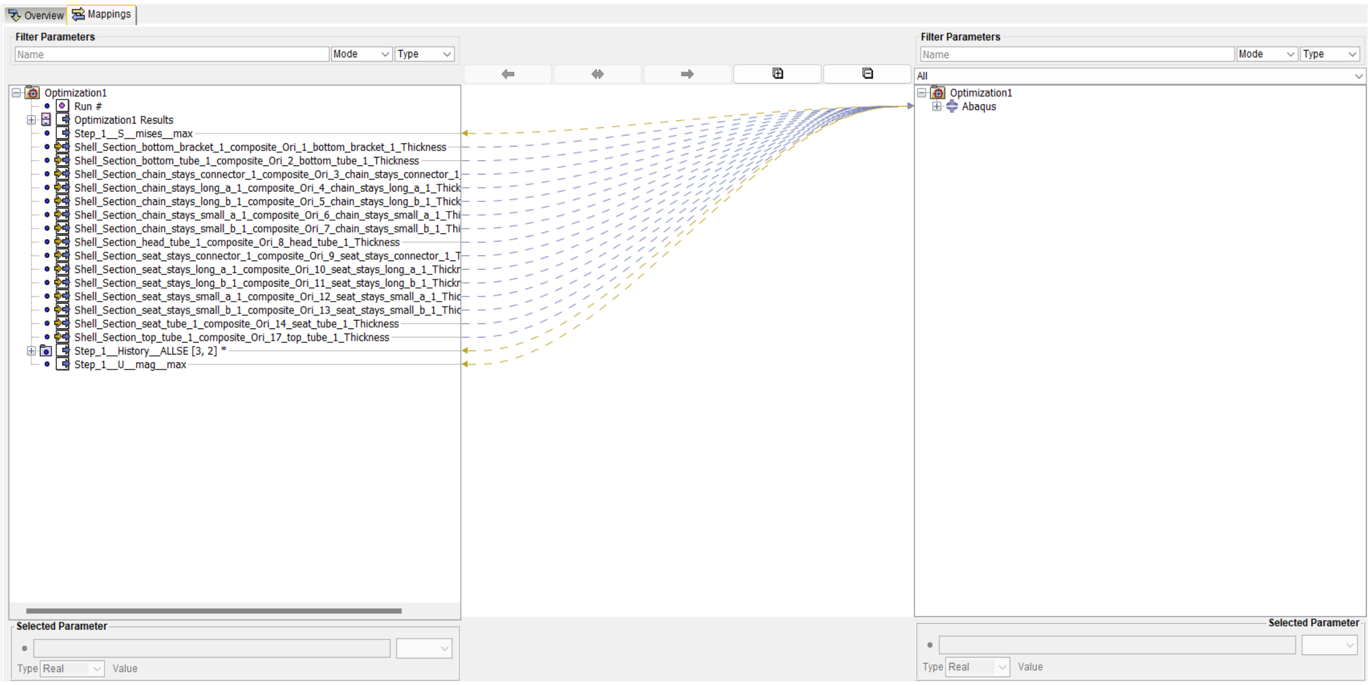


Figure 3.7: Data flow during optimization in Isight

displacements and stress is established for constraint. The displacements, in this case, has varied from 1 to 5 mm depending on the type of material, but the highest stress modulus ranges from 50 to 450 MPa. These constraint limits are usually kept below the material maximum stresses and displacements to get better result for the rough situation of real

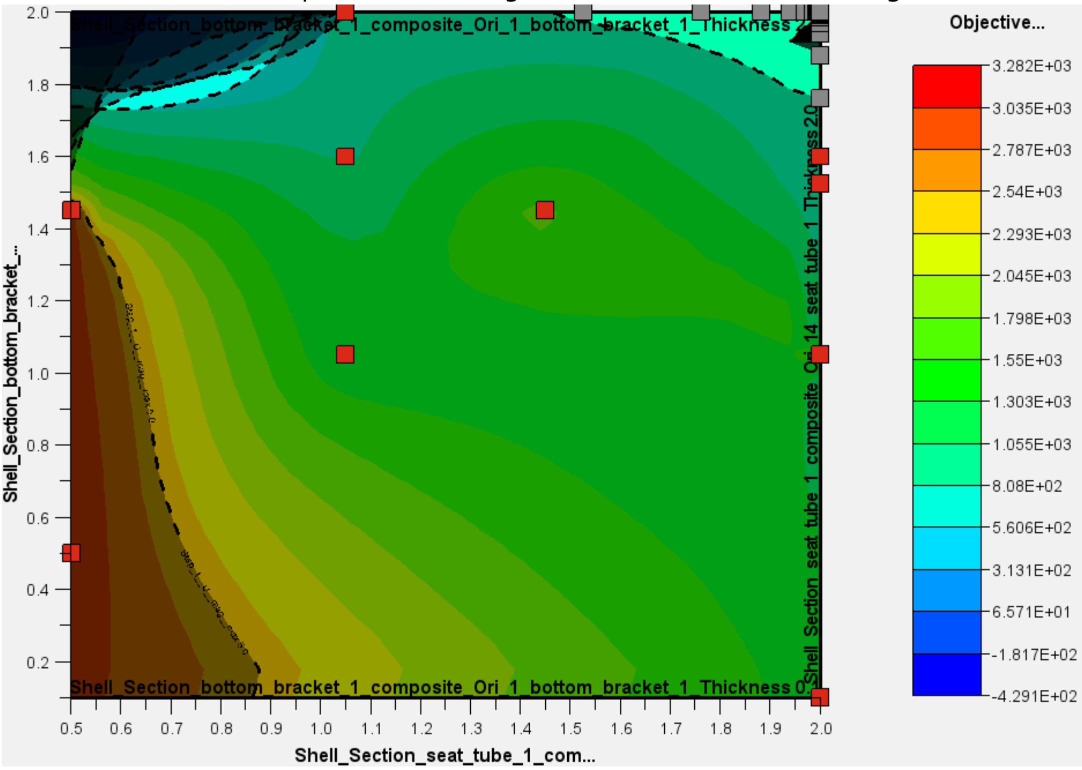


Figure 3.8: Contour plot of the optimization result to observe which results can meet objective function

life. For example, while highest displacement level is kept to 2.0mm, it means, it will consider the optimization result that will only keep the displacement up to 2.0mm not above to this limit. And by keeping this limit below their regular value, it helps to get the bicycle frame with minimum displacements. In optimization procedure, the results which can meet the objective function as per constraint condition will only be considered for future analysis. These results are visualized as grey color dot and which couldn't meet the condition and failed, they are marked as red doted. For easy understanding, figure 3.8 has taken as an example from flax-epoxy reinforced bicycle frame where red marked dot are the result from analysis that couldn't meet the objective function and green dots are the result that meet the objective functions. And for optimization, initial objective function of this study is thought to be minimizing or maximizing the strain energy. Although, this is only considered and evaluated for aluminum frame only. And for other two materials, only minimizing the strain energy is considered for optimization since that is found right way for optimization for this study.

3.4 Simapro software:

Today, a variety of computational techniques are available to assess a product's environmental impact. Simapro 9.2.0.2 has been utilized for Life Cycle Assessment in the current research due to the shortcomings of numerous alternatives and time limits. However, this software is among the top LCA software in over 80 countries in various industries and colleges due to its transparency and usability [37]. The ISO 14040 standard series were used to conduct the LCA for this paper. There are five actions as figure 3.9 shows that have been carried out in accordance with this ISO standard in this study.

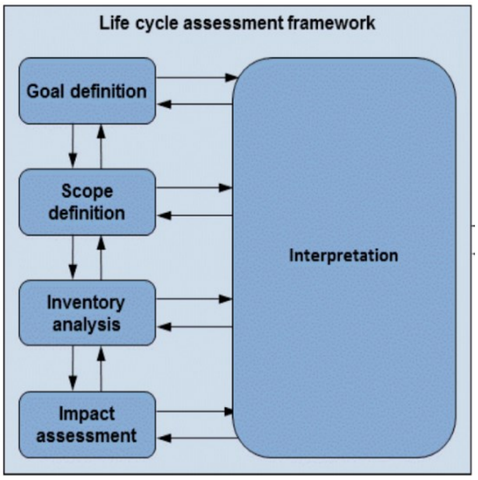


Figure 3.9: ISO 14040 -14044 Life Cycle Assessment procedure [1]

Goal and Scope: This project's goal is to evaluate the environmental impact of bicycle frames built from various materials and fulfilling the mechanical requirements. The study's focus is dedicated to the cradle-to-gate process, which means that each and every step of the manufacturing process from the collection of raw materials to the bicycle frame's final assembly will be taken into account. Global warming, acidification, ozone depletion, eutrophication, ecotoxicity, fine particulate formation, and human carcinogenic toxicity are the few mid-point categories for environmental impact categories that this study will look at for environmental assessment. The production facility for making bicycle frames has been considered Bangladesh in terms of location. So, the material or service that were not produced in Bangladesh, will import to this country. And the data input in Simapro software have also done accordingly.

Functional unit: The weight of the optimized bicycle frame from stiffness perspective is considered as the functional unit.

According to the above description of the method and uses of software’s, this proposed methodology is then implemented to the selected product bicycle frame as following sections. The findings are later analyzed critically for choosing best material. It should be noted that based on the selected product category and time limitations, the boundary of this research study is limited to only few parameters i.e., stiffness of the bicycle frame and environmental impact evaluation in cradle to gate. However, these choices haven’t any impact to develop the methodology and in implementation. Rather in this methodology and implementation part, it narratively describes and shows how several parameters that can impact during a product design and development be considered for achieving an optimized product.

4 Implementation and analysis

As described in the methodology section, before any design is finalized, the design (of the product e.g., bicycle frame for this study) is optimized taking into account several objectives or functionalities, as well as providing environmental benefits. In this study, the stiffness of the bicycle frame has been optimized structurally as the primary objective. And later environmental impact is analyzed in the fabrication of the product to check the intensity of the pollution.

The material thickness usually affects any products rigidity towards any applied load. A similar situation will analyze to the selected product of this study, bicycle frames, under a given load. The strain energy required to bend the tube, increases with tube thickness. In order to increase the rigidity of the bicycle frame, it is therefore recommended to consider decreasing strain energy in optimization process, in accordance with the approach for optimization that has been proposed, [38] [39]. Since three separate materials will be used for the analysis in this study, each testing and analysis has been described in separate parts below, along with results and commentary. As an initial step of optimization, a parametric model of a bicycle frame with no thickness is developed. And followingly, material properties and thickness are updated to the model for analysis.

4.1 Aluminum bicycle frame:

4.1.1 Model setup:

In this first analysis, as a material Aluminum has been considered. According to [40], [41], density and elastic properties have been taken into account for the model as the table 4.1. Later, several bicycle frame tube sections are assigned with material characteristics on the model with a initial thickness value of 2mm (except stays edge connector rings where thickness is 10mm). And after material attributes are allocated, the bicycle frame was depicted in the figure 4.1a.

Material	**Density, g/mm3**	**Elastic modulus, MPa**	**Poisson ration**
Aluminum	2.7×10^{-09}	70000	0.3

Table 4.1: Considered mechanical properties of Aluminum material for model

The entire model is then specified in static force. As it is shown in

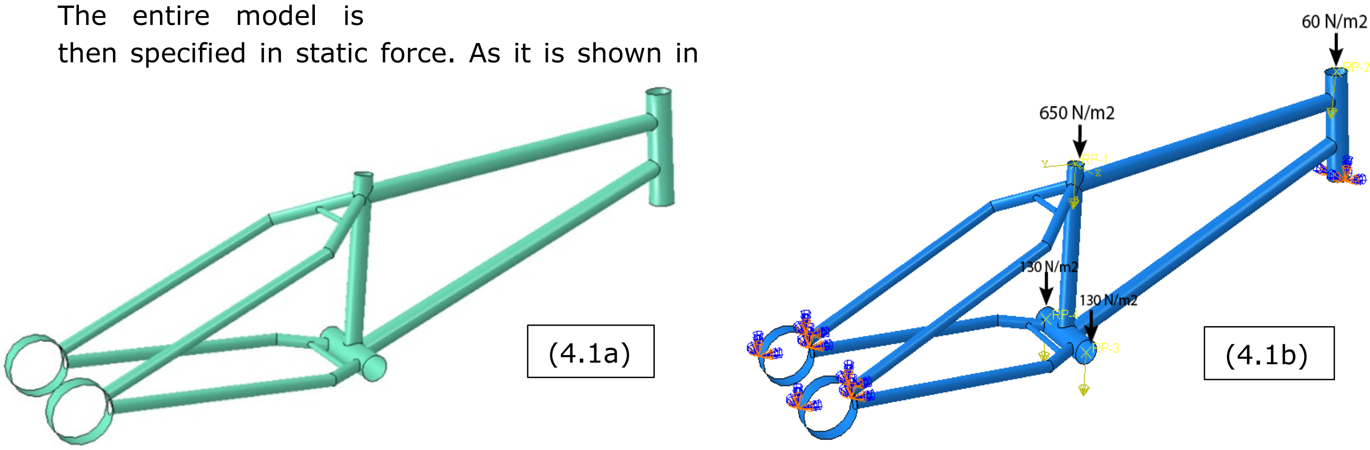


Figure 4.1: (4.1a) Bicycle frame with assigned material into tube sections (4.1b) Load and Boundary condition for job analysis

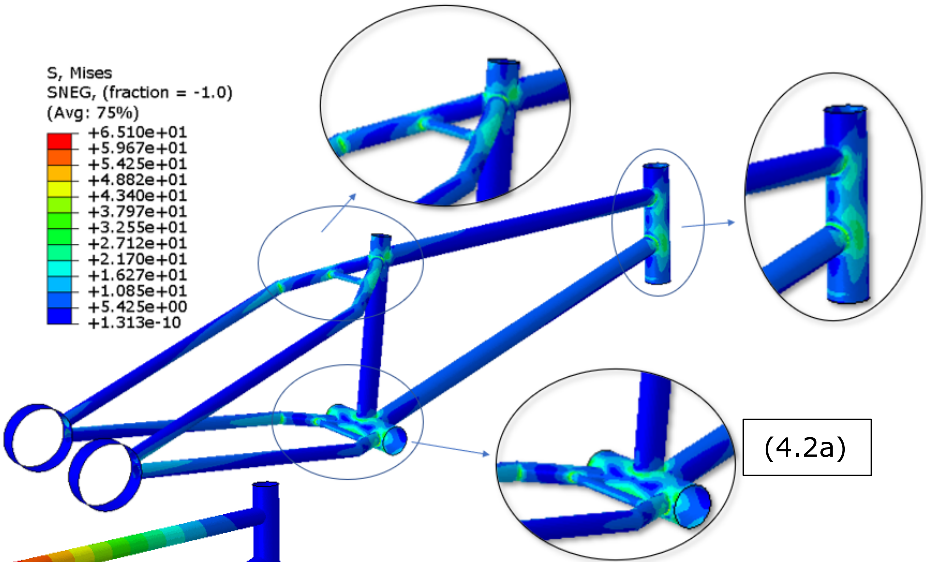
the Abaqus model's figure 4.1b, three concentric loads were applied to three reference locations.

According to an earlier discussion in the Abaqus software description section, the boundary condition was defined at stayes connectors and bottom head tube. The implementation of meshing took into account with the element size and type, respectfully 4 and quadratic. The static simulation for the applied force is then executed using a job that has been created.

In second stage, by adjusting the thickness of various section tubes in the optimization program Isight, the rigidity or stiffness of the frame is optimized based on the stresses and displacements results from the FEA. To get a more highly optimized structure, maximum stresses and displacements were kept below the normal stresses and displacements levels of aluminum. There are two approaches can be followed in this stage. For the first scenario, no deflection can be taken into account during optimization, and for the second case there are slight deflections can be considered. In this study, there is no deflection is considered, therefore the maximum stresses and displacements were considered respectively, 450MPa and 5mm. Finally, for the aluminum material, the objective function in the optimization procedure took into account both maximizing and minimizing the strain energy. This procedure will make it clearer why minimizing strain energy is a viable choice for strengthening bicycle frames. The ideal tube thickness value was discovered during the optimization process after a predetermined number of runs (between 1000 and 1500). Based on the optimum parameters, the bicycle model underwent FEA once more to confirm the optimization outcome. The findings are presented below.

4.1.2 Result and discussion of Stresses and displacements:

Prior to optimization, stress and displacement analysis is seen in the figure 4.2a and 4.2b. Here. In the seat tube area, a significant amount of pressure has been seen. This is due to the fact that the top of the seat tube and two sides of the bottom brackets received the greatest load. A similar outcome has also been seen while examining the displacement figure 4.2b. At the bottom bracket, the maximum displacement was 5.3mm. However, after the frame is optimized as



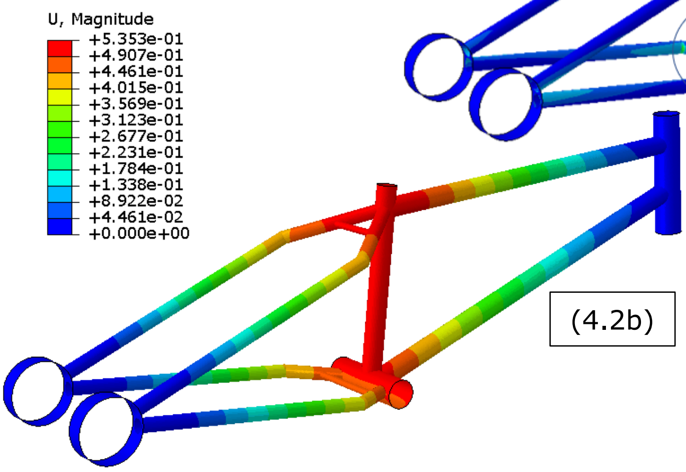


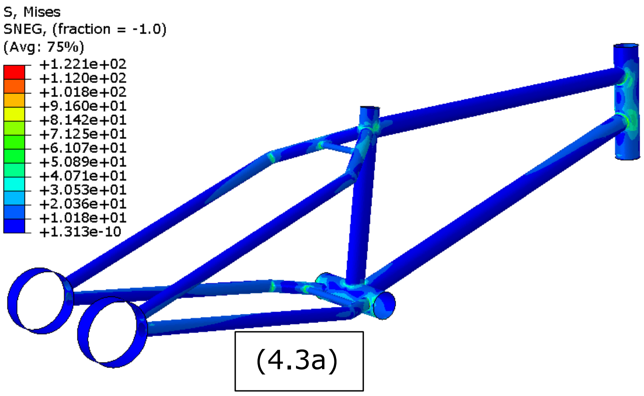
Figure 4.2: (4.2a) Stress analysis results in MPa and (4.2b) displacement analysis of aluminum frame in mm before optimization

explained earlier, the table 4.2 shows the optimized thickness values of different tube sections of bicycle frame. The average optimal thickness values from the optimization of maximizing strain energy were found to be 1.48mm for all tubes (apart from stays connecting rings), 1.74mm for the bottom bracket tube, and 1.36mm for the chain stays, respectively. Figure 4.3a and 4.3b shows the stress and displacement after updating these optimum thickness values in the model while maximizing the strain energy in optimization process. In the same load and boundary conditions where stresses modulus had also risen, it was discovered that tube deformation had increased. Similarly, stress and displacement on the design model were observed after updating the thickness value from minimizing strain energy in optimization. According to the figures 4.4a and 4.4b, tube deformation decreased when the same load and boundary conditions were used as before optimization and when the strain was maximized. From the analysis, it is understandable that while minimizing the strain energy in optimization, the bicycle frame deforms less than maximizing the strain energy. This event can also be discussed from a material perspective. While minimizing the strain energy in the optimizing process, the frame structure becomes stiffer by adding material in all the section tubes. As a result, the structure becomes stiffer and deforms less. From the mass analysis, it had found that before optimization the weight of the frame was 2.06kg. After the optimization in maximizing and minimizing strain energy, the weight of the bicycle frame had found to respectively 1.64kg and 2.89kg.

Tube reference	Thickness before optimization, mm	Thickness after optimization of maximizing strain energy, mm	Thickness after optimization of minimizing strain energy, mm
Bottom bracket tube	2.00	1.74	3.00
Bottom tube	2.00	1.56	3.00
Chain stays	2.00	1.36	3.00
Chain stays connector	2.00	1.30	3.00
Head tube	2.00	1.35	3.00
Seat stays	2.00	1.55	3.00
Seat stays connector	2.00	1.41	3.00
Seat tube	2.00	1.49	3.00
Top tube	2.00	1.55	3.00

Table 4.2: Thickness of Aluminum bicycle model before and after optimization

Maximizing strain energy:



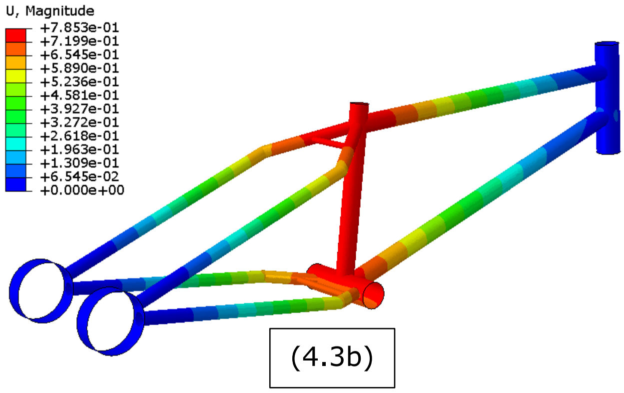
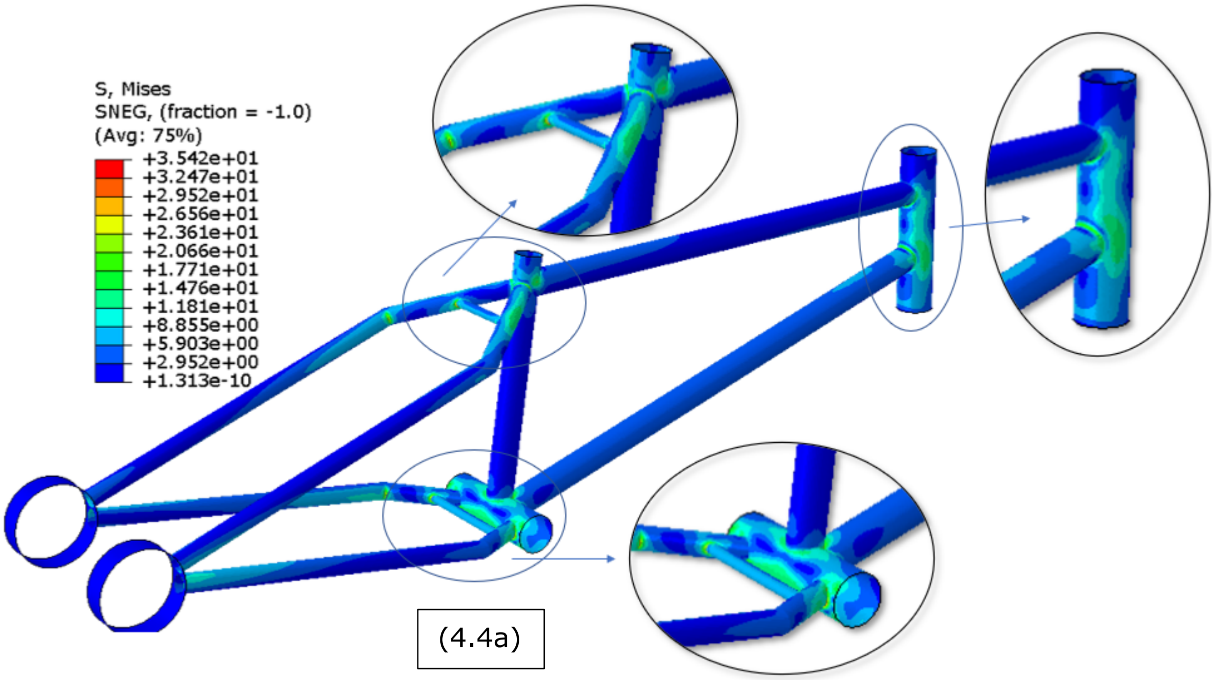


Figure 4.3: (4.3a) Stress analysis in MPa (4.3b) Displacement analysis in mm result after optimization

Minimizing strain energy:



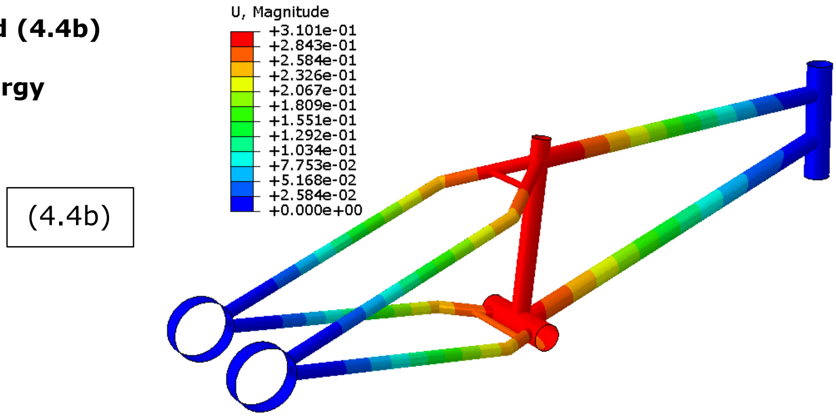


Figure 4.4: (4.4a) Stress in MPa and (4.4b) Displacement analysis in mm after optimization in minimum strain energy

4.1.3 Environmental impact assessment for Aluminium bicycle frame:

The bicycle frame's environmental impact is analyzed after structurally optimizing the product design with a range of tube thicknesses. LCA will be utilized to evaluate the environmental impact of this research, as was stated in an earlier section. Since the LCA's scope is defined from "cradle to gate," only the environmental impact of manufacturing bicycle frames will be taken into account. The 38th version of Ecoinvent 38th version [42], [43] and, and structural and optimization analysis are used to conduct inventory analysis. The table 4.3 below provides an inventory summary for bicycle frames made of aluminum.

Bauxite to alumina: Reference: [43]			
Input:	Amount	**Output:**	Amount
Bauxite	2.739 ton	By-product (recycle)	
Caustic soda	89 kg	Bauxite residue	1.1
Calcined lime	40 kg	Other	5.6
Fresh water	7.9 m3	Solid waste (landfill)	
Sea water	0.1 m3	Red mud	1,142
Diesel oil	0.7 kg	Other	25
Heavy oil	101.4 kg		
Natural gas	62.8 kg	**Alumina**	**1.0 ton**
Aluminum Anode making: Reference: [43]			
Input:		**Output:**	
Petroleum coke	681 kg	By-product (recycle)	16.6 kg
Pitch	171 kg	Solid waste (landfill)	24.5 kg
Recycled anode butts			
Fresh water	2.3 m3	**Aluminum anode**	**1 ton**
Sea water			
Refractory	6.2 kg		
Steel for anodes	5.1 kg		
Coal as fuel	2.2 kg		
Diesel oil as fuel	2.3 kg		
Heavy oil as fuel	11.3 kg		
Total thermal energy	2.6 TJ		
Electricity	129 kwh		
Aluminum: Reference: [43]			
Input:		**Output:**	
Alumina	1.923 ton	By-product (recycle)	20.0 kg
Anode paste	435 kg	Solid waste (landfill)	33.2 kg
AlF2	16.4 kg		
Cathode carbon	8.0 kg	**Aluminum**	**1.0 ton**
Refractory	5.4 kg		
Steel for cathodes	6.6 kg		
Electricity	15,289 kWh		
Aluminum Bicycle frame manufacturing: Reference: [44]			
Input		**Output**	

Section bar extrusion, Aluminum	3.77 kg		
Welding, arc, Aluminum	0.25 m	Treatment, sewage, to wastewater treatment, class 3	0.000744 m3
Powder coating, Aluminum sheet	0.35 m2	Disposal, municipal solid waste, 22.9% water, to municipal	4.5 kg
Electricity, medium voltage, at grid	0.02 kWh	**Bicycle frame**	**2.50 kg**
Light fuel oil, burned in industrial furnace 1MW, non-	0.20 MJ		
Tap water, at user	0.34 kg		
Transport, transoceanic freight ship	350.00 tkm		
Electric motor, electric vehicle, at plant	0.00001 kg		

Table 4.3: Inventory analysis of Aluminum bicycle frame manufacturing

Based on this inventory result, the assessment has conducted in Simapro software according to global ReCiPe 2016 Midpoint (H) V1.05/World (2010). There are two assessments done for two separate bicycle frame weight which is based on minimizing and maximizing strain energy in optimization process.

4.1.3.1 Simapro result for 1.65kg bicycle frame:

Transportation, municipal solid waste, and in some circumstances, selection bar extrusion procedures are found to be the most responsible production processes for environmental impact, according to the characterization result (figure 4.5 and 4.6). During the production of aluminum bicycle frames, it was found that transportation alone was responsible for more than 80% of the impact indicators for global warming, stratospheric ozone depletion, terrestrial acidification, shortage of fuel resources, ozone generation, etc. When moving the items from one location to another, the majority of the CO2, SO2, CFC, and other compounds that contribute to those impact indicators were produced. And again, municipal

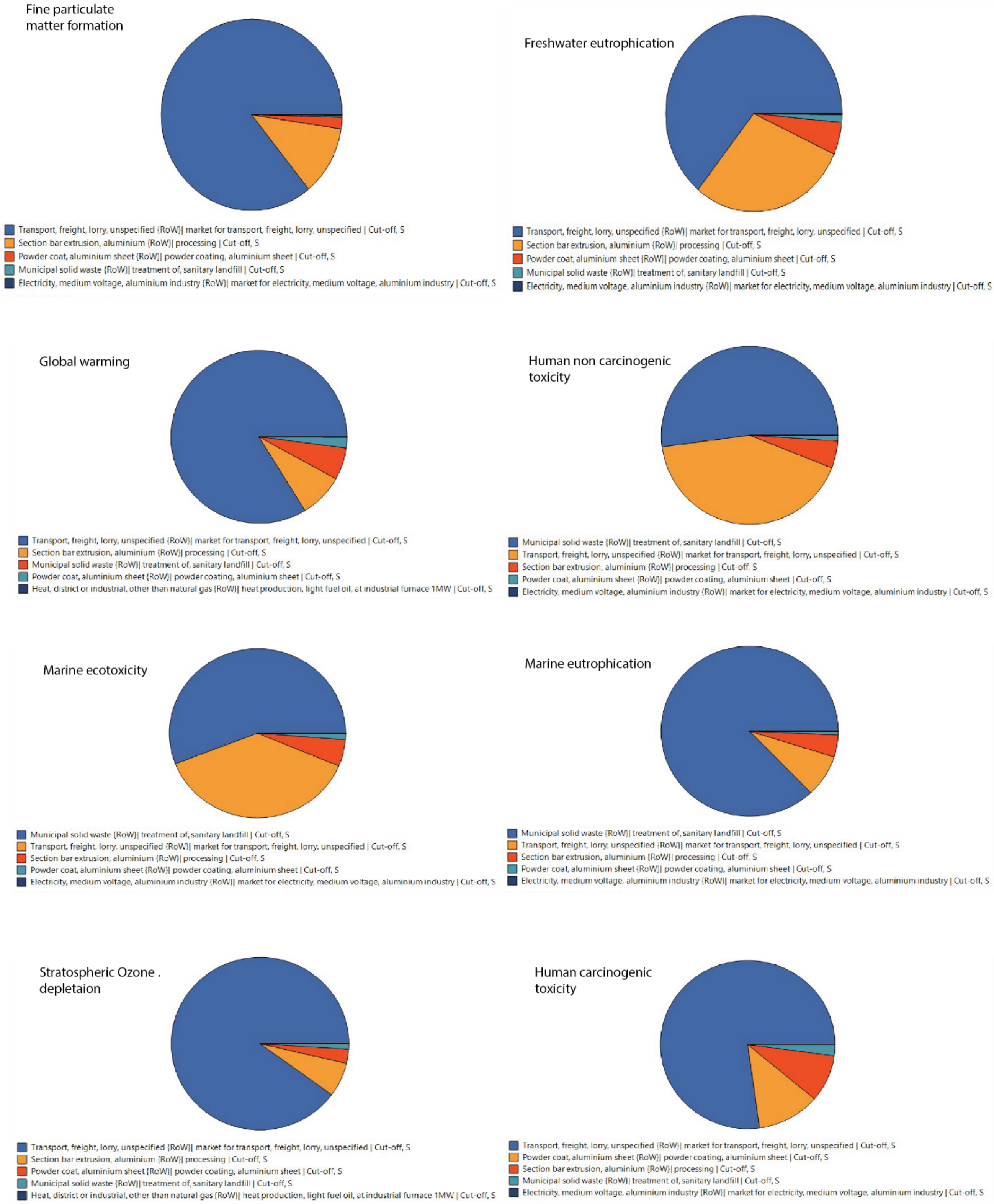


Figure 4.5: Major environmental impact indicators result on 1.65 kg Aluminum bicycle frame manufacturing

solid waste is identified as a significant contributor to freshwater ecotoxicity and marine eutrophication. This indicates that the primary cause of the pollution of water and the marine environment was the municipal solid waste. The primary causes of the human non-carcinogenic problem are discovered to be both transportation and municipal solid waste. The percentage of these contributions is plainly seen in the network diagram of these impact categories. The appendix diagrams contain all of those network diagrams.

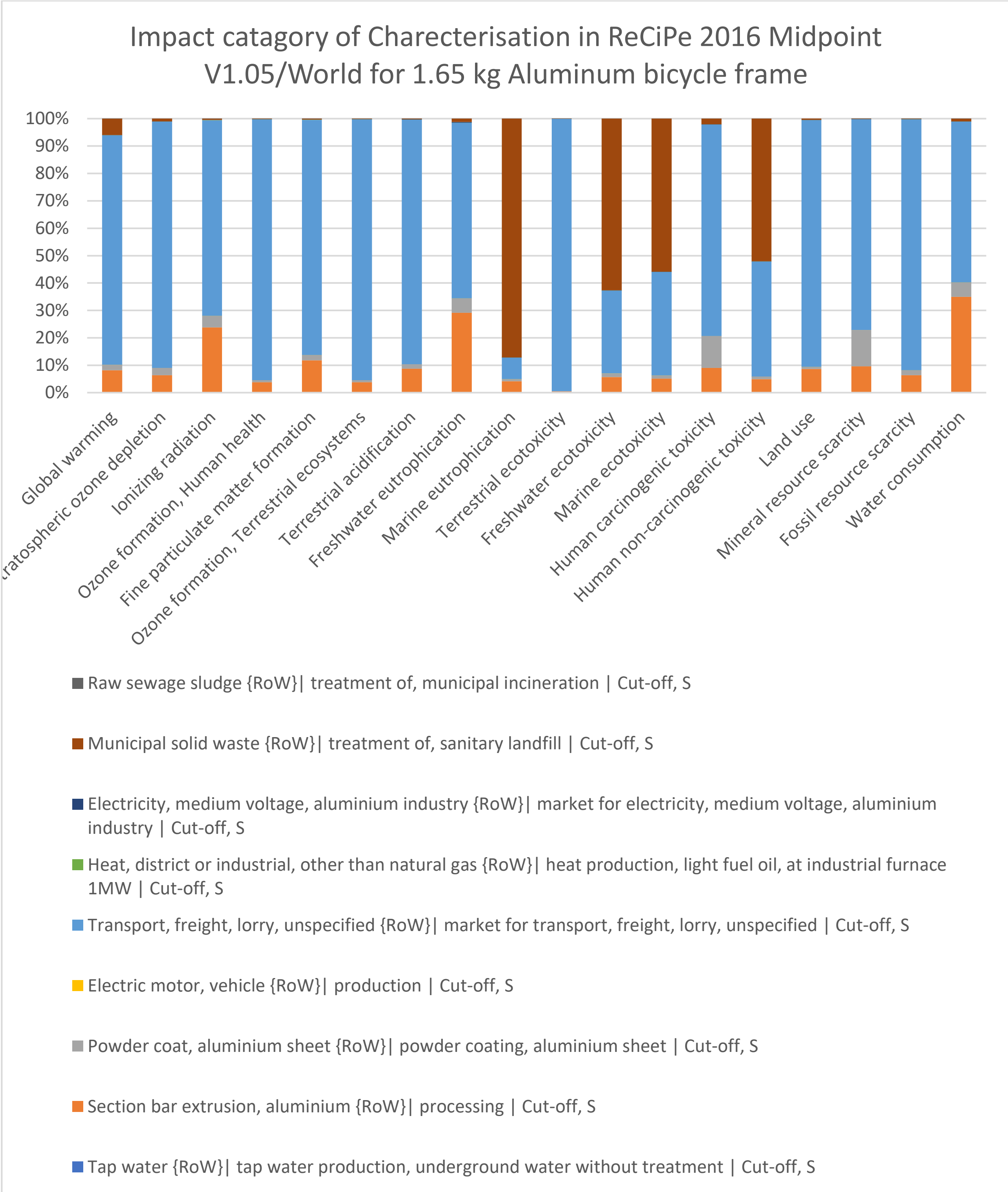


Figure 4.6: Impact of environmental indicators in 1.65kg Aluminum bicycle frame manufacturing

4.1.3.2 Simapro result for 2.89kg bicycle frame:

Similar impact result was observed for the bicycle frame of 2.89kg as frame weight 1.65kg (figure 4.7 and 4.8). Transportation was found most impact contributor for most of the

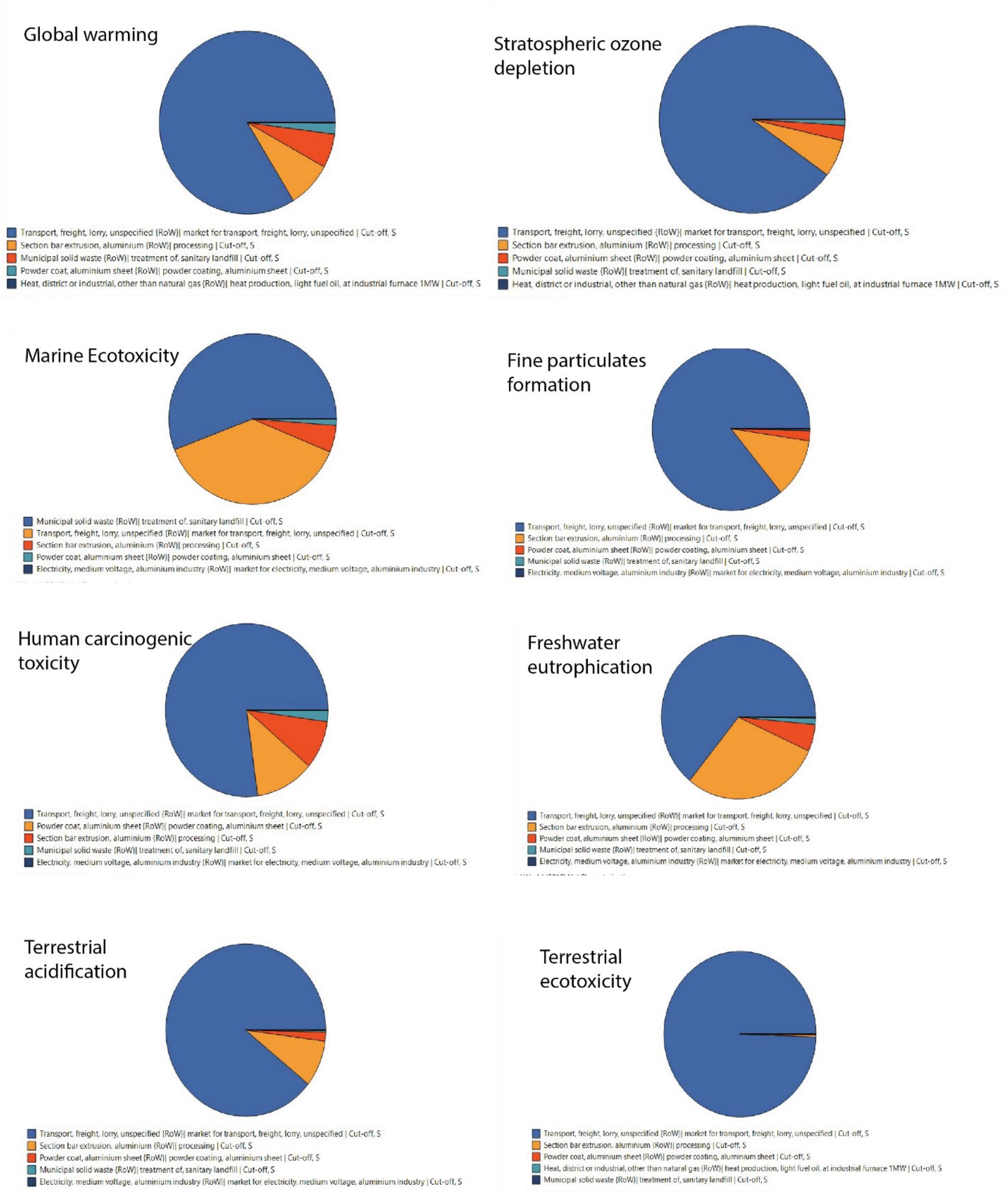


Figure 4.7: Impact of environmental major indicators in 2.89kg Aluminum bicycle frame manufacturing

indicators. Municipal solid waste was found major contributor to marine ecotoxicity and marine eutrophication. To understand the contribution, the network diagram of these impact indicators was presented on the appendix.

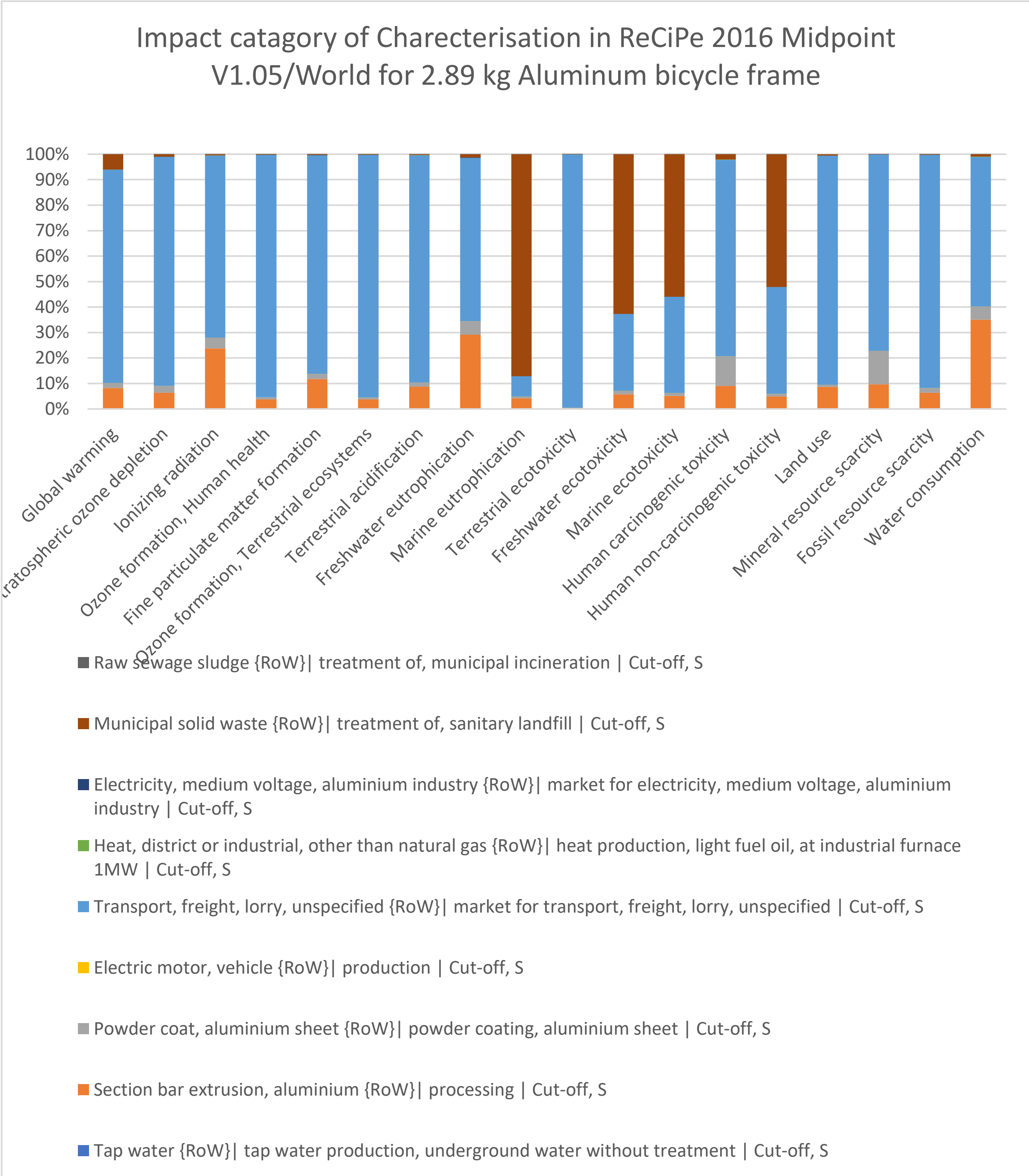


Figure 4.8: Impact of environmental indicators in 2.89kg aluminum bicycle frame manufacturing

Similar situations were observed when comparing the result to those of other studies, though. For instance, it is shown in [45] that material processing alone is responsible for 90% of CO2 emissions and global warming. This study confirms the findings of [45] research since it is restricted to the cradle-to-gate border scope for LCA, where material processing and auxiliary operations are mostly dependent on transportation processes.

The same outcomes were seen in [46] as well. Researchers calculated the full bicycle's environmental impact in this study [46]. It was discovered that material processing, namely transportation in the present article, is the biggest contributor to the carbon footprint when taking into account simply the aluminum bicycle frame and the boundary conditions.

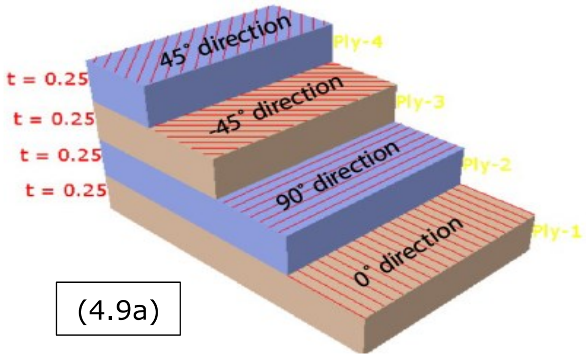
4.2 Carbon fiber reinforced epoxy composite material bicycle frame:

4.2.1 Model setup:

In the second analysis, the material is considered carbon fiber reinforced epoxy composite. The mechanical properties of the carbon fiber epoxy composite are considered as the table 4.4. Since composite materials are formed layer by layer. In this test, two different composite material kinds were taken into account. One is made of composite material in four layers, while the other is in eight layers. For these two categories, fiber direction was taken into account as a figure 4.9a and 4.9b. As seen in the figure, thickness of each layer is considered 0.25mm and directions are considered 45^0, -45^0, 90^0 and 0^0. After creating these two composite materials, they are assigned to the various tube sections of two bicycle frame model and FEA analysis is conducted. After the initial FEA analysis, the optimization procedure has followed as earlier aluminum frame analysis.

Material	**Carbon fiber composite**	
Density, g/mm3	1.7 x 10 -09	
Longitudinal and transverse modulus, MPa	E1	132000.00
	E2	8292.38
	E3	8292.38
Shear modulus, MPa	G12	3990.06
	G13	3990.15
	G23	2545.40
Poisson ratio	nu12	0.328
	nu13	0.328
	nu23	0.629

Table 4.4: Carbon fiber composite mechanical properties



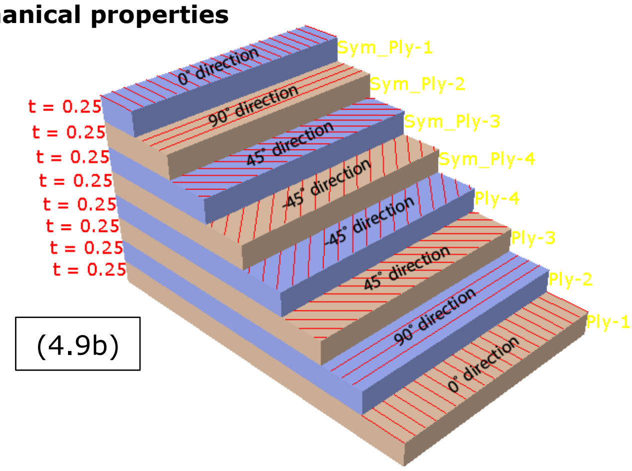


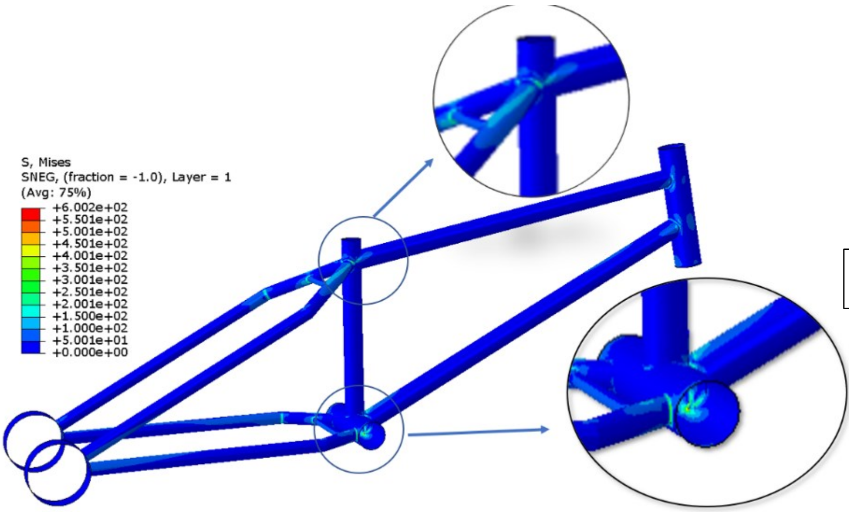
Figure 4.9: Composite laminates direction and thickness, (4.9a) 4-layers, (4.9b) 8- layers

In optimization, upper limit of Stress and displacement are two parameters considered respectively 450MPa as [47] and 5mm. Also in the optimization process, each layer of composite thickness of the tube section is optimized only by minimizing the strain energy since this approach has found the correct approach for structural optimization. The upper and lower level of thickness for each layer is limited to 0.1mm to 1.0mm. Finally, after the optimization procedure, the optimized thickness value applied to the bicycle frame of carbon composite and below stress and strain value has been observed.

4.2.2 Result and discussion of stresses and displacements:

Figures 4.10 and 4.11 represent the results of stress and deformation for two types of material-base bicycle frames before the model is optimized. The findings indicate that an eight-layer bicycle frame performs better in terms of stresses and strain than a four-layer frame. The highest, stress point in eight layers has found 141Mpa. In the four-layer frame, this has found 600.2Mpa. This also results in displacements results where eight layers have least deformation than four layers of carbon composite frame.

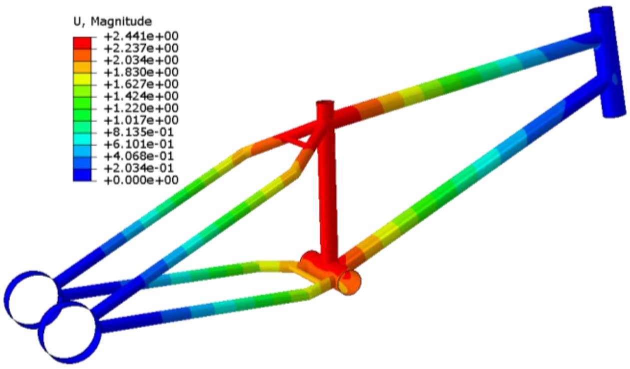
Four-layer FEA analysis before Optimization:



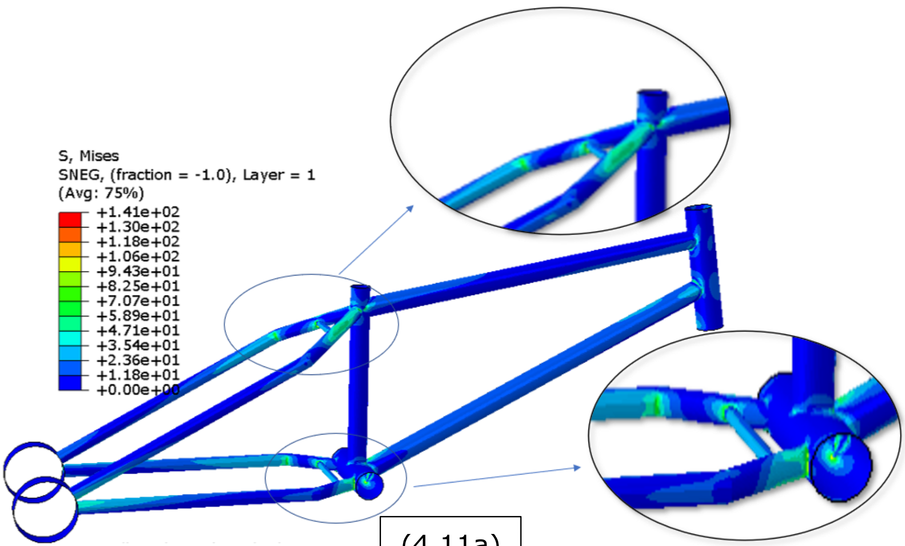
(4.10a)

Figure 4.10 (4.10a) Stress in MPa and (4.10b) displacement analysis in mm for four-layer carbon composite frame before optimization

(4.10b)



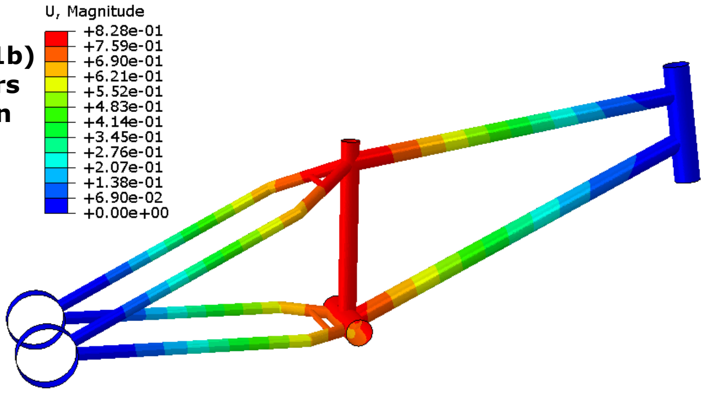
Eight layers FEA before optimization:



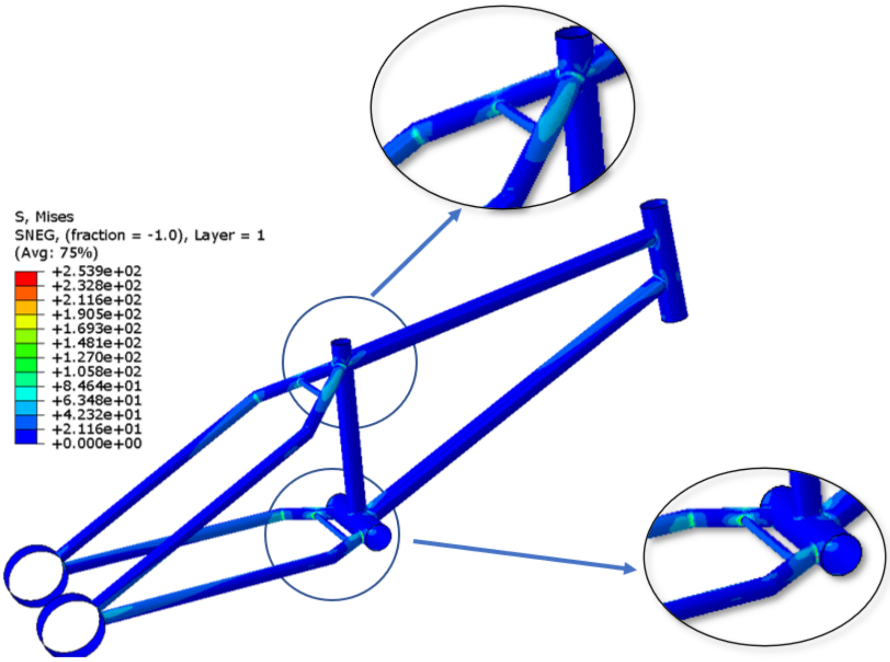
(4.11a)

Figure 4.11 (4.11a) Stress in MPa and (4.11b) displacement analysis in mm for eight-layers carbon composite frame before optimization

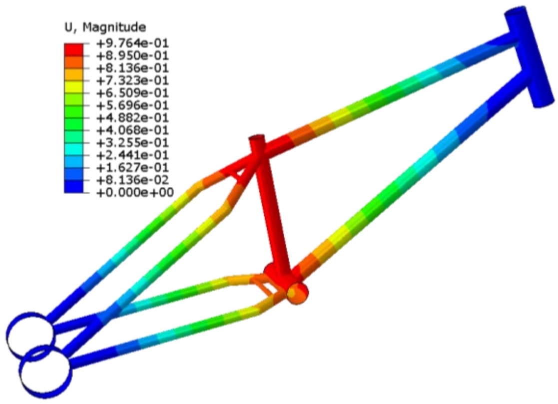
(4.11b)



<u>**FEA analysis after optimization in minimizing strain energy (four layers):**</u>



(4.12a)



(4.12b)

Figure 4.12 (4.12a) Stress in MPa and (4.12b) displacement analysis in mm of four-layer carbon composite frame in minimum strain energy in optimization.

After the optimization by minimizing strain energy in four layers composite frame, we fund the result as figure 4.12a and 4.12b. It has been observed from FEA in four layers composite frame model with optimized thickness value, maximum stress value reduced to 253.9MPa than non-optimized model. And for eight layers as figure 4.13a and 4.13b, this stress value has reduced to 19.03MPa than non-optimized model analysis. From the displacements result of FEA for four and eight layers optimized bicycle frame model, it has found eight layers deform less compared to four-layer composite frame. Comparing all the FEA analysis for both four- and eight-layers bicycle frame model, it observed that eight-layer optimized bicycle frame behaves most stiffer frame (figure 4.14).

FEA analysis after optimization in minimizing strain energy (eight layers):

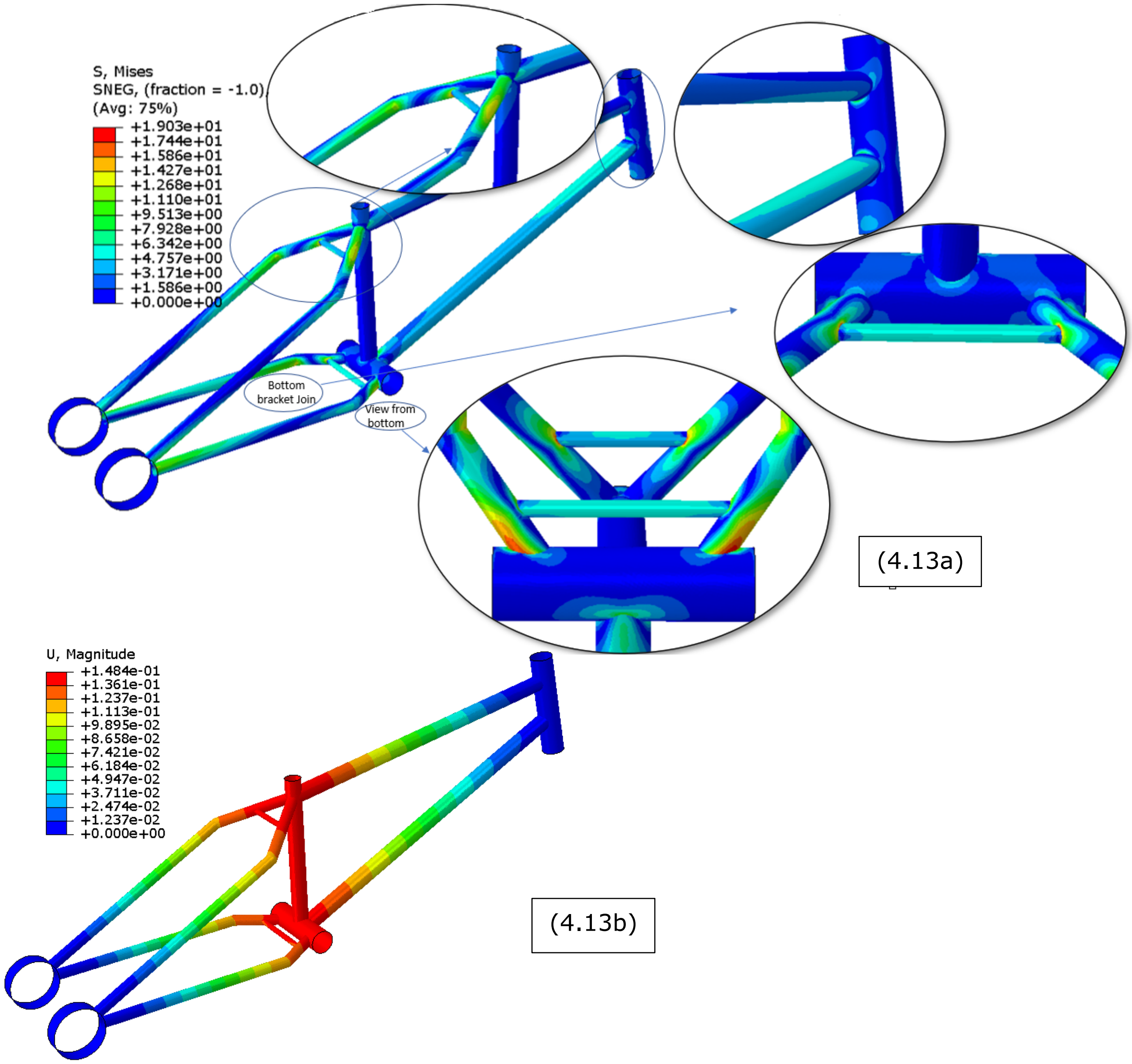


Figure 4.13: (4.13a) Stress in MPa and (4.13b) Displacement analysis in mm for eight layers of carbon composite material after minimizing strain energy in optimization

While optimizing the carbon fiber made bicycle frame structurally, weight of these frame was found 1.14kg and 4.44kg respectively for four-layers and eight-layers frame. Whereas before optimization the 0.65kg and 1.29kg respectively for four- and eight-layers frame. For environmental assessment, according to this methodology weight of the bicycle frame after optimization are considered.

4.2.3 Environmental impact assessment for carbon-epoxy bicycle frame:

For environmental impact assessment LCA method has followed as aluminum bicycle frame. The scope has defined from cradle to gate. Inventory analysis has done based on structural optimization and different literature review as mentioned in below inventory table 4.5. Similar to earlier section, environmental impact of this carbon bicycle frame will be assessed from raw material development to manufacturing of bicycle frame only

	Amount	Unit	Reference
PAN production:			
Input data			
Acrylonitrile	2.25	kg	[48]
Vinyl Acetate	0.2	kg	[48]
Energy for polymerization	487.55	MJ	[49]
Energy for spinning	477.75	MJ	[49]
Total energy required	965.3	MJ	
Output data			
PAN	2.36	kg	[48]
Carbon fiber from PAN			
Input data			
PAN	1.93	kg	[50]
electricity in oxidation	81.4	MJ	[50]
electricity in carbonization	216.1	MJ	[50]
Nitrogen in Carbonization	4.8	m3	[50]
electricity in surface treatment	4.6	MJ	[50]
coating material	0.02	kg	[50]
electricity in abatement	4.6	MJ	[50]
natural gas	13	m3	[50]
Output data			
Carbon fiber	1.02	kg	[50]
Composite frame manufacturing			
Input data			
carbon fiber	0.32	kg	[51] [52]
epoxy resin	0.206	kg	[51] [52]
hardener (di-amine)	0.051	kg	[51] [52]
peel ply	0.003	kg	[51, 53]
sealant tape	0.504	kg	
tube insulation, elastomer	0.00374	kg	
vacuum	0.005	kg	
Flow media	0.003	kg	
electricity, low voltage	4.1	kWh	

Output data			
Composite frame	0.556	kg	
Scrap	0.021	kg	[51] [52]

Table 4.5: Inventory analysis of Carbon-epoxy composite bicycle frame manufacturing

Based on this inventory data, the simulation has run in Simapro software. Similar method, Global ReCiPe 2016 Midpoint (H) V1.05/World (2010), has followed for the assessment. There are two assessments done for two separate bicycle frames based on the layers.

4.2.3.1 Simapro result of four layers carbon composite bicycle frame (1.14kg):

The frame weight of four layers carbon composite bicycle frame has obtained 1.14kg from structural optimization. So, LCA has conducted based on this frame weight. And from the result of characterization analysis as figure 4.15, it is observed. Among all the production processes, carbon fiber fabrication process contributes highest impact to the environment in most of the indicators. Again, from the individual impact characterization as figure 4.16, energy has found highest contributor to all of the mid-point indicators. Connecting these two results, it is found while carbon fiber manufacturing consumes majority of energy that used in whole process, this manufacturing process contribution to all the indicators is highest. It represents that most of the substance i.e., CO_2, SO_2 etc., which are major contributor for global warming were produced from carbon manufacturing process. Followingly, Electricity generation has found another major contributor for different environmental impact after carbon fiber manufacturing process. This is because, in most processes' electricity was essential along with energy consumption. The case where electricity wasn't necessary, there was less impact observed e.g., marine eutrophication. However, this electricity generation found almost 40% in ionizing radiation impact. For Human carcinogenic toxicity (marked as yellow in the figure 4.15), polysulfide which is a sealing compound found highest contributor for environmental impact. From the impact indicators it also observed that in Global warming and Terrestrial acidification impact categories, after the energy feeding contributor, acrylonitrile has found second high contributor. This represents, acrylonitrile process produces second highest substance that contribute global warming and terrestrial acidification.

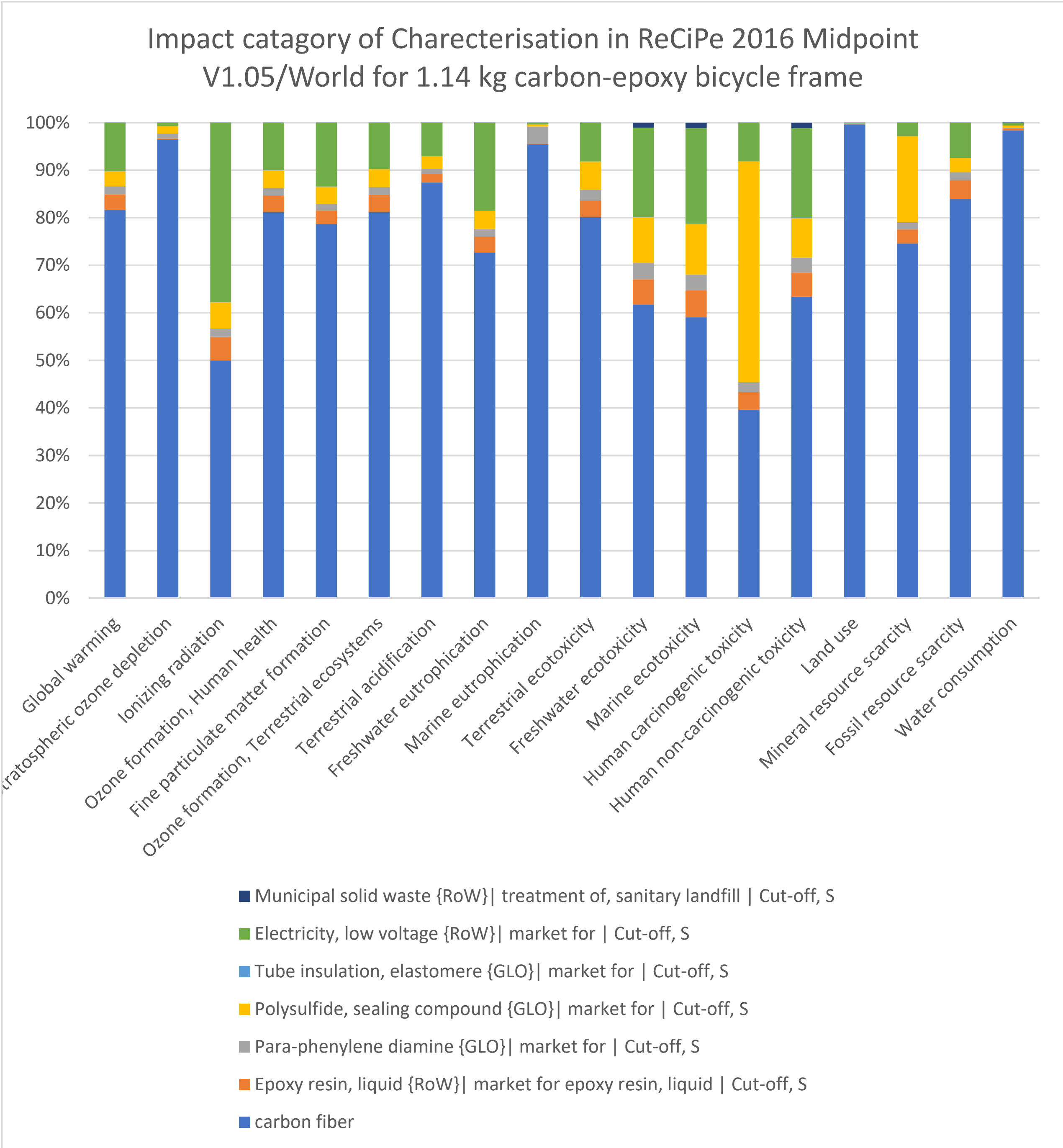


Figure 4.15 Characterization analysis of impact indicators for 1.14kg carbon composite frame

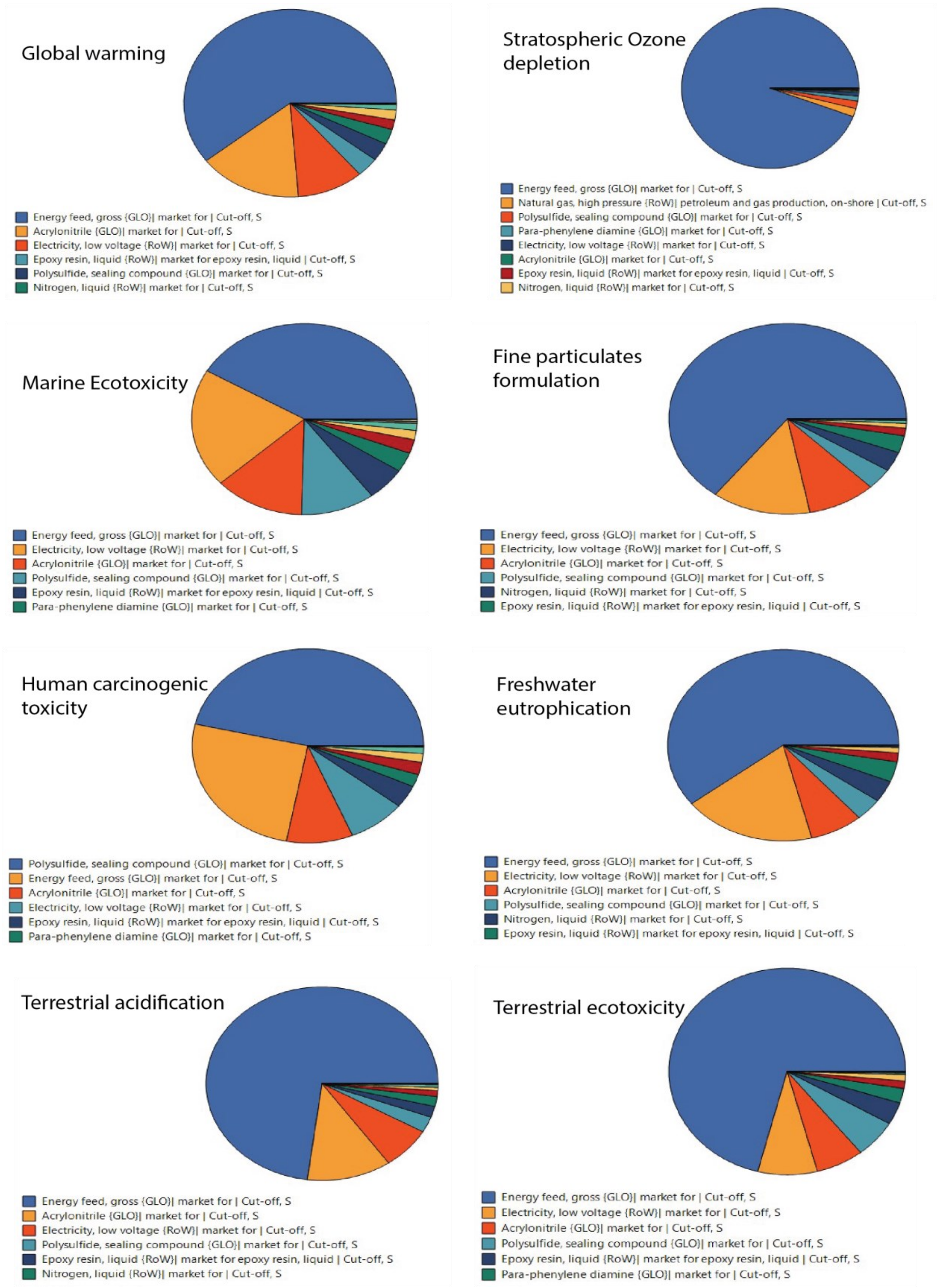


Figure 4.16 Characterization analysis of major impact indicators for 1.14kg carbon

4.2.3.2 Simapro result of four layers carbon composite bicycle frame (4.44kg):
In eight layers carbon composite frame, like earlier four-layer frame, carbon fiber manufacturing process involved in severe environmental impact. Almost in all the impact category (figure 4.17), this process contributes more than 50% of the impact except Human carcinogenic toxicity category. In Human carcinogenic category, a sealing

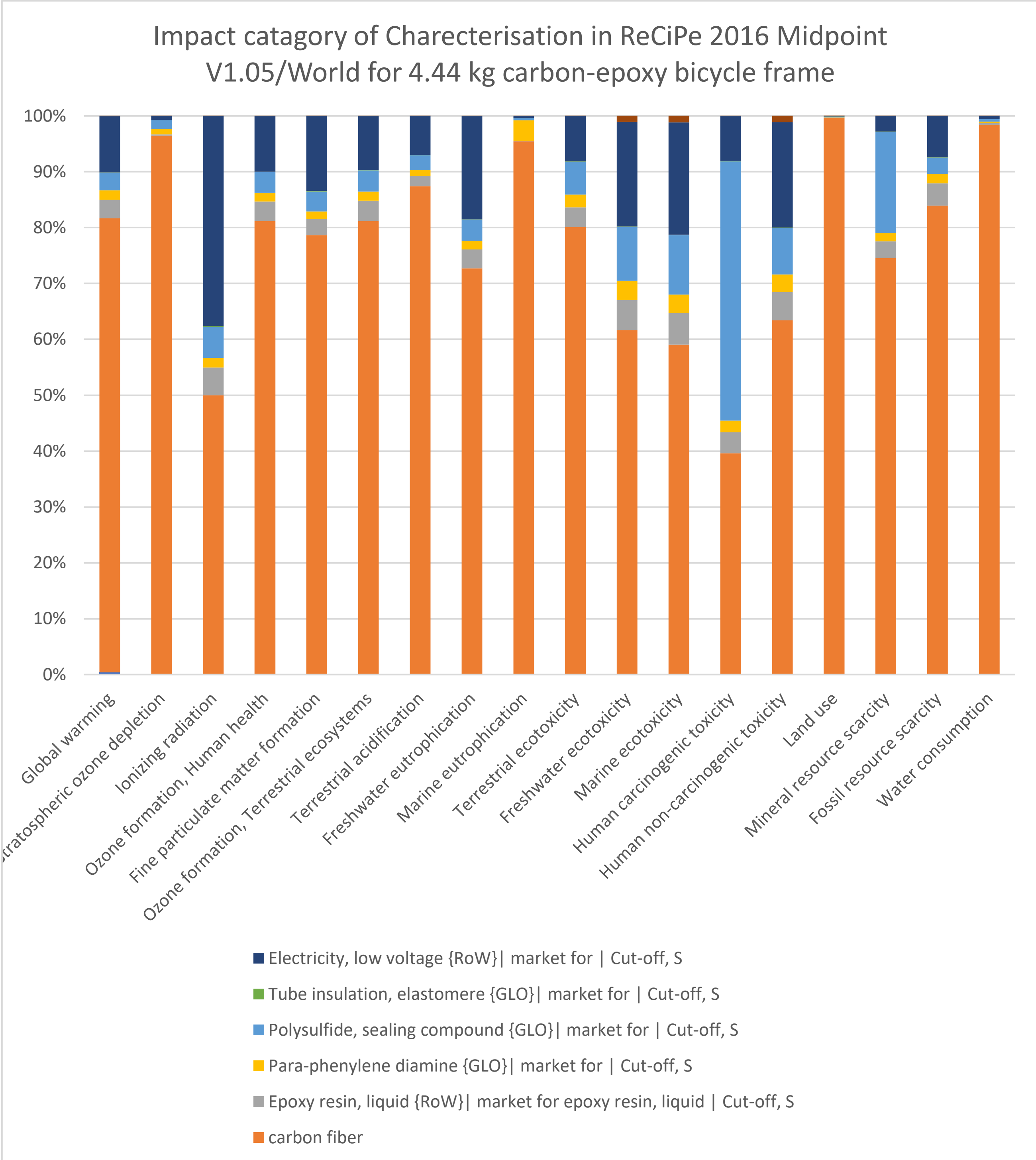


Figure 4.17: Characterization analysis of impact indicators for 4.44kg carbon composite material frame

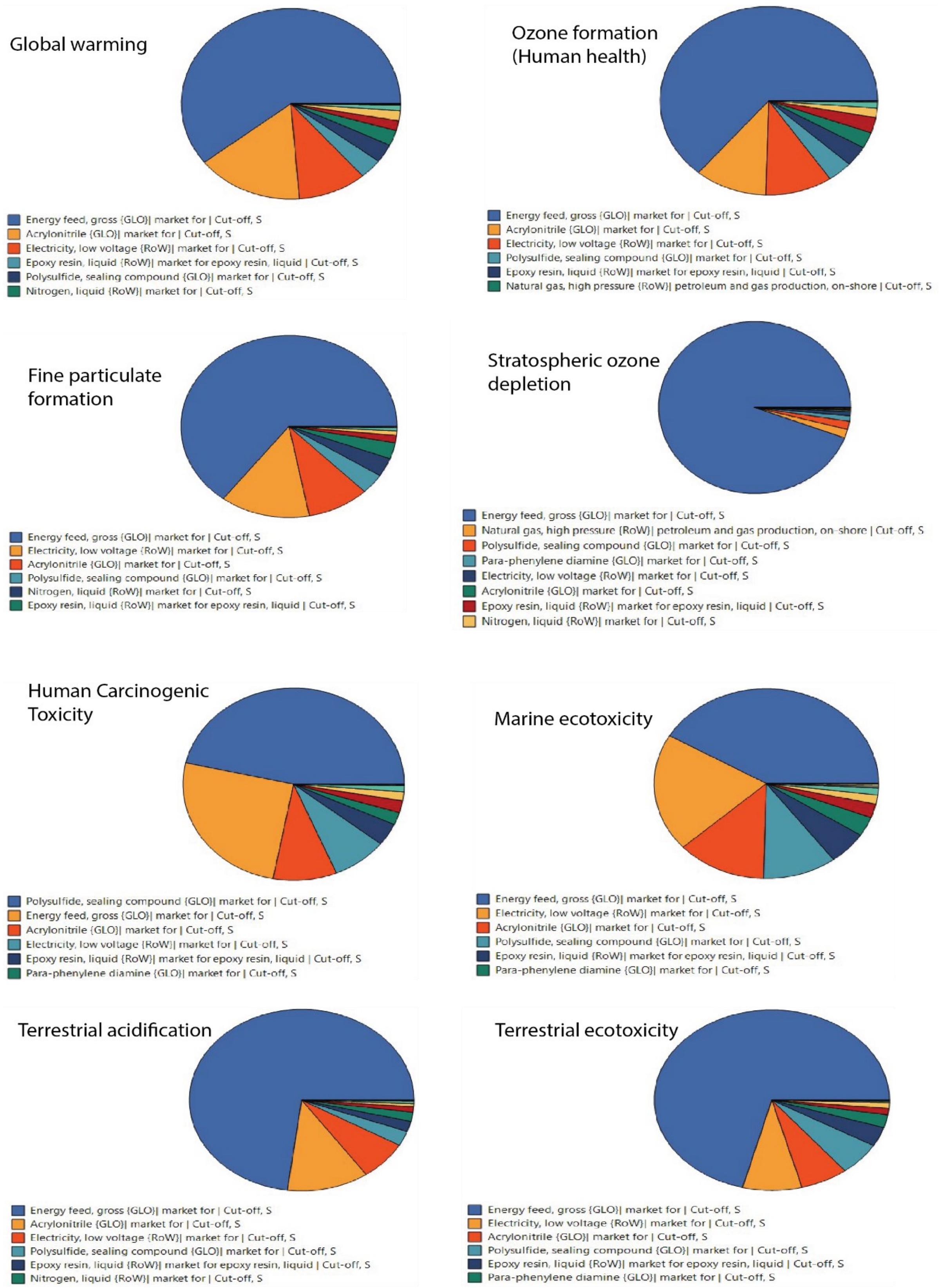


Figure 4.18: Characterization analysis of major impact indicators for 4.44kg carbon composite frame

compound polysulfide process involved in major environmental impact. Volatile Organic Compound (VOC) from several sources and other pollutants compound responsible for human toxicity were produced mainly generated from this material processing. Following the carbon manufacturing process, second major contributor observed for impacting categories is electricity. Another material named para-phenylene diamine which is used as binder for composite manufacturing responsible in a small extent for almost all impact categories. However, while individual impact category of characterization observed as figure 4.18, some interesting result found. For some impact categories i.e., Ozone formation for human health, terrestrial acidification and ecotoxicity, after the contribution of energy (which is mostly used in carbon manufacturing), Acrylonitrile processing found second higher contributor for environmental impact.

4.3 Flax-epoxy reinforced bicycle composite frame:

4.3.1 Model setup:

In this final module, the material is considered flax fiber reinforced epoxy composite. The mechanical properties of the materials are considered as table 4.6. These properties are considered according to studies of [54] [55]. To achieve better results, there are small adjustment made in these properties as option one and two. However, similar to carbon composite material, two types of composite laminates were considered. In first category, 4 flax fabric layers were considered in composite lamination and in other 8 layers of flax fabric were considered. The direction of fabric and angle is considered also as described in carbon fiber composite frame. Next after these material properties have established in the model, this material assigned in the different section of bicycle frame. FEA has implemented to the different models based on layers and material properties options. In total, there were four results obtained for different models as table 4.7. In below result section these stresses and displacements results from the analysis were discussed.

Material	Flax fiber composite		
		Option 1	**Option 2**
Density, g/mm3	1.5 x 10 -09		
Longitudinal and transverse modulus, MPa	E1	20300.00	30000.00
	E2	3600.00	3600.00
	E3	3600.00	3600.00
Shear modulus, MPa	G12	4500.00	4500.00
	G13	4500.00	4500.00
	G23	4000.00	4000.00
Poisson ratio	nu12	0.375	0.375
	nu13	0.325	0.325
	nu23	0.350	0.350

Table 4.6: Mechanical properties of flax-epoxy reinforcement composite

Properties / Layers	Option 1	Option 2
Category 1 (four layers)	Result 1	Result 2
Category 2 (eight layers)	Result 3	Result 4

Table 4.7: Categories considered of flax-epoxy reinforced composite

After the initial FEA, optimization process is followed next step. However, for flax-composite material, optimizing is not followed in same way as carbon composite optimization procedure. While in carbon frame optimization process, all the layers of composite frame were considered for optimization process but in flax based composite frame only 1st layer from the complete laminate has selected for optimization. Rest all the other layers are remain constant. This means, except the 1st layer of the composite frame, thickness value for all the fabric layers remains same as initial value 0.25mm during optimization. And for first layer of the composite frame fabric, optimization range for upper and lower limit are allowed to swing from 0.5mm to 2.0mm for four layers and 0.1mm to 1.0mm for eight layers composite frame. Also, the upper constraint limit of stress in optimization is considered 100mpa according to [54] and 5.0mm for four layers composite frame which is reduced to 60mpa and 2.0mm for eight layers composite frame. The reason to follow this procedure in this optimization process is to minimize the simulation time in Isight software. During the simulation it found that within the boundary condition, simulation time became very high when all the layers are considered for optimization and sometimes there is no result found after 1000-1500 runs of simulation.

And after the optimization, again FEA is applied to earlier established flax-epoxy base composite frame with updated thickness value. The results are summarized as below.

4.3.2 Result and discussion of stresses and displacements:

From the table 4.8 of FEA results, it observed that for result 1 (figure 4.19a) before optimization, maximum stress found 422.5mpa which is reduced to 85.65 after optimization (figure 4.23a). For result 2 this has been optimized from 484.3mpa (figure 4.20a) to 107.3mpa (figure 4.24a). on the other hand, in eight layers composite frame, as result 3 before optimization maximum stress point is found 105.3mpa (figure 4.21a), which is after optimization reduced to 78.3mpa (figure 4.25a). And in other material properties this is observed 117.5 (figure 4.22a) to 57.86mpa (figure 4.26a).

Flax FEA Results	Maximum stresses before optimization in MPa	Maximum stresses after optimization in MPa	Maximum displacements before optimization in mm	Maximum displacements after optimization in mm
Result 1	422.50	85.65	9.55	1.94
Result 2	484.30	107.10	7.54	1.52
Result 3	105.30	78.30	2.65	2.34
Result 4	117.50	57.86	3.41	1.11

Table 4.8: Maximum stresses and displacements result before and after optimization

In below, FEA results before optimization are presented.

4 layers composite frame before optimization:

Result 1:

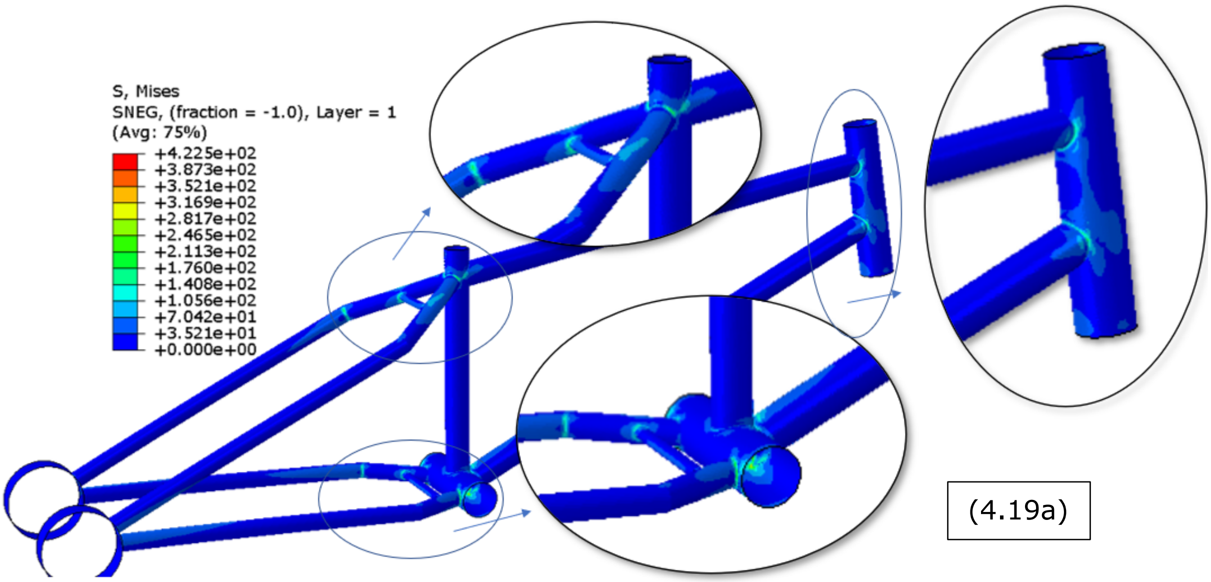
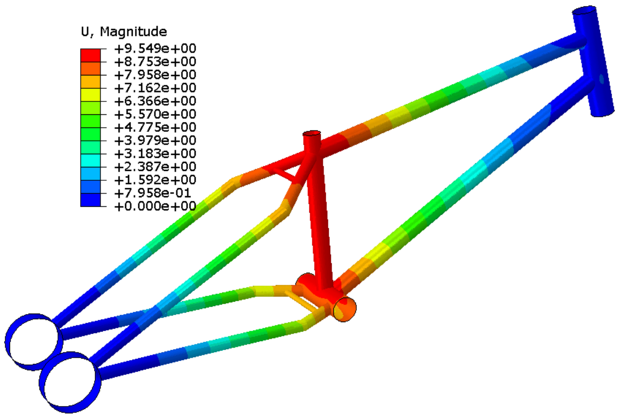


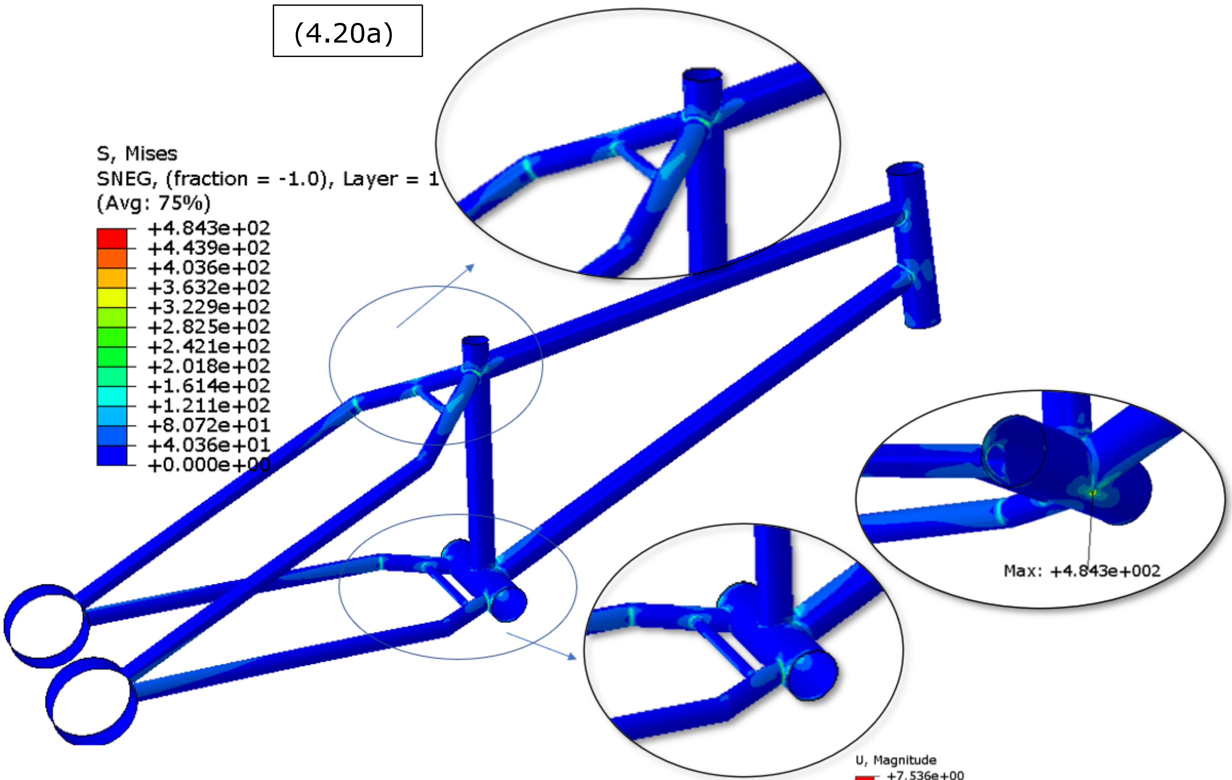
Figure 4.19: Before optimization (4.19a) stress in MPa and (4.19b) Displacement analysis in mm for result 1 option

(4.19b)



Result 2:

(4.20a)



(4.20b)

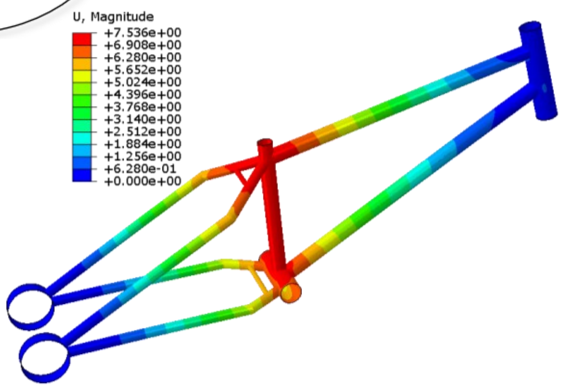
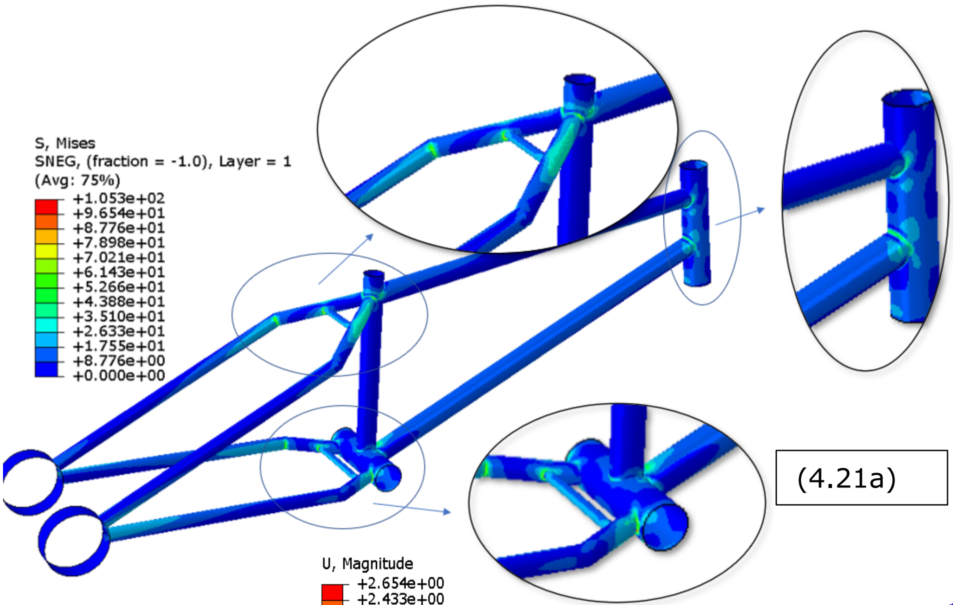


Figure 4.20: Before optimization (4.20a) stress in MPa and (4.20b) displacement analysis in mm for result 2 option

8 layers composite frame before optimization:

Result 3:



(4.21a)

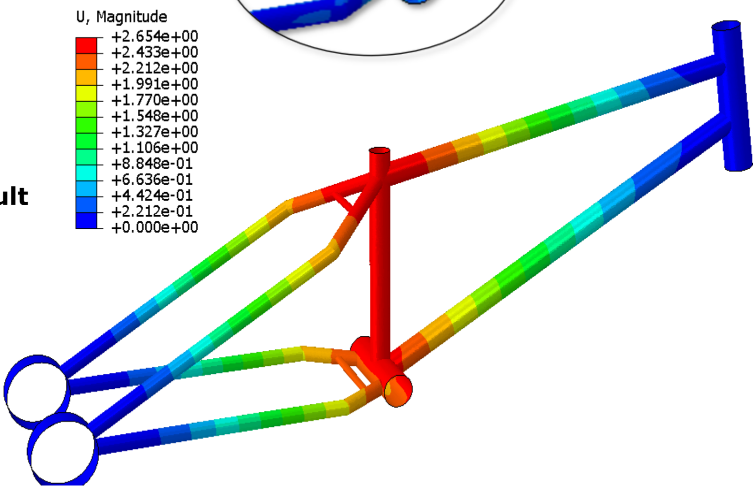
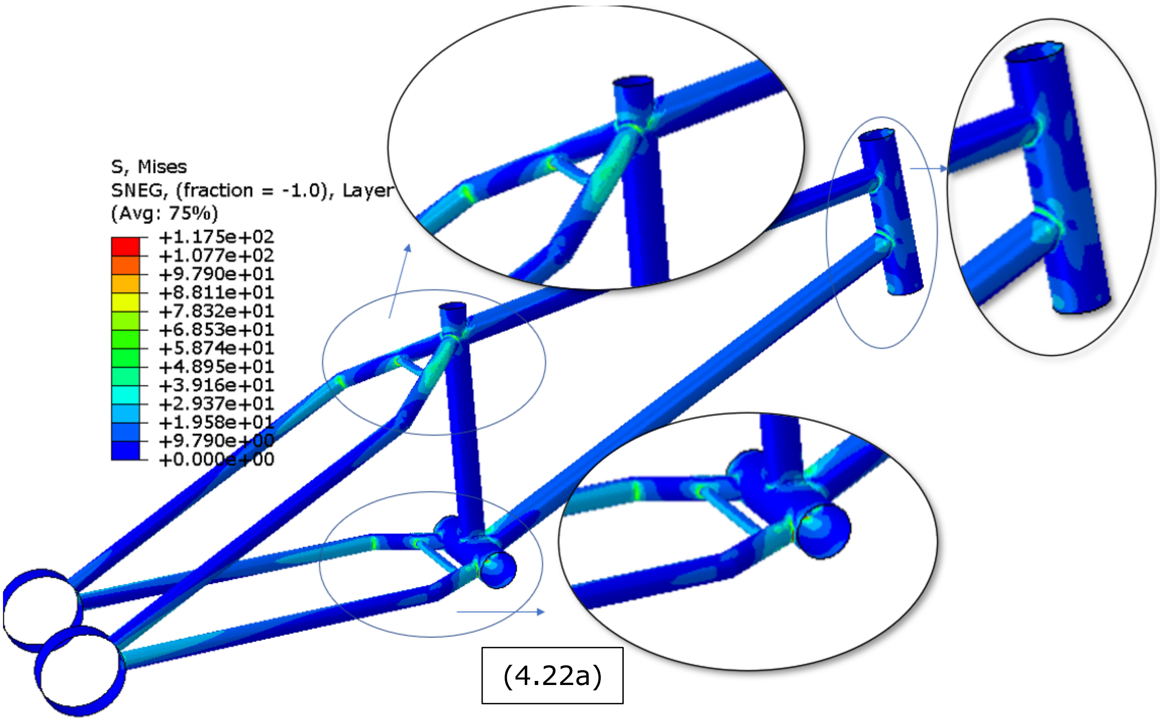


Figure 4.21: Before optimization (4.21a) stress in MPa and (4.21b) displacement analysis in mm for result 3 option

(4.21b)

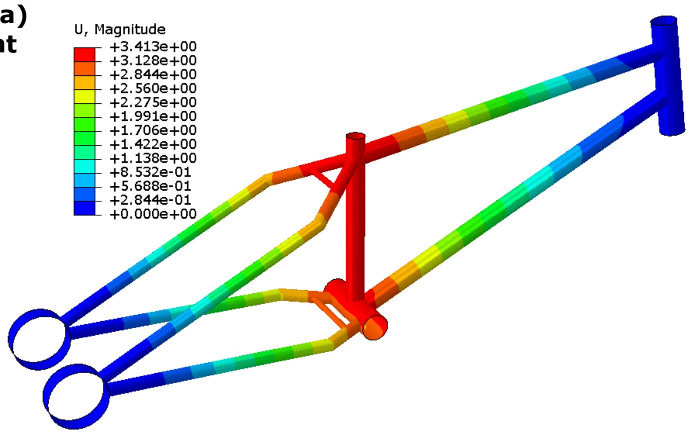
Result 4:



(4.22a)

Figure 4.22: Before optimization (4.22a) stress in MPa and (4.22b) displacement analysis in mm for result 4 option

(4.22b)



In below, FEA results after optimization are presented.

<u>4 layers composite frame after optimization:</u>

Result 1:

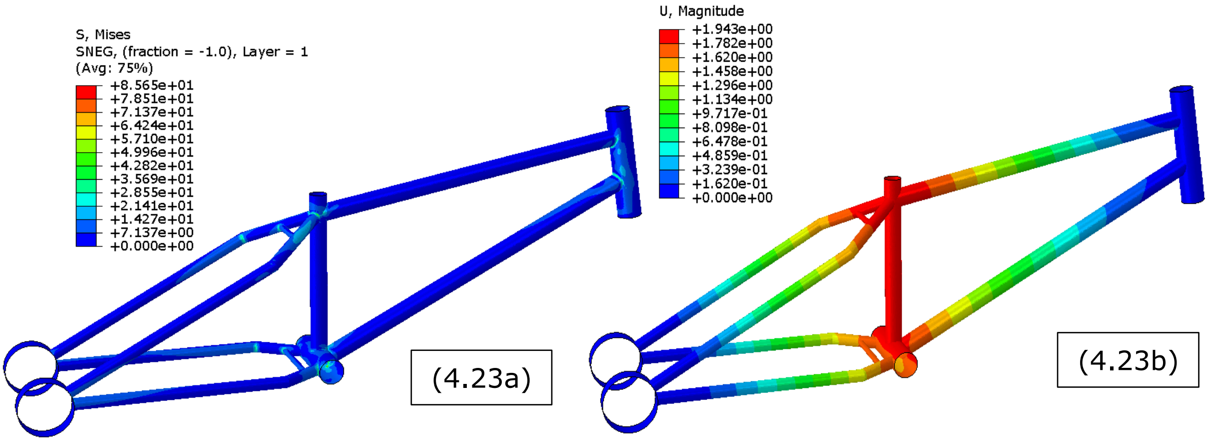


Figure 4.23: After optimization (4.23a) stress in MPa and (4.23b) displacement analysis in mm for result 1 option

Result 2:

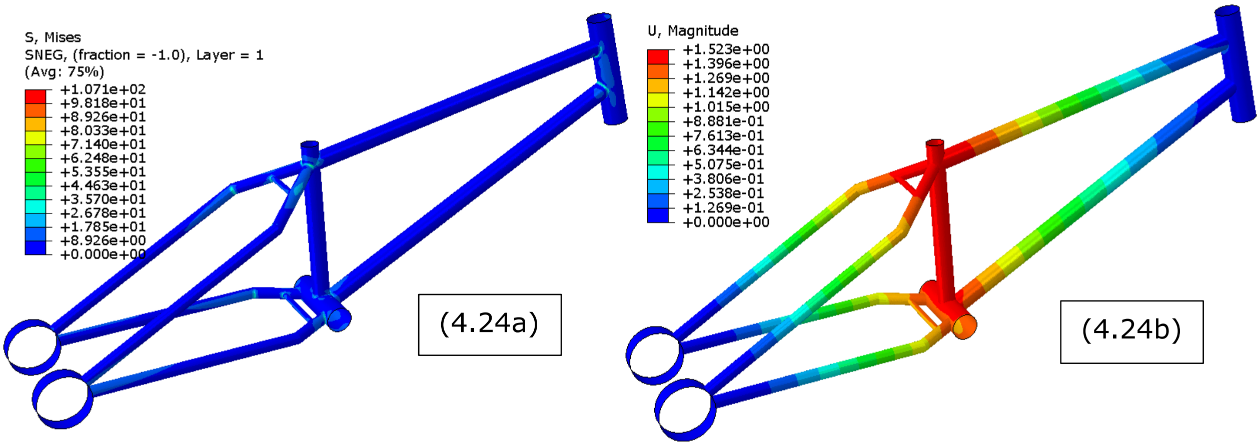


Figure 4.24: After optimization (4.24a) stress in MPa and (4.24b) displacement analysis in mm for result 2 option

8 layers composite frame after optimization:

Result 3:

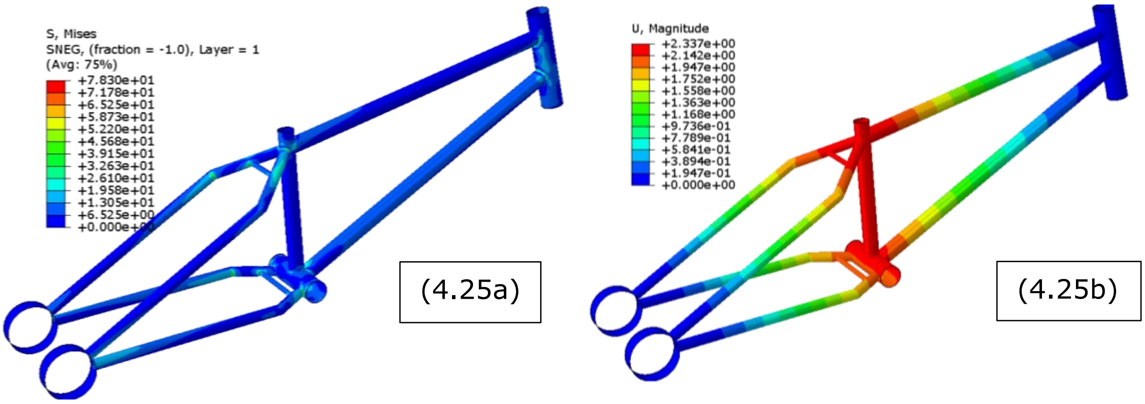


Figure 4.25: After optimization (4.25a) stress in MPa and (4.25b) displacement analysis in mm for result 3

Result 4:

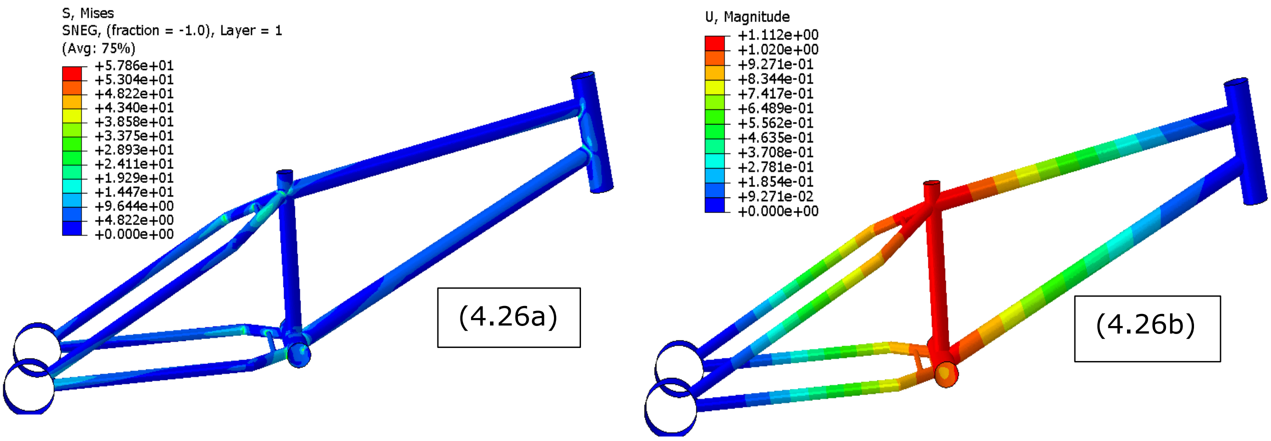


Figure 4.26: After optimization (4.26a) stress in MPa and (4.26b) displacement analysis in mm for result 4

Also from the displacements results, it observed that before optimization the maximum displacement has found for result one option's 9.55mm (figure 4.19b) which is reduced to 1.94mm (figure 4.23b). For result 2 option's, this displacement for the applied force (as earlier mentioned) has optimized from 7.54mm (figure 4.20b) to 1.52mm (figure 4.24b). For eight layers composite this displacement hasn't reduced as much as four layers. In result 3 option's, this is reduced from 2.65mm (figure 4.21b) to 2.34mm (figure 74.25b) and for result 4 option's it has been 3.41mm (figure 4.22b) to 1.11mm (figure 4.26b).

Again, in terms of weight of the frame, for four layers bicycle frame the weight has increased from 0.57kg to 1.38kg after optimization. And for eight layers bicycle frame, this has increased from 1.14 kg to 1.39kg for result 3 option's and for 1.84kg for result 4 options. Considering the highest weight for four- and eight-layers composite frame, environmental impacts are analyzed.

Frame weight result in kg	Before Optimization	After Optimization
Result 1	0.57	1.38
Result 2	0.57	1.38
Result 3	1.14	1.39
Result 4	1.14	1.84

Table 4.9: Before and after weight of flax reinforced composite bicycle frame

4.3.3 Environmental impact assessment for flax-epoxy bicycle frame:

Considering the weight of optimized bicycle frame from earlier portion, inventory analysis is made for flax-epoxy bicycle frame manufacturing as table 4.10 according to [56], [57], [58] and Structural analysis from earlier part.

Flax cultivation:						
Input:				**Output:**		
Scutching	Retted flax stems	8.92	kg	Long flax fibers	2.08	kg
	Electricity	1.07	kWh	Short flax fibers	1.14	kg
	Transport by lorry	45	tkm	Flax shives	3.61	kg
				Flax flakes	0.71	kg
				Seeds	0.49	kg
				Waste and emission:		
				Solid waste to incineration	0.87	kg
Hackling	Long flax fibers	2.08	kg	Hackled fib fibers res	1.34	kg
	Electricity	1.14	kWh	Hackled tows	0.62	kg
	Transport by train	500	km	**Waste and emission:**		
				Solid waste to incineration	0.12	kg
Flax dry	Hackled fibers	1.34	kg	Yarns	1.29	kg
Spinning	Electricity	3.22	kWh	**Waste and emission:**		
				Solid waste to incineration	0.054	kg
Flax manufacturing						
Input:				**Output:**		
Weaving	yarns	1.29	kg	Flax fabric	1.26	kg
Composite manufacturing						
Input:				**Output:**		
Epoxy resin, liquid		0.27	kg	Waste	0.6337 4	kg
Flax Fabric		0.05	kg	Composite frame	0.323	kg
Peel ply		0.003	kg			
Sealant tape		0.504	kg			
Tube insulation, elastomer		0.0037 4	kg			
Flow media		0.003	kg			

Electricity, low voltage		4.1	kWh			

Table 4.10: Inventory result of Flax-epoxy reinforced composite bicycle frame

Similar to other two part of the materials, in this part similar method, Global ReCiPe 2016 Midpoint (H) V1.05/World (2010), has followed for the environmental assessment. There are two assessments done for two separate bicycle frames based on the layers.

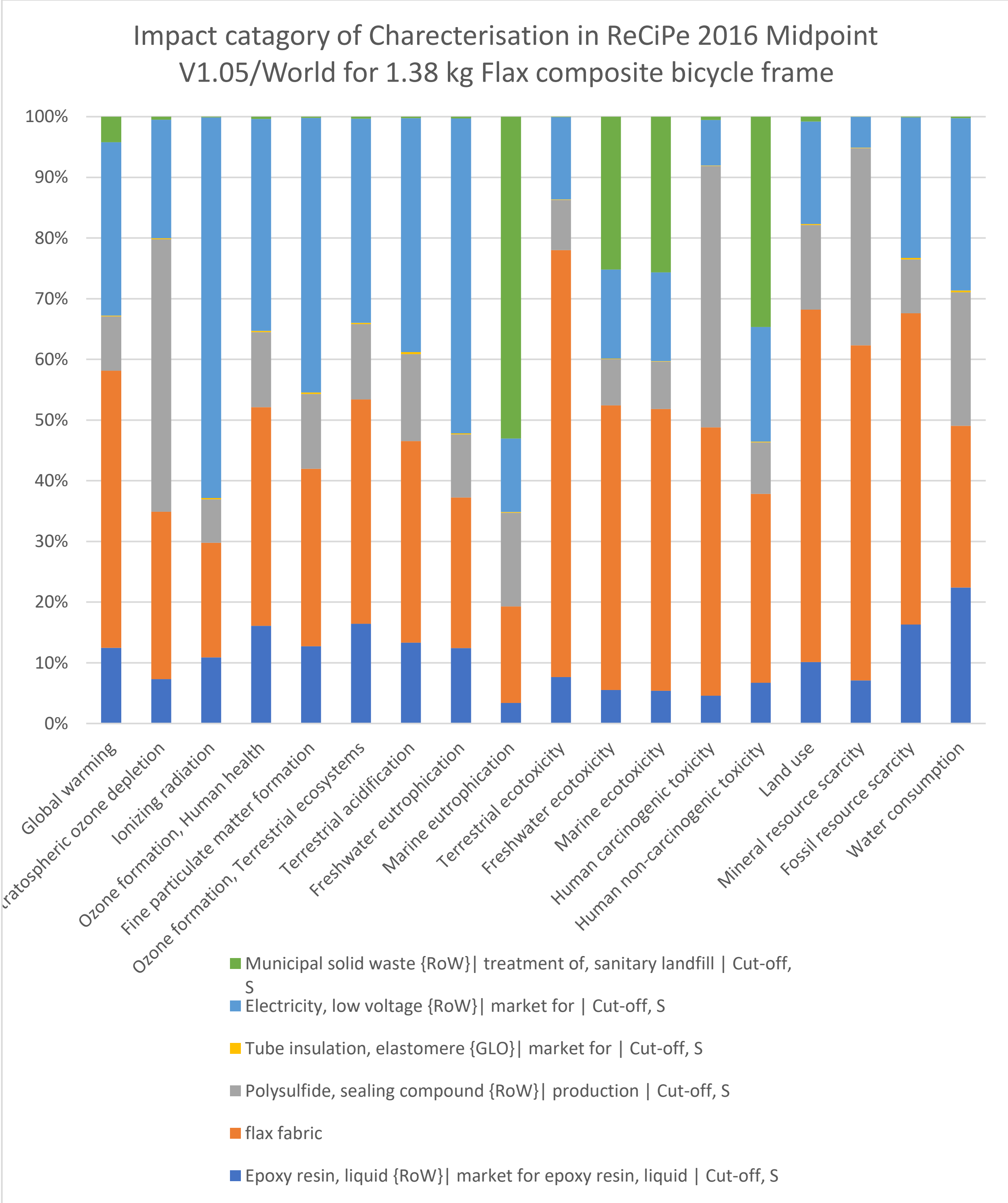


Figure 4.27 Characterization results of impact indicators for 1.38kg flax fiber composite frame

4.3.3.1 Simapro result for 1.38kg flax composite material bicycle frame (four layers):

From the figure 4.27 and 4.28, impact categories of characterization is shown for 1.38kg flax composite bicycle frame.

Figure 4.28 Characterization analysis of individual impact indicators for 1.38kg flax fiber composite frame

It has seen from the figure 4.27, in most cases flax fabric manufacturing, electricity and in few cases municipal solid waste are the major impact contributor. Meanwhile, in a small extent sealing compound, polysulfide, and epoxy resin are also involved in all indicators of environmental impact. Electricity has found almost 70% contributor for terrestrial ecotoxicity. In, Global warming, Mineral resource scarcity, fossil resource scarcity, Ecotoxicity of fresh and Marine, Human carcinogenic toxicity environmental indicators flax manufacturing has more than 40% contribution for the impact. Again, in Ozone formation, flax fabric manufacturing has more than 30% contribution to environmental impact. However, for Ionizing radiation, electricity has more than 60% contribution to the impact. And in marine eutrophication, Municipal solid waste has more than 50% contribution to the

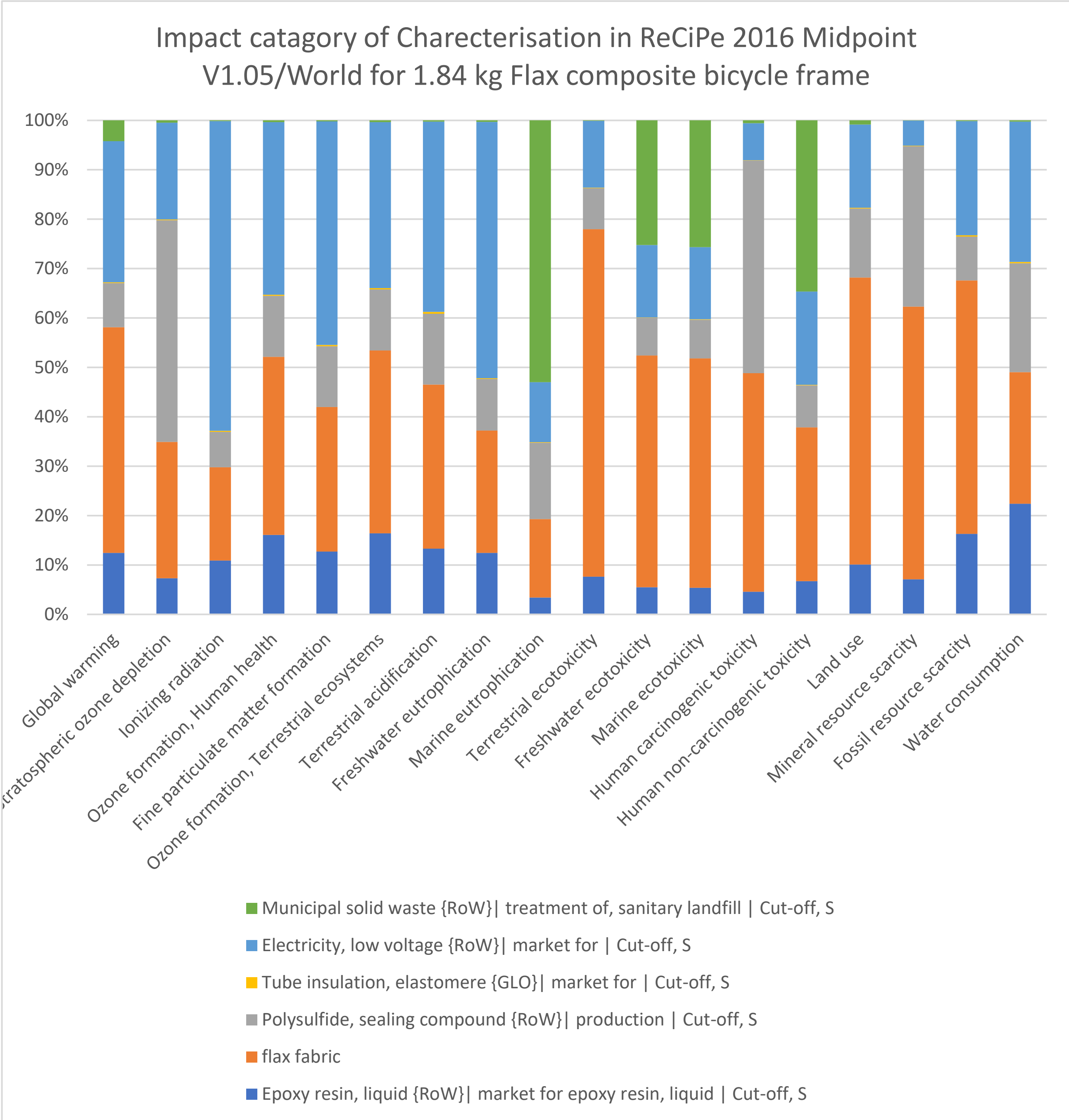


Figure 4.29 Characterization analysis of impact indicators for 1.84kg flax fiber composite frame

impact. These all-major impact indicators are also clearly understandable from figure 4.28 where impact contributors are visualizing for each indicator in pie diagrams.

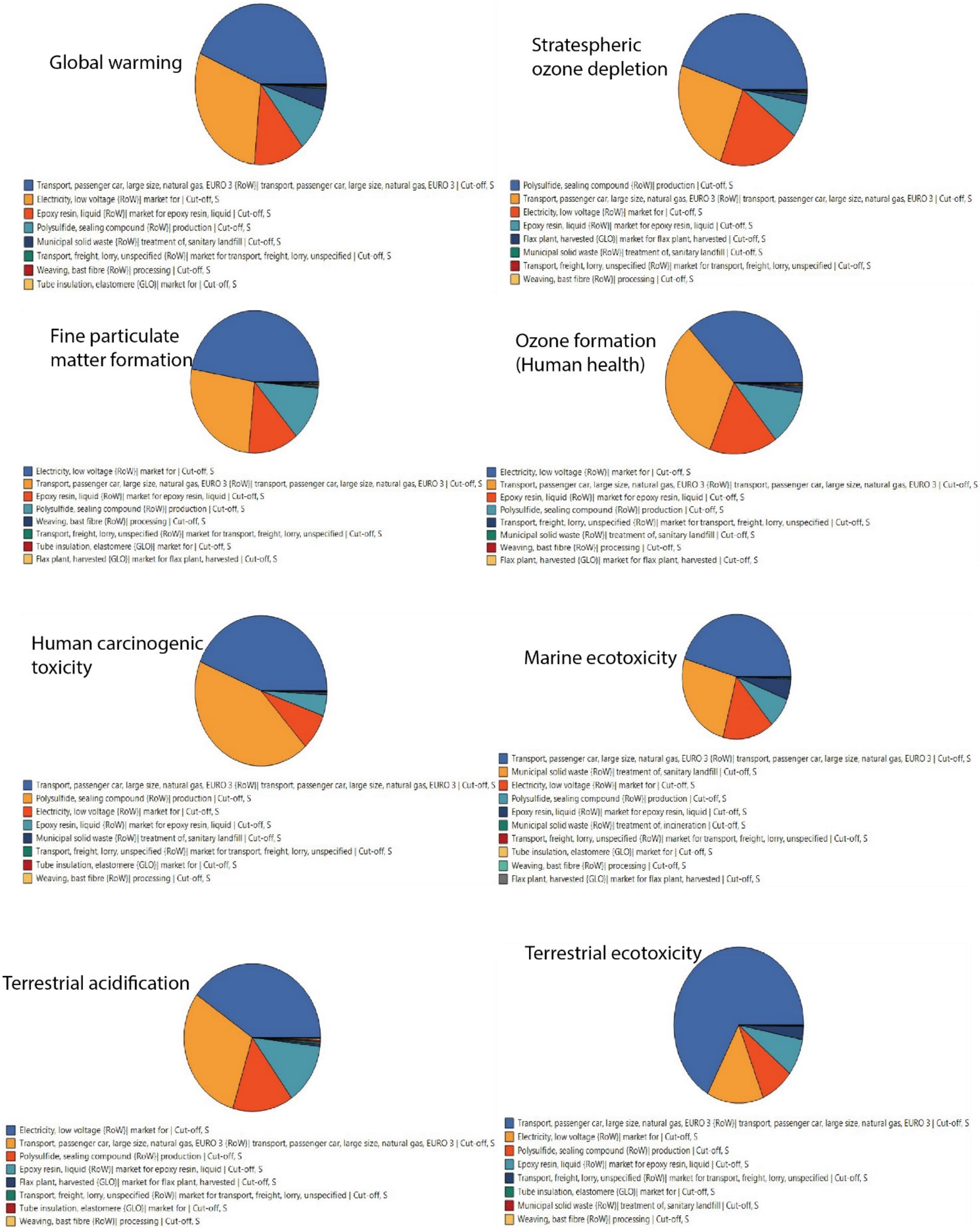


Figure 4.30 Characterization analysis of major impact indicators for 1.84kg flax fiber composite frame

4.3.3.2 Simapro result of 1.84kg flax composite material bicycle frame (eight layers):

Similar to four layers composite frame of flax-epoxy, in eight layers major contributors for each of the impact indicators are Flax fabric manufacturing, electricity (figure 4.29). In terrestrial ecotoxicity indicator, flax fabric manufacturing has almost 70% contribution to the environment. Also, similar to four layers flax composite frame, in ionizing radiation electricity has more than 60% contribution and in marine eutrophication municipal solid waste has more than 50% contribution. These situations also clearly visible from the pie chart of major impact indicators in figure 4.30. Like, while looking at global warming in the figure 4.30, electricity and transport, which is mostly related to flax fabric manufacturing, are major contributor for global worming indicator. And again, when looking at the Human carcinogenic indicator diagram in figure 4.30, polysulfide, the sealing tape, is the major contributor of this indicator. Optimized Bicycle frame weight of different materials

5 General discussion

Structural analysis is implemented at the beginning of the test study on bicycle frames which are made from three types of materials, Aluminum, Carbon-Epoxy composite, and Flax-epoxy composite. Based on the initial results of the FEA on those model frames, optimization has been implemented in next. And later FEA has applied again to those frames which are optimized in thicknesses in the same load and boundary condition. This procedure validated how improved the updated frames become after the optimization. The summarized results are visualized in figures 5.1 and 5.2 which are for stresses and displacements analysis. However, since stress is related to strength, another way to plot Figure 5.1 is to divide the maximum stress by the strength of the material. But in this study, to keep it simple, only raw data were plotted. From those results, it has been observed that bicycle frames made of four layers of carbon fiber composite material received the highest stresses among those frames. Before optimization, this maximum stress has been observed close to 600MPa as plotted in figure 5.1. And, after optimization,

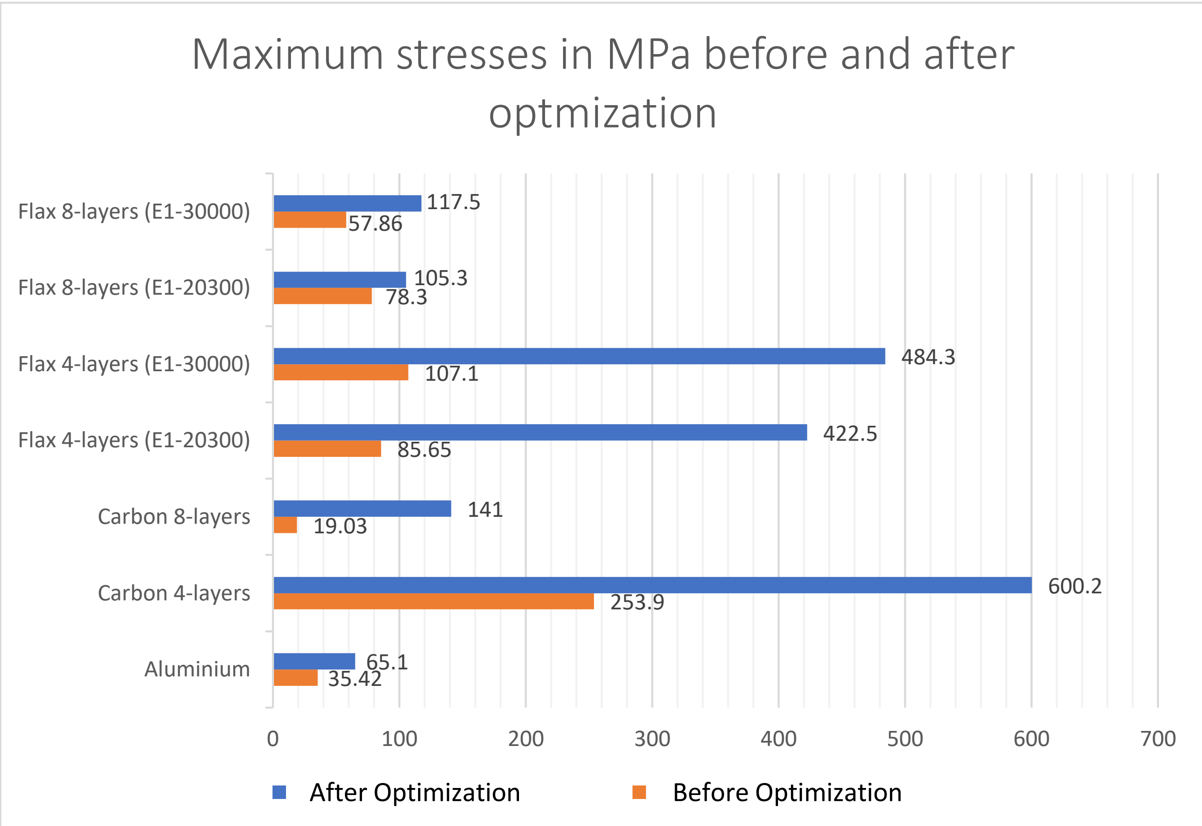


Figure 5.1: Maximum stresses value of optimized bicycle frame for different materials

this highest stress has reduced to closure to 250Mpa. On the other side, among all of those materials mentioned in figure 5.1, the lowest stress has been faced by the optimized eight layers of the carbon-epoxy composite frame. However, Aluminium also faced significantly less stresses than other materials. On the other side, similar to this stresses result, the displacements of this material under defined load and boundary conditions is observed in figure 5.2. It observed from figure 5.2, four layers flax-epoxy composite (where E1 in the

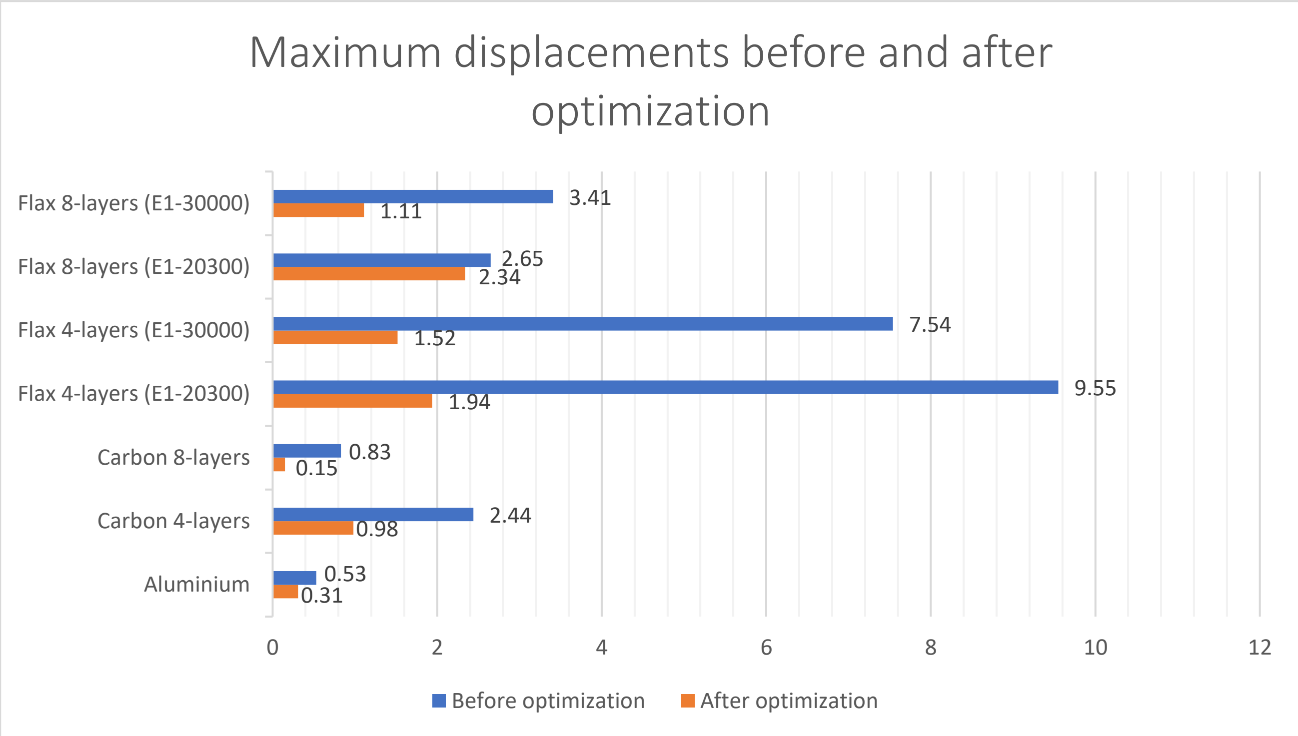


Figure 5.2: Maximum displacements value in mm before and after optimization

mechanical properties is 20300MPa, which is option 1 in the flax analysis) frame has the highest displacements before optimization, but it improved after the optimization. This displacement is improved from over 9.0mm to below 2.0mm. This improvement of displacement is more compared to eight layers flax-epoxy composite (E1=30000MPa, option 4 in flax analysis) frame. This is also the highest improvement of displacement among all the materials through optimization that improves the stiffness of the bicycle

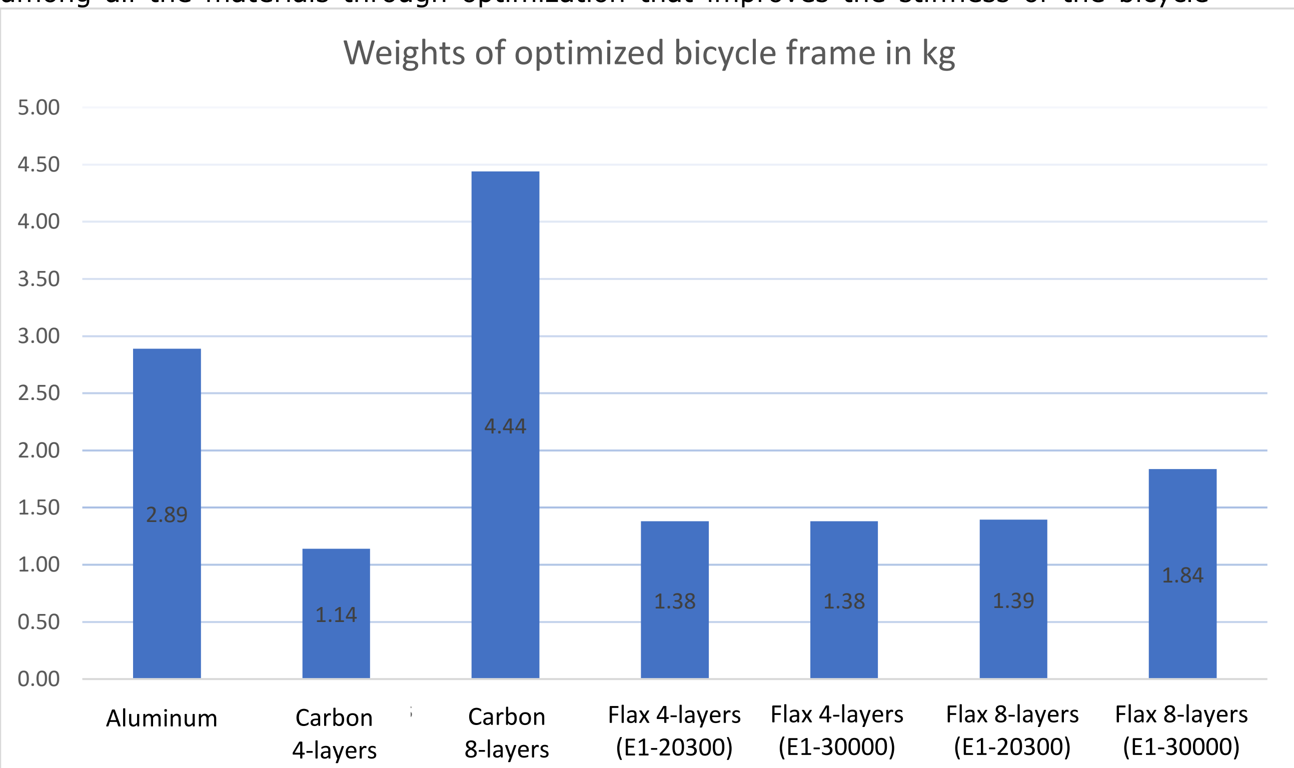


Figure 5.3: Optimized Bicycle frame weight of different materials

frame. However, by optimizing eight layers of carbon-epoxy composite bicycle frame, displacement of the frame has possible to improve closure to 0.4mm from 0.9mm. However, while looking at the weight of these bicycle frames of different materials, column chart as figure 5.3 is found. The highest weight is observed in eight layers carbon-epoxy composite frame which is 4.44kg. Following to this frame, the optimized aluminium frame

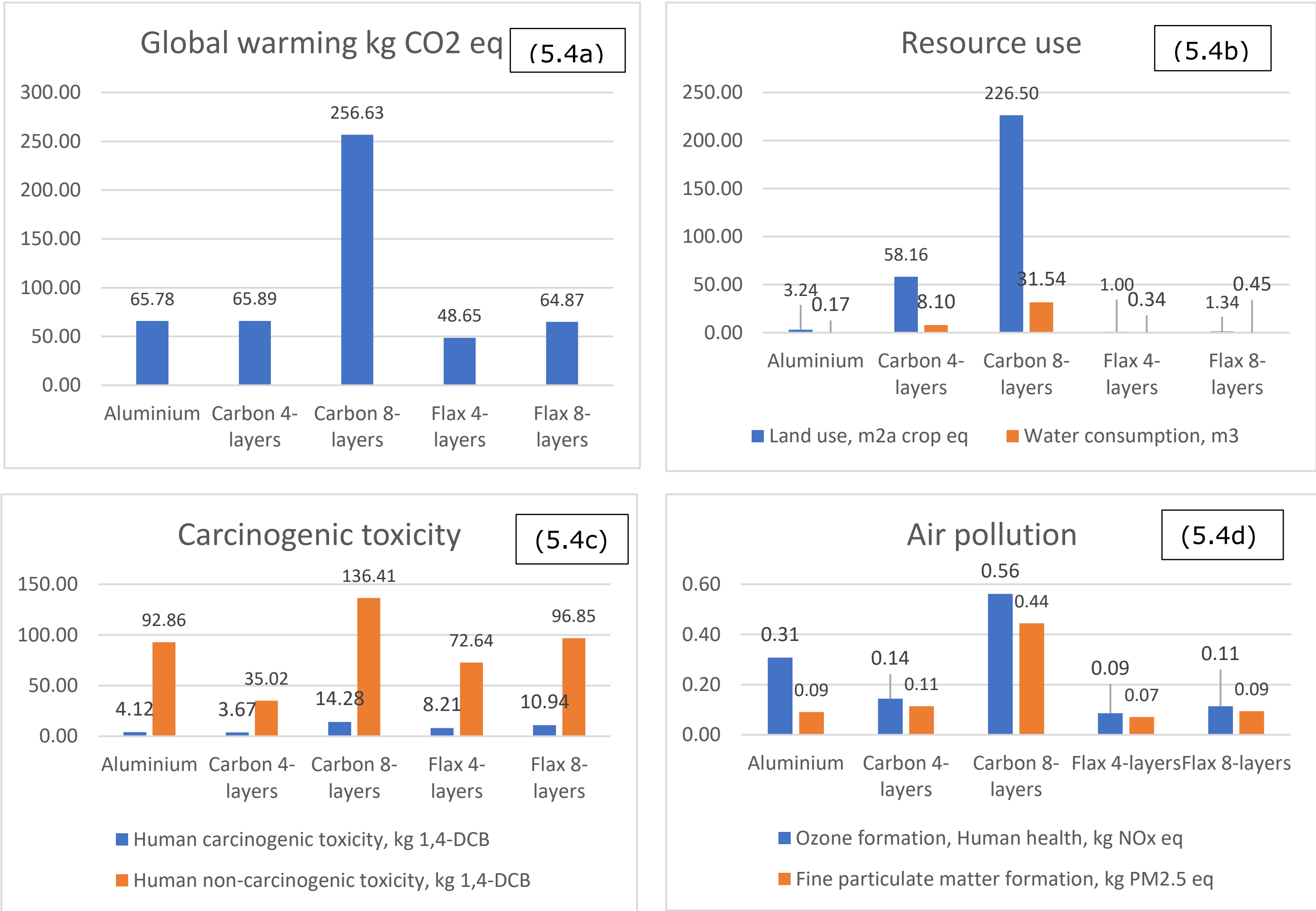


Figure 5.4 Environmental assessment of different materials bicycle frame, (5.4a) Global warming indicators; (5.4b) Land use and water consumption; (5.4c) Carcinogenic toxicity; (5.4d) Ozone formation and Fine particulate matter formation.

is found in 2.89kg. Flax-based composite frames are found below 2.0 kg. But the lowest weight is observed in the four-layer carbon-epoxy composite frame which is 1.14kg. And Based on these stiffness optimized frames, the environmental assessment is conducted to evaluate which material can be the best candidate for the reduction of environmental impact while manufacture this product. In figure 5.4, comparison of different impact categories on different materials for manufacturing the bicycle is visualised. In figure (5.4a), contribution to global warming in manufacturing the bicycle frame for different materials are shown. It is seen, eight layers carbon-epoxy composite bicycle frame produce highest CO_2 to the environment during manufacturing. Least CO_2 produced from four layers flax-epoxy composite bicycle frame. In (5.4b), use of natural resources, Land, and water consumption, are shown during manufacturing each bicycle frame for different materials. It has found that carbon fiber base bicycle frame uses maximum land during fabrication and lowest is found for four layers flax composite frame. On the other side, for water consumption lowest is found aluminium frame. In (5.4c), carcinogenic toxicity data is visualised. The lowest and highest human carcinogenic compound are produced from four layers carbon composite frame and eight layers flax fiber base composite frame. On the other hand, for non-carcinogenic toxicity, highest contributor observed in eight layers carbon composite frame but at the same time lowest has found in four layers carbon composite frame. Finally in figure (5.4d), it is seen, highest ozone formation and fine particulate matter formation are produced from eight layers carbon base composite frame. The lowest values for both indicators are observed for four layers flax base composite frame.

From the environmental perspective, it is seen in most cases eight layers carbon composite frame has the highest impact on the different impact indicators. One major reason is eight-layer carbon composite frame has the highest weight than other compared materials here. It is also found from these data, apart from case carbon fibre composites material frame, aluminium frame manufacturing has also greater environmental impact compared to flax-composite frame manufacturing. Although, from the structural analysis, it has found both Aluminium and carbon composite shows greater stiffness performance prior to optimization. But after the optimization, the gap for stresses and displacements improved significantly for flax composite frame than other two materials. It should be noted as earlier mentioned, while optimizing, half of the maximum strength of each material is set up highest strength limit for respective materials. So as, it’s possible to optimize every material with their maximum benefits and can be improve the frame stiffness evenly. But looking at the 5.1 figure in strength analysis, although every material went through similar boundary condition during optimization, but flax composite material frame’s improvement got the highest after optimization. Being more specific, looking at the optimized Flax-reinforced composite frame in four layers which have the lowest environmental impact and meet the structural requirement to most extent can be good option for the desire bicycle frame. Therefore, in this study example of bicycle frame, considering the described materials, boundary condition and testing procedure, optimized four layers flax composite material frame can meet the objective for the stiffer bicycle frame.

6 Conclusion

In this modern era, optimization of product design needs to encounter many factors. Adding environmental issues to this optimization process increases the number of requirements in this process. From the idea generation to the manufacture of the product need to follow a systematic way of orders. So that, it becomes convenient for new product engineers and developers to develop an optimized product that can meet structural, geometrical, manufacturing, and finally environmental requirements. In this study, an attempt has given to establish such a noble methodology. With the example of a bicycle frame as a product in this study, the proposed methodology is tried to implement and validate for a real-life product. Again, during the implementation of optimization on bicycle frame design in the proposed methodology, due to time limitation, only one variable i.e., stiffness of the bicycle frame, is taken into consideration from the plethora of parameters or requirements for structural optimization. And later environmental issues are analyzed based on that result. However, the majority of manufacturers still prefer aluminum over other materials like steel, titanium, carbon fiber, and Natural fiber composites like flax which is the latest addition to the material group. But from the result and analysis, it was observed that for bicycle frames, flax-reinforced epoxy composite shows a very good result after optimization. In the result section, it is seen, compared to the other materials described in this study, aluminum offers a good strength-to-weight ratio and is also recyclable from the environmental perspective. However, it observed form the analysis, aluminum production is vulnerable to environmental problems than these other elements. And further carbon fiber composite has the more severe impact on the environment than aluminum in most of cases. Flax on the other side shows the good result from the environmental and also structural perspective at the end after optimization.

6.1 Future Work:

There were several opportunities to widen the scope of the proposed optimization methodology. As mentioned, due to time limitations, it was not possible to take into consideration all the initial thoughts behind this study. The more factors that can be included in the structural optimization the better the structural and functional bicycle frame will result. The cost of materials and manufacturing play a significant role during product development which results in the final product price as well. So, cost issues could be added to this methodology and implementation part. In LCA, in this study, scope is limited to cradle to gate. However, this scope could be extended to cradle to crave. So that, while assessing environmental issues for the product, it can consider the service life stage and recyclability options of the product as well. However, this proposed methodology is the initial effort to bring sustainability to product design and development that engineers are now trying to establish for a sustainable future. The more research that will be done on this matter, it will become easier for the product developer to produce a product that can meet both different quality parameters and reduce the environmental burden.

7 References

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8 Appendices

8.1 Load and Boundary condition findings for FEA of a bicycle frame

Reference paper	**Loading category**	**Loading point**	**Constrained/ fixed point**	**Frame position**	**Applied load**	**remarks**
[59]	Tortional loading	Static force downwards to rigid bar	2 points. Head tube and rear dropout	Horizontal	10kgf or 98N	A fixed rigid bar is used as a fork in head tube
,,	Frontal loading	Static front load to fork or head tube	2 Rear dropout points	vertical	490N on each fork (Total=490N+490N)	
,,	Vertical loading	Loads are applied head (F1), seat tube(F2) and bottom bracket (F3a, F3b)	Front fork or head tube lower edge, rear dropouts	vertical	F1=58.8N F2=656.6N F3a & F3b =132.3N	
[33]	Pedal axis	On pedal at 7.5,15,22.5130-degree angel	Rear dropouts and heat tube	vertical	1200N	100000 cycles fatigue life is considered for both but half cycles are considered in this paper for each pedal.
,,	Fork axis	On fork or head tube	Rear dropouts	horizontal	Forward-1200N, backward-600N	50000 cycles are considered for fatigue life.

,,	Vertically downwards load	Seat installation point	Not specific	vertical		50000 cycles are considered for fatigue life
[60]	Front Deflection	On rigid head tube rod, and above 230mm from the bottom end	Bottom bracket tube is fixed with clump	Horizontal	211.3N	A rigid steel rod is placed on the head tube
	Rear deflection	On axle placed on rear dropouts	,,	,,	211.3N	An axle is placed on the rear dropouts
[61]	Variants-1: Biker load is considered on seat tube	seat tube	Rear dropouts and head tube	vertical	900N	
	Variants-2: biker load is considered in bottom bracket	Bottom bracket	Rear dropouts and head tube	vertical	900N	
	Variants-3: biker load is distributed on bottom bracket and head tube	Bottom bracket, Head tube.	Not specific	vertical	Bottom bracket-600N, Head tube-300N	

8.2 Python Script of Bicycle frame Model for Abaqus

```
###coding_start###

###-----library import-----

from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *

import math
import random
import numpy as np
import time
import sys

session.journalOptions.setValues(replayGeometry=COORDINATE,
recoverGeometry=COORDINATE)
outputFile='outFile.txt'

###-----library import-----

###-------- Input parameters ---------
#seat_tube, (part1)
```

```
seat_tube_radius=15.0
seat_tube_length=296.0

#top_tube, (part2)
top_tube_radius=15.0
top_tube_length=578.0
angel_top_seat=100
distance_top_origin=35

#head_tube (part 4)
head_tube_radius=21.50
head_tube_length=200.0
upward_distance_top_tube_join=50

#bottom__bracket (part 6)
bottom__bracket_radius=21.50
bottom__bracket_length=150.0

#Bottom_tube (part 8)
distance_top_bottm_at_head=9
bottom_tube_radius=16.00
bottom_tube_length= 655

#chain_stays (part 11 and 12)
chain_stays_long_length=400.0
chain_stays_small_length_y=88.0
chain_stays_small_length_z=60.0
chain_stays_small_radius=10.0
distance_chain_stays_mid_bracket=40

#seat_stays (part 15 and 16)
ratio=(1.0-chain_stays_small_length_y/chain_stays_long_length)
```

```
seat_stays_length_total=math.sqrt((seat_tube_length-
distance_top_origin)**2+(chain_stays_long_length+chain_stays_small_length_y
)**2)

seat_stays_long_length=ratio * seat_stays_length_total

seat_stays_small_length=seat_stays_length_total-seat_stays_long_length


#stays_connector (part 17 and 19)

stays_connector_length=
2*(chain_stays_small_length_z+distance_chain_stays_mid_bracket)

stays_connector_radius=5.0


#stays_edge_connector (part 27)

stays_edge_connector_length=28.0

stays_edge_connector_radius=45.0


###-------- Input parameters ---------


###-----global parameters------


mdb.Model(name='Model-1')


caeName='x01.cae'

caeNameJnl='x01.jnl'

q = mdb.models['Model-1']


###-----global parameters------


#seat_tube, (part1)

q.ConstrainedSketch(name='__profile__', sheetSize=200.0)

q.sketches['__profile__'].CircleByCenterPerimeter(center=(

    0.0, 0.0), point1=(seat_tube_radius, 0.0))

q.Part(dimensionality=THREE_D, name='Part-1', type=

    DEFORMABLE_BODY)

q.parts['Part-1'].BaseShellExtrude(depth=seat_tube_length, sketch=
```

```
    q.sketches['__profile__'])
del q.sketches['__profile__']


#top_tube, (part2)
q.ConstrainedSketch(name='__profile__', sheetSize=200.0)
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(top_tube_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-2', type=
    DEFORMABLE_BODY)
q.parts['Part-2'].BaseShellExtrude(depth=top_tube_length, sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
#assembly
q.rootAssembly.DatumCsysByDefault(CARTESIAN)
q.rootAssembly.Instance(dependent=ON, name='Part-1-1',
    part=q.parts['Part-1'])
q.rootAssembly.Instance(dependent=ON, name='Part-2-1',
    part=q.parts['Part-2'])
#rotate part 2
q.rootAssembly.rotate(angle=angel_top_seat,
axisDirection=(seat_tube_radius, 0.0,
    0.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Part-2-1', ))
#move part 2
q.rootAssembly.translate(instanceList=('Part-2-1', ),
    vector=(0.0, 0.0, distance_top_origin))


#merge part 1 and part 2 to create part 3
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-1-1'],
    q.rootAssembly.instances['Part-2-1']),
    keepIntersections=ON, name='Part-3', originalInstances=SUPPRESS)
#cut part 3
q.parts['Part-3'].DatumPlaneByPrincipalPlane(offset=0.0,
    principalPlane=XYPLANE)
```

```
q.ConstrainedSketch(gridSpacing=34.25, name='__profile__',
    sheetSize=1370.23, transform=
    q.parts['Part-3'].MakeSketchTransform(
    sketchPlane=q.parts['Part-3'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-3'].edges.findAt((0.0, seat_tube_radius,
    0.0), ), sketchOrientation=RIGHT, origin=(0.0, 0.0, 0.0)))

q.parts['Part-3'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(seat_tube_radius, 0.0))
q.parts['Part-3'].CutExtrude(flipExtrudeDirection=ON,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-3'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-3'].edges.findAt((0.0, seat_tube_radius, 0.0), ))
del q.sketches['__profile__']

#bring back part 1
q.rootAssembly.regenerate()
q.rootAssembly.features['Part-1-1'].resume()

#head_tube (part 4)
q.ConstrainedSketch(name='__profile__', sheetSize=200.0)
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(head_tube_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-4', type=
    DEFORMABLE_BODY)
q.parts['Part-4'].BaseShellExtrude(depth=head_tube_length, sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
```

```
#assembly
q.rootAssembly.Instance(dependent=ON, name='Part-4-1',
    part=q.parts['Part-4'])

###move
q.rootAssembly.translate(instanceList=('Part-4-1', ),
    vector=(0.0, 0.0, -upward_distance_top_tube_join))

q.rootAssembly.rotate(angle=-(angel_top_seat-90.0), axisDirection=(-1.0,
    0.0, 0.0), axisPoint=(1.0, 0.0, 0.0), instanceList=('Part-4-1', ))

q.rootAssembly.translate(instanceList=('Part-4-1', ),
    vector=(0.0, -(569.22), -65.368647))

#merge part 3 and part 4
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-3-1'],
    q.rootAssembly.instances['Part-4-1']),
    keepIntersections=ON, name='Part-5', originalInstances=SUPPRESS)

#cut part 5
q.parts['Part-5'].PartitionEdgeByParam(edges=
    mdb.models['Model-1'].parts['Part-5'].edges.findAt(((0.0, -539.364224,
    -110.875599), )), parameter=0.5)
q.parts['Part-5'].DatumPlaneByThreePoints(point1=
    q.parts['Part-5'].vertices.findAt((head_tube_radius, -560.537591,
    -114.609035), ), point2=
    q.parts['Part-5'].InterestingPoint(
    q.parts['Part-5'].edges.findAt((-15.202796,
    -575.509422, -117.248972), ), MIDDLE), point3=
    q.parts['Part-5'].vertices.findAt((-head_tube_radius, -560.537591,
    -114.609035), ))
```

```
q.ConstrainedSketch(gridSpacing=36.51, name='__profile__',
    sheetSize=1460.7, transform=
    q.parts['Part-5'].MakeSketchTransform(
    sketchPlane=q.parts['Part-5'].datums[3],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-5'].edges.findAt((
    -15.202796, -575.509422, -117.248972), ), sketchOrientation=RIGHT,
origin=(
    0.0, -560.537591, -114.609035)))
q.parts['Part-5'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(head_tube_radius, 0.0))
q.parts['Part-5'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-5'].datums[3],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-5'].edges.findAt((-15.202796,
    -575.509422, -117.248972), ))
del q.sketches['__profile__']

#resume part 4
q.rootAssembly.features['Part-4-1'].resume()

#bottom__bracket (part 6)
q.ConstrainedSketch(name='__profile__', sheetSize=200.0)
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(bottom__bracket_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-6', type=
    DEFORMABLE_BODY)
q.parts['Part-6'].BaseShellExtrude(depth=bottom__bracket_length, sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
```

```
#assembly
q.rootAssembly.Instance(dependent=OFF, name='Part-6-1',
    part=q.parts['Part-6'])
#rotate
q.rootAssembly.rotate(angle=90.0, axisDirection=(0.0, -1.0,
    0.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Part-6-1', ))

#move x
q.rootAssembly.translate(instanceList=('Part-6-1', ),
    vector=(bottom__bracket_length/2, 0.0, 0.0))
#move z
q.rootAssembly.translate(instanceList=('Part-6-1', ),
    vector=(0.0, 0.0, seat_tube_length))
#merge part 6 and creat 7
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-1-1'],
    q.rootAssembly.instances['Part-6-1']), name='Part-7',
    originalInstances=SUPPRESS)

#cut
q.parts['Part-
7'].DatumPlaneByPrincipalPlane(offset=(bottom__bracket_length/2),
    principalPlane=YZPLANE)

q.ConstrainedSketch(gridSpacing=20.77, name='__profile__',
    sheetSize=831.04, transform=
    q.parts['Part-7'].MakeSketchTransform(
    sketchPlane=q.parts['Part-7'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-
7'].edges.findAt(((bottom__bracket_length/2),
    bottom__bracket_radius, seat_tube_length), ), sketchOrientation=RIGHT,
origin=((bottom__bracket_length/2), 0.0, seat_tube_length)))
q.parts['Part-7'].projectReferencesOntoSketch(filter=
```

```
    COPLANAR_EDGES, sketch=mdb.models['Model-1'].sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(bottom__bracket_radius, 0.0))
q.parts['Part-7'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-7'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-7'].edges.findAt(((bottom__bracket_length/2),
bottom__bracket_radius, seat_tube_length), ))
del q.sketches['__profile__']



#bring back part 6
q.rootAssembly.features['Part-6-1'].resume()

#bottom_tube (part 8)

q.ConstrainedSketch(name='__profile__', sheetSize=200.0)
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(bottom_tube_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-8', type=
    DEFORMABLE_BODY)
q.parts['Part-8'].BaseShellExtrude(depth=bottom_tube_length, sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']

#assembly
q.rootAssembly.Instance(dependent=OFF, name='Part-8-1',
    part=q.parts['Part-8'])

rad8=math.atan((seat_tube_length-
distance_top_bottm_at_head)/top_tube_length)
ang8=rad8*180/math.pi
q.rootAssembly.rotate(angle=-(90.0-ang8), axisDirection=(1.0, 0.0,
```

```
    0.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Part-8-1', ))

#move
q.rootAssembly.translate(instanceList=('Part-8-1', ),
    vector=(0.0, -(top_tube_length+10), (distance_top_bottm_at_head)))

#merge seat_tube_and_bottom_tube
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-8-1'],
    q.rootAssembly.instances['Part-7-1']),
    keepIntersections=ON, name='Part-9', originalInstances=SUPPRESS)

q.parts['Part-9'].DatumPlaneByPrincipalPlane(offset=0.0,
    principalPlane=XYPLANE)

q.ConstrainedSketch(gridSpacing=37.26, name='__profile__',
    sheetSize=1490.57, transform=
    q.parts['Part-9'].MakeSketchTransform(
    sketchPlane=q.parts['Part-9'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-9'].edges.findAt((0.0, seat_tube_radius,
    0.0), ), sketchOrientation=RIGHT, origin=(-seat_tube_radius, 0.0,
0.0)))
q.parts['Part-9'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    seat_tube_radius, 0.0), point1=(18.63, 14.5541437398424))
q.sketches['__profile__'].vertices.findAt((18.63,
    14.554144))
q.sketches['__profile__'].geometry.findAt((29.265848,
    -4.635255))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((18.63,
```

```
    14.5541437398424), ), entity2=
    q.sketches['__profile__'].geometry.findAt((29.265848,
    -4.635255), ))
q.parts['Part-9'].CutExtrude(flipExtrudeDirection=ON,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-9'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-9'].edges.findAt((0.0, seat_tube_radius, 0.0), ))
del q.sketches['__profile__']

q.rootAssembly.features['Part-7-1'].resume()

#merge of part 9 and 6, created 10
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-6-1'],
    q.rootAssembly.instances['Part-9-1']),
    keepIntersections=ON, name='Part-10', originalInstances=SUPPRESS)

#cut
q.parts['Part-
10'].DatumPlaneByPrincipalPlane(offset=bottom__bracket_length/2,
    principalPlane=YZPLANE)

q.ConstrainedSketch(gridSpacing=39.02, name='__profile__',
    sheetSize=1561.05, transform=
    q.parts['Part-10'].MakeSketchTransform(
    sketchPlane=q.parts['Part-10'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-10'].edges.findAt((bottom__bracket_length/2,
    bottom__bracket_radius, seat_tube_length), ), sketchOrientation=RIGHT,
origin=(bottom__bracket_length/2, 0.0, 274.5)))
q.parts['Part-10'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
```

```
    bottom__bracket_radius, 0.0), point1=(2.34040775486028, 9.755))
q.sketches['__profile__'].vertices.findAt((2.340408,
    9.755))
q.sketches['__profile__'].geometry.findAt((41.947715,
    -6.643865))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    2.34040775486028, 9.755), ), entity2=
    q.sketches['__profile__'].geometry.findAt((41.947715,
    -6.643865), ))
q.parts['Part-10'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-10'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-10'].edges.findAt((bottom__bracket_length/2,
bottom__bracket_radius, seat_tube_length), ))
del q.sketches['__profile__']

q.rootAssembly.features['Part-6-1'].resume()

#merge bottom_tube (9) and heat_tube (4), created part 22
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-10-1'],
    q.rootAssembly.instances['Part-4-1']),
    keepIntersections=ON, name='Part-22', originalInstances=SUPPRESS)

#cut
q.parts['Part-22'].PartitionEdgeByParam(edges=
    q.parts['Part-22'].edges.findAt(((0.0, -616.440593,
    78.61908), )), parameter=0.5)
q.parts['Part-22'].DatumPlaneByThreePoints(point1=
    q.parts['Part-22'].vertices.findAt((-head_tube_radius, -595.267227,
    82.352516), ), point2=
```

```
    q.parts['Part-22'].InterestingPoint(
    q.parts['Part-22'].edges.findAt((15.202796,
    -610.239058, 79.712578), ), MIDDLE), point3=
    q.parts['Part-22'].vertices.findAt((head_tube_radius, -595.267227,
    82.352516), ))

q.ConstrainedSketch(gridSpacing=42.19, name='__profile__',
    sheetSize=1687.64, transform=
    q.parts['Part-22'].MakeSketchTransform(
    sketchPlane=q.parts['Part-22'].datums[3],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-22'].edges.findAt((
    15.202796, -610.239058, 79.712578), ), sketchOrientation=RIGHT,
origin=(
    0.0, -595.267227, 82.352516)))
q.parts['Part-22'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 3.36279413204466e-07), point1=(head_tube_radius,
3.36279413204466e-07))
q.parts['Part-22'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-22'].datums[3],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-22'].edges.findAt((15.202796,
    -610.239058, 79.712578), ))
del q.sketches['__profile__']

q.rootAssembly.features['Part-4-1'].resume()

#chain_stays (part 11)
q.ConstrainedSketch(name='__sweep__', sheetSize=200.0)
q.sketches['__sweep__'].Line(point1=(0.0, 0.0), point2=(
    chain_stays_long_length, 0.0))
```

```
q.sketches['__sweep__'].geometry.findAt(((chain_stays_long_length/2), 0.0))
q.sketches['__sweep__'].HorizontalConstraint(addUndoState=
    False, entity=q.sketches['__sweep__'].geometry.findAt((
    (chain_stays_long_length/2), 0.0), ))
q.sketches['__sweep__'].Line(point1=(chain_stays_long_length, 0.0),
point2=(
    (chain_stays_long_length+chain_stays_small_length_y),
chain_stays_small_length_z))
q.ConstrainedSketch(name='__profile__', sheetSize=200.0,
    transform=(0.0, -1.0, 0.0, -0.0, 0.0, 1.0, -1.0, -0.0, -0.0, 0.0, 0.0,
    0.0))
q.sketches['__profile__'].ConstructionLine(point1=(-100.0,
    0.0), point2=(100.0, 0.0))
q.sketches['__profile__'].ConstructionLine(point1=(0.0,
    -100.0), point2=(0.0, 100.0))
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(chain_stays_small_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-11', type=
    DEFORMABLE_BODY)
q.parts['Part-11'].BaseShellSweep(path=
    q.sketches['__sweep__'], sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
del q.sketches['__sweep__']

#assembly part 11
q.rootAssembly.Instance(dependent=ON, name='Part-11-1',
    part=q.parts['Part-11'])
q.rootAssembly.rotate(angle=-90.0, axisDirection=(0.0, 0.0,
    1.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Part-11-1', ))
#move to 0
mdb.models['Model-1'].rootAssembly.translate(instanceList=('Part-11-1', ),
    vector=(-chain_stays_small_length_z,
(chain_stays_long_length+chain_stays_small_length_y), 0.0))
```

```
#move in z
mdb.models['Model-1'].rootAssembly.translate(instanceList=('Part-11-1', ),
    vector=(0.0, 0.0, seat_tube_length))
#move in x
q.rootAssembly.translate(instanceList=('Part-11-1', ),
    vector=(-distance_chain_stays_mid_bracket, 0.0, 0.0))

#merge part 6 and 11, created 12
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-6-1'],
    q.rootAssembly.instances['Part-11-1']), name='Part-12',
    originalInstances=SUPPRESS)

#cut
q.parts['Part-12'].DatumPlaneByPrincipalPlane(offset=-
bottom__bracket_length/2,
    principalPlane=YZPLANE)
q.ConstrainedSketch(gridSpacing=30.19, name='__profile__',
    sheetSize=1207.97, transform=
    q.parts['Part-12'].MakeSketchTransform(
    sketchPlane=q.parts['Part-12'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-12'].edges.findAt((-
bottom__bracket_length/2,
    -bottom__bracket_radius,seat_tube_length), ), sketchOrientation=RIGHT,
origin=(-bottom__bracket_length/2, 0.0, 317.5)))
q.parts['Part-12'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    -bottom__bracket_radius, 0.0), point1=(-6.19016737517995, -15.095))
q.sketches['__profile__'].vertices.findAt((-6.190167,
    -15.095))
q.sketches['__profile__'].geometry.findAt((-1.052285,
    -6.643865))
```

```
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    -6.19016737517995, -15.095), ), entity2=
    q.sketches['__profile__'].geometry.findAt((-1.052285,
    -6.643865), ))
q.parts['Part-12'].CutExtrude(flipExtrudeDirection=ON,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-12'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-12'].edges.findAt((-bottom__bracket_length/2, -
bottom__bracket_radius, seat_tube_length),
    ))
del q.sketches['__profile__']

q.rootAssembly.features['Part-6-1'].resume()

#part 13
q.ConstrainedSketch(name='__sweep__', sheetSize=200.0)
q.sketches['__sweep__'].Line(point1=(0.0, 0.0), point2=(
    chain_stays_long_length, 0.0))
q.sketches['__sweep__'].geometry.findAt(((chain_stays_long_length/2), 0.0))
q.sketches['__sweep__'].HorizontalConstraint(addUndoState=
    False, entity=q.sketches['__sweep__'].geometry.findAt((
    (chain_stays_long_length/2), 0.0), ))
q.sketches['__sweep__'].Line(point1=(chain_stays_long_length, 0.0),
point2=(
    chain_stays_long_length+chain_stays_small_length_y, -
chain_stays_small_length_z))
q.ConstrainedSketch(name='__profile__', sheetSize=200.0,
    transform=(0.0, -1.0, 0.0, -0.0, 0.0, 1.0, -1.0, -0.0, -0.0, 0.0, 0.0,
    0.0))
q.sketches['__profile__'].ConstructionLine(point1=(-100.0,
    0.0), point2=(100.0, 0.0))
```

```
q.sketches['__profile__'].ConstructionLine(point1=(0.0,
    -100.0), point2=(0.0, 100.0))
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(chain_stays_small_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-13', type=
    DEFORMABLE_BODY)
q.parts['Part-13'].BaseShellSweep(path=
    q.sketches['__sweep__'], sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
del q.sketches['__sweep__']

#assembly
q.rootAssembly.Instance(dependent=ON, name='Part-13-1',
    part=q.parts['Part-13'])

#rotate
q.rootAssembly.rotate(angle=-90.0, axisDirection=(0.0, 0.0,
    1.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Part-13-1', ))

q.rootAssembly.translate(instanceList=('Part-13-1', ),
    vector=(chain_stays_small_length_z,
(chain_stays_long_length+chain_stays_small_length_y), 0.0))

q.rootAssembly.translate(instanceList=('Part-13-1', ),
    vector=(0.0, 0.0, seat_tube_length))

q.rootAssembly.translate(instanceList=('Part-13-1', ),
    vector=(distance_chain_stays_mid_bracket, 0.0,0.0))

#merge part 13 and 6, created 14
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-13-1'],
    q.rootAssembly.instances['Part-6-1']),
```

```
    keepIntersections=ON, name='Part-14', originalInstances=SUPPRESS)

#cut
q.parts['Part-
14'].DatumPlaneByPrincipalPlane(offset=bottom__bracket_length/2,
    principalPlane=YZPLANE)

q.ConstrainedSketch(gridSpacing=30.19, name='__profile__',
    sheetSize=1207.97, transform=
    q.parts['Part-14'].MakeSketchTransform(
    sketchPlane=q.parts['Part-14'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-14'].edges.findAt((bottom__bracket_length/2,
    bottom__bracket_radius, seat_tube_length), ), sketchOrientation=RIGHT,
origin=(bottom__bracket_length/2, 0.0, 274.5)))
q.parts['Part-14'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    bottom__bracket_radius, 0.0), point1=(37.7375, -14.0923239300701))
q.sketches['__profile__'].vertices.findAt((37.7375,
    -14.092324))
q.sketches['__profile__'].geometry.findAt((41.947715,
    -6.643865))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
   q.sketches['__profile__'].vertices.findAt((37.7375,
    -14.0923239300701), ), entity2=
   q.sketches['__profile__'].geometry.findAt((41.947715,
    -6.643865), ))
q.parts['Part-14'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-14'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
```

```
    q.parts['Part-14'].edges.findAt((bottom__bracket_length/2,
bottom__bracket_radius, seat_tube_length), ))
del q.sketches['__profile__']
q.rootAssembly.features['Part-6-1'].resume()


#seat_stays (part 15)
q.ConstrainedSketch(name='__sweep__', sheetSize=200.0)
q.sketches['__sweep__'].Line(point1=(0.0, 0.0), point2=(
    seat_stays_long_length, 0.0))
q.sketches['__sweep__'].geometry.findAt(((seat_stays_long_length/2), 0.0))
q.sketches['__sweep__'].HorizontalConstraint(addUndoState=
    False, entity=q.sketches['__sweep__'].geometry.findAt((
    (seat_stays_long_length/2), 0.0), ))


q.sketches['__sweep__'].Line(point1=(seat_stays_long_length, 0.0), point2=(
    (seat_stays_long_length+seat_stays_small_length),
(chain_stays_small_length_z+distance_chain_stays_mid_bracket)))


q.ConstrainedSketch(name='__profile__', sheetSize=200.0,
    transform=(0.0, -1.0, 0.0, -0.0, 0.0, 1.0, -1.0, -0.0, -0.0, 0.0, 0.0,
    0.0))
q.sketches['__profile__'].ConstructionLine(point1=(-100.0,
    0.0), point2=(100.0, 0.0))
q.sketches['__profile__'].ConstructionLine(point1=(0.0,
    -100.0), point2=(0.0, 100.0))
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(chain_stays_small_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-15', type=
    DEFORMABLE_BODY)
q.parts['Part-15'].BaseShellSweep(path=
    q.sketches['__sweep__'], sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
del q.sketches['__sweep__']
```

```
q.rootAssembly.Instance(dependent=ON, name='Part-15-1',
    part=q.parts['Part-15'])
q.rootAssembly.rotate(angle=-90.0, axisDirection=(0.0, 0.0,
    1.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Part-15-1', ))

q.rootAssembly.translate(instanceList=('Part-15-1', ),
    vector=(-(chain_stays_small_length_z+distance_chain_stays_mid_bracket),
(seat_stays_long_length+seat_stays_small_length), 0.0))

q.rootAssembly.translate(instanceList=('Part-15-1', ),
    vector=(0.0, 0.0, distance_top_origin))
#rotate
rad15=math.atan((seat_tube_length-
distance_top_origin)/(chain_stays_long_length+chain_stays_small_length_y))
ang15=rad15*180/math.pi

q.rootAssembly.rotate(angle=ang15, axisDirection=(1.0, 0.0,
    0.0), axisPoint=(0.0, 0.0, distance_top_origin), instanceList=('Part-
15-1', ))

#merge part 6 and 15, created 18
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-15-1'],
    q.rootAssembly.instances['Part-7-1']),
    keepIntersections=ON, name='Part-18', originalInstances=SUPPRESS)

#cut
q.parts['Part-18'].DatumPlaneByPrincipalPlane(offset=0.0,
    principalPlane=XYPLANE)

q.ConstrainedSketch(gridSpacing=33.0, name='__profile__',
    sheetSize=1320.18, transform=
    q.parts['Part-18'].MakeSketchTransform(
```

```
    sketchPlane=q.parts['Part-18'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-18'].edges.findAt((0.0,
    seat_tube_radius, 0.0), ), sketchOrientation=RIGHT, origin=(-
seat_tube_radius, 0.0, 0.0)))
q.parts['Part-18'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    seat_tube_radius, 0.0), point1=(16.5, 14.9248115565988))
q.sketches['__profile__'].vertices.findAt((16.5,
    14.924812))
q.sketches['__profile__'].geometry.findAt((29.265848,
    -4.635255))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((16.5,
    14.9248115565988), ), entity2=
    q.sketches['__profile__'].geometry.findAt((29.265848,
    -4.635255), ))
q.parts['Part-18'].CutExtrude(flipExtrudeDirection=ON,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-18'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-18'].edges.findAt((0.0, seat_tube_radius, 0.0), ))
del q.sketches['__profile__']

q.rootAssembly.features['Part-7-1'].resume()

#part 16
seat_stays_length_total=math.sqrt((seat_tube_length-
distance_top_origin)**2+(chain_stays_long_length+chain_stays_small_length_y
)**2)
seat_stays_long_length=ratio*seat_stays_length_total
seat_stays_small_length=seat_stays_length_total-seat_stays_long_length
```

```
q.ConstrainedSketch(name='__sweep__', sheetSize=200.0)
q.sketches['__sweep__'].Line(point1=(0.0, 0.0), point2=(
    seat_stays_long_length, 0.0))
q.sketches['__sweep__'].geometry.findAt(((seat_stays_long_length/2), 0.0))
q.sketches['__sweep__'].HorizontalConstraint(addUndoState=
    False, entity=q.sketches['__sweep__'].geometry.findAt((
    (seat_stays_long_length/2), 0.0), ))

q.sketches['__sweep__'].Line(point1=(seat_stays_long_length, 0.0), point2=(
    (seat_stays_long_length+seat_stays_small_length), -
(chain_stays_small_length_z+distance_chain_stays_mid_bracket)))

q.ConstrainedSketch(name='__profile__', sheetSize=200.0,
    transform=(0.0, -1.0, 0.0, -0.0, 0.0, 1.0, -1.0, -0.0, -0.0, 0.0, 0.0,
    0.0))
q.sketches['__profile__'].ConstructionLine(point1=(-100.0,
    0.0), point2=(100.0, 0.0))
q.sketches['__profile__'].ConstructionLine(point1=(0.0,
    -100.0), point2=(0.0, 100.0))
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(chain_stays_small_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-16', type=
    DEFORMABLE_BODY)
q.parts['Part-16'].BaseShellSweep(path=
    q.sketches['__sweep__'], sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
del q.sketches['__sweep__']

#assembly_part_16
q.rootAssembly.Instance(dependent=ON, name='Part-16-1',
    part=q.parts['Part-16'])
q.rootAssembly.rotate(angle=-90.0, axisDirection=(0.0, 0.0,
```

```
    1.0), axisPoint=(0.0, 0.0, 0.0), instanceList=('Part-16-1', ))


q.rootAssembly.translate(instanceList=('Part-16-1', ),
    vector=(+(chain_stays_small_length_z+distance_chain_stays_mid_bracket),
(seat_stays_long_length+seat_stays_small_length), 0.0))


q.rootAssembly.translate(instanceList=('Part-16-1', ),
    vector=(0.0, 0.0, distance_top_origin))
#rotate
rad15=math.atan((seat_tube_length-
distance_top_origin)/(chain_stays_long_length+chain_stays_small_length_y))
ang15=rad15*180/math.pi


q.rootAssembly.rotate(angle=ang15, axisDirection=(1.0, 0.0,
    0.0), axisPoint=(0.0, 0.0, distance_top_origin), instanceList=('Part-
16-1', ))


#merge
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-16-1'],
    q.rootAssembly.instances['Part-7-1']),
    keepIntersections=ON, name='Part-20', originalInstances=SUPPRESS)


#cut
q.parts['Part-20'].DatumPlaneByPrincipalPlane(offset=0.0,
    principalPlane=XYPLANE)


q.ConstrainedSketch(gridSpacing=33.0, name='__profile__',
    sheetSize=1320.18, transform=
    q.parts['Part-20'].MakeSketchTransform(
    sketchPlane=q.parts['Part-20'].datums[2],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-20'].edges.findAt((0.0,
    seat_tube_radius, 0.0), ), sketchOrientation=RIGHT,
origin=(seat_tube_radius, 0.0, 0.0)))
```

```
q.parts['Part-20'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    -seat_tube_radius, 0.0), point1=(-16.5, -14.9248115565988))
q.sketches['__profile__'].vertices.findAt((-16.5,
    -14.924812))
q.sketches['__profile__'].geometry.findAt((-0.734152,
    -4.635255))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((-16.5,
    -14.9248115565988), ), entity2=
    q.sketches['__profile__'].geometry.findAt((-0.734152,
    -4.635255), ))
q.parts['Part-20'].CutExtrude(flipExtrudeDirection=ON,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-20'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-20'].edges.findAt((0.0, seat_tube_radius, 0.0), ))
del q.sketches['__profile__']

q.rootAssembly.features['Part-7-1'].resume()

# part 17 (Top-stays connector)
#q.rootAssembly.regenerate()
q.rootAssembly.features['Part-15-1'].resume()
q.rootAssembly.features['Part-16-1'].resume()

p15=q.rootAssembly.instances['Part-15-1']
P1x_15=p15.edges[1].pointOn[0][0]
P1y_15=p15.edges[1].pointOn[0][1]
P1z_15=p15.edges[1].pointOn[0][2]
```

```
P2x_15=p15.edges[2].pointOn[0][0]
P2y_15=p15.edges[2].pointOn[0][1]
P2z_15=p15.edges[2].pointOn[0][2]

P3x_15=p15.edges[3].pointOn[0][0]
P3y_15=p15.edges[3].pointOn[0][1]
P3z_15=p15.edges[3].pointOn[0][2]


D21x_15 = P2x_15-P1x_15
D21y_15 = P2y_15-P1y_15
D21z_15 = P2z_15-P1z_15
D31x_15 = P3x_15-P1x_15
D31y_15 = P3y_15-P1y_15
D31z_15 = P3z_15-P1z_15

F2_15 = 1.0/2.0*(D21x_15**2+D21y_15**2+D21z_15**2)
F3_15 = 1.0/2.0*(D31x_15**2+D31y_15**2+D31z_15**2)

M23xy_15 = D21x_15*D31y_15-D21y_15*D31x_15
M23yz_15 = D21y_15*D31z_15-D21z_15*D31y_15
M23xz_15 = D21z_15*D31x_15-D21x_15*D31z_15

F23x_15 = F2_15*D31x_15-F3_15*D21x_15
F23y_15 = F2_15*D31y_15-F3_15*D21y_15
F23z_15 = F2_15*D31z_15-F3_15*D21z_15

Cx_15 = P1x_15+(M23xy_15*F23y_15-
M23xz_15*F23z_15)/(M23xy_15**2+M23yz_15**2+M23xz_15**2)
Cy_15 = P1y_15+(M23yz_15*F23z_15-
M23xy_15*F23x_15)/(M23xy_15**2+M23yz_15**2+M23xz_15**2)
Cz_15 = P1z_15+(M23xz_15*F23x_15-
M23yz_15*F23y_15)/(M23xy_15**2+M23yz_15**2+M23xz_15**2)
```

```
p16=q.rootAssembly.instances['Part-16-1']
P1x_16=p16.edges[1].pointOn[0][0]
P1y_16=p16.edges[1].pointOn[0][1]
P1z_16=p16.edges[1].pointOn[0][2]

P2x_16=p16.edges[2].pointOn[0][0]
P2y_16=p16.edges[2].pointOn[0][1]
P2z_16=p16.edges[2].pointOn[0][2]

P3x_16=p16.edges[3].pointOn[0][0]
P3y_16=p16.edges[3].pointOn[0][1]
P3z_16=p16.edges[3].pointOn[0][2]

D21x_16 = P2x_16-P1x_16
D21y_16 = P2y_16-P1y_16
D21z_16 = P2z_16-P1z_16
D31x_16 = P3x_16-P1x_16
D31y_16 = P3y_16-P1y_16
D31z_16 = P3z_16-P1z_16

F2_16 = 1.0/2.0*(D21x_16**2+D21y_16**2+D21z_16**2)
F3_16 = 1.0/2.0*(D31x_16**2+D31y_16**2+D31z_16**2)

M23xy_16 = D21x_16*D31y_16-D21y_16*D31x_16
M23yz_16 = D21y_16*D31z_16-D21z_16*D31y_16
M23xz_16 = D21z_16*D31x_16-D21x_16*D31z_16

F23x_16 = F2_16*D31x_16-F3_16*D21x_16
F23y_16 = F2_16*D31y_16-F3_16*D21y_16
F23z_16 = F2_16*D31z_16-F3_16*D21z_16

Cx_16 = P1x_16+(M23xy_16*F23y_16-
M23xz_16*F23z_16)/(M23xy_16**2+M23yz_16**2+M23xz_16**2)
```

```
Cy_16 = P1y_16+(M23yz_16*F23z_16-
M23xy_16*F23x_16)/(M23xy_16**2+M23yz_16**2+M23xz_16**2)

Cz_16 = P1z_16+(M23xz_16*F23x_16-
M23yz_16*F23y_16)/(M23xy_16**2+M23yz_16**2+M23xz_16**2)


p15_x=0+(Cx_15-0)*0.5

p15_y=0+(Cy_15-0)*0.5

p15_z=distance_top_origin+(Cz_15-distance_top_origin)*0.5


p16_x=0+(Cx_16-0)*0.5

p16_y=0+(Cy_16-0)*0.5

p16_z=distance_top_origin+(Cz_16-distance_top_origin)*0.5


seat_stays_connetor_lenght= math.sqrt((p16_x-p15_x)**2+(p16_y-
p15_y)**2+(p16_z-p15_z)**2)


q.ConstrainedSketch(name='__profile__', sheetSize=200.0)

q.sketches['__profile__'].CircleByCenterPerimeter(center=(

    0.0, 0.0), point1=(stays_connector_radius, 0.0))

q.Part(dimensionality=THREE_D, name='Part-26', type=

    DEFORMABLE_BODY)

q.parts['Part-26'].BaseShellExtrude(depth=seat_stays_connetor_lenght,
sketch=

    q.sketches['__profile__'])

del q.sketches['__profile__']


#assmle of part_17

q.rootAssembly.Instance(dependent=ON, name='Part-26-1',

    part=q.parts['Part-26'])

#rotation of part_17

q.rootAssembly.translate(instanceList=('Part-26-1', ),

    vector=(p15_x, p15_y, p15_z))


q.rootAssembly.rotate(angle=90.0, axisDirection=(0.0, 10.0,

    0.0), axisPoint=(p15_x, p15_y, p15_z), instanceList=(
```

```
    'Part-26-1', ))

#merge part_15 and part_17(connector)
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-26-1'],
    q.rootAssembly.instances['Part-15-1']),
    keepIntersections=ON, name='Part-19', originalInstances=SUPPRESS)

#cut
q.parts['Part-19'].PartitionEdgeByParam(edges=
    q.parts['Part-19'].edges.findAt(((0.0, 4.716196,
    26.181979), )), parameter=0.5)
q.parts['Part-19'].DatumPlaneByThreePoints(point1=
    q.parts['Part-19'].InterestingPoint(
    q.parts['Part-19'].edges.findAt((5.464208, 0.622702,
    43.351926), ), MIDDLE), point2=
    q.parts['Part-19'].vertices.findAt((-7.727558,
    -5.596829, 32.006614), ), point3=
    q.parts['Part-19'].InterestingPoint(
    q.parts['Part-19'].edges.findAt((-5.464208, -0.622702,
    26.648074), ), MIDDLE))
q.parts['Part-19'].PartitionEdgeByParam(edges=
    q.parts['Part-19'].edges.findAt(((-100.0, 483.283804,
    304.818021), )), parameter=0.5)
q.parts['Part-19'].DatumPlaneByThreePoints(point1=
    q.parts['Part-19'].vertices.findAt((-110.0,
(chain_stays_long_length+chain_stays_small_length_y),
    seat_tube_length), ), point2=q.parts['Part-19'].InterestingPoint(
    q.parts['Part-19'].edges.findAt((-107.071068,
    484.665146, 302.235283), ), MIDDLE), point3=
    q.parts['Part-19'].vertices.findAt((-90.0,
(chain_stays_long_length+chain_stays_small_length_y),
    seat_tube_length), ))
```

```
q.ConstrainedSketch(gridSpacing=54.85, name='__profile__',
    sheetSize=2194.11, transform=
    q.parts['Part-19'].MakeSketchTransform(
    sketchPlane=q.parts['Part-19'].datums[3],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=mdb.models['Model-1'].parts['Part-
19'].edges.findAt((5.464208,
    0.622702, 43.351926), ), sketchOrientation=RIGHT, origin=(0.0, 0.0,
35.0)))
q.parts['Part-19'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(-7.84304574479229, -6.20375962180159))
q.sketches['__profile__'].vertices.findAt((-7.843046,
    -6.20376))
q.sketches['__profile__'].geometry.findAt((9.876883,
    -1.564345))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    -7.84304574479229, -6.20375962180159), ), entity2=
    mdb.models['Model-
1'].sketches['__profile__'].geometry.findAt((9.876883,
    -1.564345), ))
q.parts['Part-19'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-19'].datums[3],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-19'].edges.findAt((5.464208, 0.622702,
    43.351926), ))
del q.sketches['__profile__']
q.ConstrainedSketch(gridSpacing=54.85, name='__profile__',
    sheetSize=2194.11, transform=
```

```
    q.parts['Part-19'].MakeSketchTransform(
    sketchPlane=q.parts['Part-19'].datums[5],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-19'].edges.findAt((
    -92.928932, 491.334854, 289.764717), ), sketchOrientation=RIGHT,
origin=(
    -(chain_stays_small_length_z+distance_chain_stays_mid_bracket),
(chain_stays_long_length+chain_stays_small_length_y), seat_tube_length)))
q.parts['Part-19'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(-10.0, 0.0))
q.parts['Part-19'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-19'].datums[5],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-19'].edges.findAt((-92.928932,
    491.334854, 289.764717), ))
del q.sketches['__profile__']

#merge part_16 and 19(connector)
q.rootAssembly.regenerate()
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-16-1'],
    q.rootAssembly.instances['Part-19-1']),
    keepIntersections=ON, name='Part-21', originalInstances=SUPPRESS)

#cut
q.parts['Part-21'].PartitionEdgeByParam(edges=
    q.parts['Part-21'].edges.findAt(((0.0, 4.716196,
    26.181979), )), parameter=0.5)
q.parts['Part-21'].DatumPlaneByThreePoints(point1=
    q.parts['Part-21'].vertices.findAt((7.727558,
    -5.596829, 32.006614), ), point2=
```

```
    q.parts['Part-21'].InterestingPoint(
    q.parts['Part-21'].edges.findAt((5.464208, -7.29241,
    39.118639), ), MIDDLE), point3=
    q.parts['Part-21'].vertices.findAt((-7.727558,
    5.596829, 37.993386), ))
q.parts['Part-21'].PartitionEdgeByParam(edges=
    q.parts['Part-21'].edges.findAt(((100.0, 483.283804,
    304.818021), )), parameter=0.5)
q.parts['Part-21'].DatumPlaneByThreePoints(point1=
    q.parts['Part-21'].vertices.findAt((110.0,
(chain_stays_long_length+chain_stays_small_length_y),
    seat_tube_length), ), point2=q.parts['Part-21'].InterestingPoint(
    q.parts['Part-21'].edges.findAt((107.071068,
    491.334854, 289.764717), ), MIDDLE), point3=
    q.parts['Part-21'].vertices.findAt((90.0,
(chain_stays_long_length+chain_stays_small_length_y),
    seat_tube_length), ))


q.ConstrainedSketch(gridSpacing=54.71, name='__profile__',
    sheetSize=2188.78, transform=
    q.parts['Part-21'].MakeSketchTransform(
    sketchPlane=q.parts['Part-21'].datums[3],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-21'].edges.findAt((5.464208,
    -7.29241, 39.118639), ), sketchOrientation=RIGHT, origin=(0.0, -
4.716196,
    43.818021)))
q.parts['Part-21'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    1.9153082675416e-07, 9.99999995334284), point1=(1.91530827366484e-07,
0.0))
q.sketches['__profile__'].vertices.findAt((0.0, 0.0))
q.sketches['__profile__'].geometry.findAt((9.876884,
    8.435655))
```

```
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    1.91530827366484e-07, 0.0), ), entity2=
    q.sketches['__profile__'].geometry.findAt((9.876884,
    8.435655), ))
q.sketches['__profile__'].vertices.findAt((-10.0, 10.0))
q.sketches['__profile__'].vertices.findAt((10.0, 10.0))
q.sketches['__profile__'].vertices.findAt((0.0, 0.0))
q.sketches['__profile__'].EqualDistanceConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    -9.99999980846917, 9.99999995334285), ), entity2=
    q.sketches['__profile__'].vertices.findAt((
    10.0000001915308, 9.99999995334289), ), midpoint=
    q.sketches['__profile__'].vertices.findAt((
    1.91530827366484e-07, 0.0), ))
q.parts['Part-21'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-21'].datums[3],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-21'].edges.findAt((5.464208, -7.29241,
    39.118639), ))
del q.sketches['__profile__']
q.ConstrainedSketch(gridSpacing=54.71, name='__profile__',
    sheetSize=2188.78, transform=
    q.parts['Part-21'].MakeSketchTransform(
    sketchPlane=q.parts['Part-21'].datums[5],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-21'].edges.findAt((
    107.071068, 491.334854, 289.764717), ), sketchOrientation=RIGHT,
origin=(
    (chain_stays_small_length_z+distance_chain_stays_mid_bracket),
(chain_stays_long_length+chain_stays_small_length_y), seat_tube_length)))
```

```
q.parts['Part-21'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(5.05561557945538, -8.62790537226551))
q.sketches['__profile__'].vertices.findAt((5.055616,
    -8.627905))
q.sketches['__profile__'].geometry.findAt((9.876883,
    -1.564345))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    5.05561557945538, -8.62790537226551), ), entity2=
    q.sketches['__profile__'].geometry.findAt((9.876883,
    -1.564345), ))
q.parts['Part-21'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-21'].datums[5],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-21'].edges.findAt((107.071068,
    491.334854, 289.764717), ))
del q.sketches['__profile__']

# part 19 (bottom-stays connector)
q.rootAssembly.features['Part-11-1'].resume()
q.rootAssembly.features['Part-13-1'].resume()

p11=q.rootAssembly.instances['Part-11-1']
P1x_11=p11.edges[1].pointOn[0][0]
P1y_11=p11.edges[1].pointOn[0][1]
P1z_11=p11.edges[1].pointOn[0][2]

P2x_11=p11.edges[2].pointOn[0][0]
P2y_11=p11.edges[2].pointOn[0][1]
```

```
P2z_11=p11.edges[2].pointOn[0][2]


P3x_11=p11.edges[3].pointOn[0][0]

P3y_11=p11.edges[3].pointOn[0][1]

P3z_11=p11.edges[3].pointOn[0][2]


D21x_11 = P2x_11-P1x_11

D21y_11 = P2y_11-P1y_11

D21z_11 = P2z_11-P1z_11

D31x_11 = P3x_11-P1x_11

D31y_11 = P3y_11-P1y_11

D31z_11 = P3z_11-P1z_11


F2_11 = 1.0/2.0*(D21x_11**2+D21y_11**2+D21z_11**2)

F3_11 = 1.0/2.0*(D31x_11**2+D31y_11**2+D31z_11**2)


M23xy_11 = D21x_11*D31y_11-D21y_11*D31x_11

M23yz_11 = D21y_11*D31z_11-D21z_11*D31y_11

M23xz_11 = D21z_11*D31x_11-D21x_11*D31z_11


F23x_11 = F2_11*D31x_11-F3_11*D21x_11

F23y_11 = F2_11*D31y_11-F3_11*D21y_11

F23z_11 = F2_11*D31z_11-F3_11*D21z_11


Cx_11 = P1x_11+(M23xy_11*F23y_11-
M23xz_11*F23z_11)/(M23xy_11**2+M23yz_11**2+M23xz_11**2)

Cy_11 = P1y_11+(M23yz_11*F23z_11-
M23xy_11*F23x_11)/(M23xy_11**2+M23yz_11**2+M23xz_11**2)

Cz_11 = P1z_11+(M23xz_11*F23x_11-
M23yz_11*F23y_11)/(M23xy_11**2+M23yz_11**2+M23xz_11**2)



p13=q.rootAssembly.instances['Part-13-1']

P1x_13=p13.edges[1].pointOn[0][0]
```

```
P1y_13=p13.edges[1].pointOn[0][1]
P1z_13=p13.edges[1].pointOn[0][2]

P2x_13=p13.edges[2].pointOn[0][0]
P2y_13=p13.edges[2].pointOn[0][1]
P2z_13=p13.edges[2].pointOn[0][2]

P3x_13=p13.edges[3].pointOn[0][0]
P3y_13=p13.edges[3].pointOn[0][1]
P3z_13=p13.edges[3].pointOn[0][2]


D21x_13 = P2x_13-P1x_13
D21y_13 = P2y_13-P1y_13
D21z_13 = P2z_13-P1z_13
D31x_13 = P3x_13-P1x_13
D31y_13 = P3y_13-P1y_13
D31z_13 = P3z_13-P1z_13

F2_13 = 1.0/2.0*(D21x_13**2+D21y_13**2+D21z_13**2)
F3_13 = 1.0/2.0*(D31x_13**2+D31y_13**2+D31z_13**2)

M23xy_13 = D21x_13*D31y_13-D21y_13*D31x_13
M23yz_13 = D21y_13*D31z_13-D21z_13*D31y_13
M23xz_13 = D21z_13*D31x_13-D21x_13*D31z_13

F23x_13 = F2_13*D31x_13-F3_13*D21x_13
F23y_13 = F2_13*D31y_13-F3_13*D21y_13
F23z_13 = F2_13*D31z_13-F3_13*D21z_13

Cx_13 = P1x_13+(M23xy_13*F23y_13-
M23xz_13*F23z_13)/(M23xy_13**2+M23yz_13**2+M23xz_13**2)
Cy_13 = P1y_13+(M23yz_13*F23z_13-
M23xy_13*F23x_13)/(M23xy_13**2+M23yz_13**2+M23xz_13**2)
```

```
Cz_13 = P1z_13+(M23xz_13*F23x_13-
M23yz_13*F23y_13)/(M23xy_13**2+M23yz_13**2+M23xz_13**2)


p11_x=0+(Cx_11-distance_chain_stays_mid_bracket)*0.5

p11_y=0+(Cy_11-0)*0.5

p11_z=seat_tube_length+(Cz_11-seat_tube_length)*0.5


p13_x=0+(Cx_13-(-distance_chain_stays_mid_bracket))*0.5

p13_y=0+(Cy_13-0)*0.5

p13_z=seat_tube_length+(Cz_13-seat_tube_length)*0.5


chain_stays_connetor_lenght= math.sqrt((p13_x-p11_x)**2+(p13_y-
p11_y)**2+(p13_z-p11_z)**2)


q.ConstrainedSketch(name='__profile__', sheetSize=200.0)

q.sketches['__profile__'].CircleByCenterPerimeter(center=(

    0.0, 0.0), point1=(stays_connector_radius, 0.0))

q.Part(dimensionality=THREE_D, name='Part-24', type=

    DEFORMABLE_BODY)

q.parts['Part-24'].BaseShellExtrude(depth=chain_stays_connetor_lenght,
sketch=

    q.sketches['__profile__'])

del q.sketches['__profile__']




#assembe of part_19

q.rootAssembly.Instance(dependent=ON, name='Part-24-1',

    part=q.parts['Part-24'])


#rotation of part_19

q.rootAssembly.translate(instanceList=('Part-24-1', ),

    vector=(p11_x, p11_y, seat_tube_length))


q.rootAssembly.rotate(angle=90.0, axisDirection=(0.0, 10.0,
```

```
    0.0), axisPoint=(p11_x, p11_y, seat_tube_length), instanceList=('Part-
24-1',

    ))


#merge of part_19 and part_11

q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,

    instances=(q.rootAssembly.instances['Part-11-1'],

    q.rootAssembly.instances['Part-24-1']),

    keepIntersections=ON, name='Part-17', originalInstances=SUPPRESS)


#cut

q.parts['Part-17'].PartitionEdgeByParam(edges=

    q.parts['Part-17'].edges.findAt(((-distance_chain_stays_mid_bracket,
0.0, 286.0),

    )), parameter=0.5)

q.parts['Part-17'].DatumPlaneByThreePoints(point1=

    q.parts['Part-17'].vertices.findAt((-31.737727,

    5.633368, 296.0), ), point2=

    q.parts['Part-17'].InterestingPoint(

    q.parts['Part-17'].edges.findAt((-34.15769, 3.983393,

    303.071068), ), MIDDLE), point3=

    q.parts['Part-17'].vertices.findAt((-48.262273,

    -5.633368, 296.0), ))

q.parts['Part-17'].PartitionEdgeByParam(edges=

    q.parts['Part-17'].edges.findAt(((-
(chain_stays_small_length_z+distance_chain_stays_mid_bracket),
(chain_stays_long_length+chain_stays_small_length_y),

    306.0), )), parameter=0.5)

q.parts['Part-17'].DatumPlaneByThreePoints(point1=

    q.parts['Part-17'].vertices.findAt((-90.0,
(chain_stays_long_length+chain_stays_small_length_y),

    seat_tube_length), ), point2=q.parts['Part-17'].InterestingPoint(

    q.parts['Part-17'].edges.findAt((-92.928932, 488.0,

    288.928932), ), MIDDLE), point3=

    q.parts['Part-17'].vertices.findAt((-110.0,
(chain_stays_long_length+chain_stays_small_length_y),
```

```
    seat_tube_length), ))

q.ConstrainedSketch(gridSpacing=33.35, name='__profile__',
    sheetSize=1334.1, transform=
    q.parts['Part-17'].MakeSketchTransform(
    sketchPlane=q.parts['Part-17'].datums[3],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-17'].edges.findAt((
    -45.84231, -3.983393, 288.928932), ), sketchOrientation=RIGHT, origin=(
    -distance_chain_stays_mid_bracket, 0.0, seat_tube_length)))
q.parts['Part-17'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(5.52142135233407, -8.3375))
q.sketches['__profile__'].vertices.findAt((5.521421,
    -8.3375))
q.sketches['__profile__'].geometry.findAt((9.876883,
    -1.564345))
q.sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    5.52142135233407, -8.3375), ), entity2=
    q.sketches['__profile__'].geometry.findAt((9.876883,
    -1.564345), ))
q.parts['Part-17'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-17'].datums[3],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    mdb.models['Model-1'].parts['Part-17'].edges.findAt((-45.84231, -
3.983393,
    288.928932), ))
del q.sketches['__profile__']
q.ConstrainedSketch(gridSpacing=33.35, name='__profile__',
    sheetSize=1334.1, transform=
```

```
    q.parts['Part-17'].MakeSketchTransform(
    sketchPlane=q.parts['Part-17'].datums[5],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-17'].edges.findAt((
    -92.928932, 488.0, 288.928932), ), sketchOrientation=RIGHT, origin=(-
(chain_stays_small_length_z+distance_chain_stays_mid_bracket),
    (chain_stays_long_length+chain_stays_small_length_y),
seat_tube_length)))
q.parts['Part-17'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(10.0, 0.0))
q.parts['Part-17'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-17'].datums[5],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-17'].edges.findAt((-92.928932, 488.0,
    288.928932), ))
del q.sketches['__profile__']



#merge part_17 and part_13
q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,
    instances=(q.rootAssembly.instances['Part-13-1'],
    q.rootAssembly.instances['Part-17-1']),
    keepIntersections=ON, name='Part-23', originalInstances=SUPPRESS)


#cut
q.parts['Part-23'].PartitionEdgeByParam(edges=
    q.parts['Part-23'].edges.findAt(((distance_chain_stays_mid_bracket,
0.0, 286.0), ))
    , parameter=0.5)
q.parts['Part-23'].DatumPlaneByThreePoints(point1=
    q.parts['Part-23'].InterestingPoint(
```

```
    q.parts['Part-23'].edges.findAt((34.15769, 3.983393,
    288.928932), ), MIDDLE), point2=
    q.parts['Part-23'].vertices.findAt((48.262273,
    -5.633368, seat_tube_length), ), point3=
    q.parts['Part-23'].InterestingPoint(
    q.parts['Part-23'].edges.findAt((45.84231, -3.983393,
    303.071068), ), MIDDLE))
q.parts['Part-23'].PartitionEdgeByParam(edges=
    q.parts['Part-
23'].edges.findAt((((chain_stays_small_length_z+distance_chain_stays_mid_br
acket), (chain_stays_long_length+chain_stays_small_length_y), 306.0),
    )), parameter=0.5)
q.parts['Part-23'].DatumPlaneByThreePoints(point1=
    q.parts['Part-23'].InterestingPoint(
    q.parts['Part-23'].edges.findAt((107.071068, 488.0,
    288.928932), ), MIDDLE), point2=
    q.parts['Part-23'].vertices.findAt((90.0,
(chain_stays_long_length+chain_stays_small_length_y),
    seat_tube_length), ), point3=q.parts['Part-23'].InterestingPoint(
    q.parts['Part-23'].edges.findAt((92.928932, 488.0,
    303.071068), ), MIDDLE))


q.ConstrainedSketch(gridSpacing=33.13, name='__profile__',
    sheetSize=1325.55, transform=
    q.parts['Part-23'].MakeSketchTransform(
    sketchPlane=q.parts['Part-23'].datums[5],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-23'].edges.findAt((
    107.071068, 488.0, 288.928932), ), sketchOrientation=RIGHT,
origin=((chain_stays_small_length_z+distance_chain_stays_mid_bracket),
    (chain_stays_long_length+chain_stays_small_length_y),
seat_tube_length)))
q.parts['Part-23'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=mdb.models['Model-1'].sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
```

```
    0.0, 0.0), point1=(10.0, 0.0))
q.parts['Part-23'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-23'].datums[5],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-23'].edges.findAt((107.071068, 488.0,
    288.928932), ))
del q.sketches['__profile__']
q.ConstrainedSketch(gridSpacing=33.13, name='__profile__',
    sheetSize=1325.55, transform=
    q.parts['Part-23'].MakeSketchTransform(
    sketchPlane=q.parts['Part-23'].datums[3],
    sketchPlaneSide=SIDE1,
    sketchUpEdge=q.parts['Part-23'].edges.findAt((34.15769,
    3.983393, 288.928932), ), sketchOrientation=RIGHT,
origin=(distance_chain_stays_mid_bracket, 0.0,
    seat_tube_length)))
q.parts['Part-23'].projectReferencesOntoSketch(filter=
    COPLANAR_EDGES, sketch=q.sketches['__profile__'])
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(10.0, 0.0))
q.parts['Part-23'].CutExtrude(flipExtrudeDirection=OFF,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-23'].datums[3],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-23'].edges.findAt((34.15769, 3.983393,
    288.928932), ))
del q.sketches['__profile__']

# stays_edge_connector (part 27)
q.ConstrainedSketch(name='__sweep__', sheetSize=200.0)
q.sketches['__sweep__'].Line(point1=(0.0, 0.0), point2=(
    stays_edge_connector_length, 0.0))
```

```
q.sketches['__sweep__'].geometry.findAt((stays_edge_connector_length/2,
0.0))
q.sketches['__sweep__'].HorizontalConstraint(addUndoState=
    False, entity=q.sketches['__sweep__'].geometry.findAt((
    stays_edge_connector_length/2, 0.0), ))
q.ConstrainedSketch(name='__profile__', sheetSize=200.0,
    transform=(0.0, -1.0, 0.0, -0.0, 0.0, 1.0, -1.0, -0.0, -0.0, 0.0, 0.0,
    0.0))
q.sketches['__profile__'].ConstructionLine(point1=(-100.0,
    0.0), point2=(100.0, 0.0))
q.sketches['__profile__'].ConstructionLine(point1=(0.0,
    -100.0), point2=(0.0, 100.0))
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(stays_edge_connector_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-27', type=
    DEFORMABLE_BODY)
q.parts['Part-27'].BaseShellSweep(path=
    q.sketches['__sweep__'], sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
del q.sketches['__sweep__']

#assembly of part 27
q.rootAssembly.Instance(dependent=ON, name='Part-27-1',
    part=q.parts['Part-27'])

#move x
q.rootAssembly.translate(instanceList=('Part-27-1', ),
    vector=(-
((chain_stays_small_length_z+distance_chain_stays_mid_bracket)+stays_edge_c
onnector_length/2), 0.0, 0.0))

#move z
q.rootAssembly.translate(instanceList=('Part-27-1', ),
```

```
    vector=(0.0, 0.0, seat_tube_length))

#move y

q.rootAssembly.translate(instanceList=('Part-27-1', ),

    vector=(0.0, (chain_stays_long_length+chain_stays_small_length_y),
0.0))


#merge part_27, part_11 and part_15

q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,

    instances=(q.rootAssembly.instances['Part-18-1'],

    q.rootAssembly.instances['Part-12-1'],

    q.rootAssembly.instances['Part-27-1']),

    keepIntersections=ON, name='Part-25', originalInstances=SUPPRESS)


#cut

mdb.models['Model-1'].parts['Part-25'].DatumPlaneByPrincipalPlane(offset=-
((chain_stays_small_length_z+distance_chain_stays_mid_bracket)+stays_edge_c
onnector_length/2),

    principalPlane=YZPLANE)



mdb.models['Model-1'].ConstrainedSketch(gridSpacing=34.34,
name='__profile__',

    sheetSize=1373.82, transform=

    mdb.models['Model-1'].parts['Part-25'].MakeSketchTransform(

    sketchPlane=mdb.models['Model-1'].parts['Part-25'].datums[2],

    sketchPlaneSide=SIDE1,

    sketchUpEdge=mdb.models['Model-1'].parts['Part-25'].edges.findAt((-
((chain_stays_small_length_z+distance_chain_stays_mid_bracket)+stays_edge_c
onnector_length/2),

    488, 341.0), ), sketchOrientation=RIGHT, origin=(-
((chain_stays_small_length_z+distance_chain_stays_mid_bracket)+stays_edge_c
onnector_length/2), (chain_stays_long_length+chain_stays_small_length_y),
seat_tube_length)))

mdb.models['Model-1'].parts['Part-25'].projectReferencesOntoSketch(filter=

    COPLANAR_EDGES, sketch=mdb.models['Model-1'].sketches['__profile__'])

mdb.models['Model-
1'].sketches['__profile__'].CircleByCenterPerimeter(center=(
```

```
    0.0, 0.0), point1=(-42.925, 13.5071971555899))
mdb.models['Model-1'].sketches['__profile__'].vertices.findAt((-42.925,
    13.507197))
mdb.models['Model-1'].sketches['__profile__'].geometry.findAt((42.797543,
    -13.905765))
mdb.models['Model-1'].sketches['__profile__'].CoincidentConstraint(
    addUndoState=False, entity1=
    mdb.models['Model-1'].sketches['__profile__'].vertices.findAt((-42.925,
    13.5071971555899), ), entity2=
    mdb.models['Model-
1'].sketches['__profile__'].geometry.findAt((42.797543,
    -13.905765), ))
mdb.models['Model-1'].parts['Part-25'].CutExtrude(flipExtrudeDirection=ON,
    sketch=mdb.models['Model-1'].sketches['__profile__'],
sketchOrientation=
    RIGHT, sketchPlane=mdb.models['Model-1'].parts['Part-25'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    mdb.models['Model-1'].parts['Part-25'].edges.findAt((-
((chain_stays_small_length_z+distance_chain_stays_mid_bracket)+stays_edge_c
onnector_length/2), (chain_stays_long_length+chain_stays_small_length_y),
341.0),
    ))
del mdb.models['Model-1'].sketches['__profile__']


mdb.models['Model-1'].rootAssembly.regenerate()
mdb.models['Model-1'].rootAssembly.features['Part-27-1'].resume()


# stays_edge_connector (part 28)


q.ConstrainedSketch(name='__sweep__', sheetSize=200.0)
q.sketches['__sweep__'].Line(point1=(0.0, 0.0), point2=(
    stays_edge_connector_length, 0.0))
q.sketches['__sweep__'].geometry.findAt((stays_edge_connector_length/2,
0.0))
q.sketches['__sweep__'].HorizontalConstraint(addUndoState=
    False, entity=q.sketches['__sweep__'].geometry.findAt((
```

```
    stays_edge_connector_length/2, 0.0), ))
q.ConstrainedSketch(name='__profile__', sheetSize=200.0,
    transform=(0.0, -1.0, 0.0, -0.0, 0.0, 1.0, -1.0, -0.0, -0.0, 0.0, 0.0,
    0.0))
q.sketches['__profile__'].ConstructionLine(point1=(-100.0,
    0.0), point2=(100.0, 0.0))
q.sketches['__profile__'].ConstructionLine(point1=(0.0,
    -100.0), point2=(0.0, 100.0))
q.sketches['__profile__'].CircleByCenterPerimeter(center=(
    0.0, 0.0), point1=(stays_edge_connector_radius, 0.0))
q.Part(dimensionality=THREE_D, name='Part-28', type=
    DEFORMABLE_BODY)
q.parts['Part-28'].BaseShellSweep(path=
    q.sketches['__sweep__'], sketch=
    q.sketches['__profile__'])
del q.sketches['__profile__']
del q.sketches['__sweep__']

#assembly of part 28
q.rootAssembly.Instance(dependent=ON, name='Part-28-1',
    part=q.parts['Part-28'])

#move x
q.rootAssembly.translate(instanceList=('Part-28-1', ),
    vector=(((chain_stays_small_length_z+distance_chain_stays_mid_bracket)-
stays_edge_connector_length/2), 0.0, 0.0))


#move z
q.rootAssembly.translate(instanceList=('Part-28-1', ),
    vector=(0.0, 0.0, seat_tube_length))
#move y
q.rootAssembly.translate(instanceList=('Part-28-1', ),
    vector=(0.0, (chain_stays_long_length+chain_stays_small_length_y),
0.0))
```

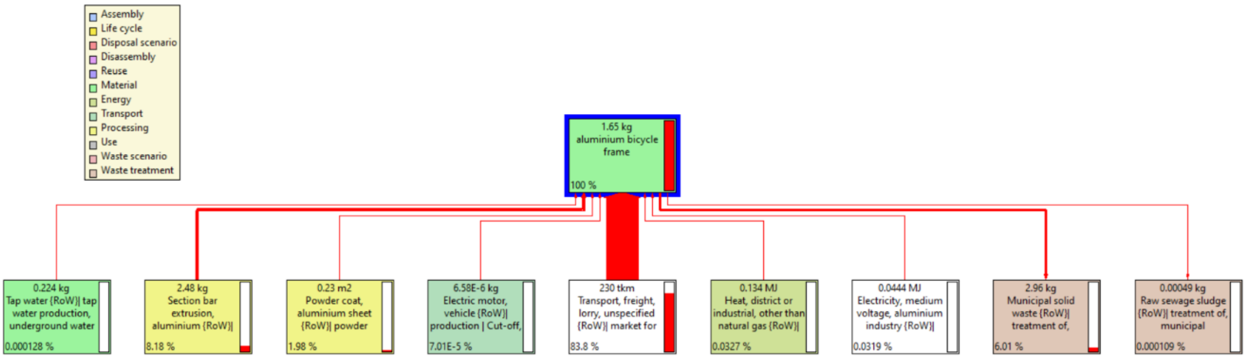
```
#merge

q.rootAssembly.InstanceFromBooleanMerge(domain=GEOMETRY,

    instances=(q.rootAssembly.instances['Part-28-1'],

    q.rootAssembly.instances['Part-20-1'],

    q.rootAssembly.instances['Part-14-1']),

    keepIntersections=ON, name='Part-29', originalInstances=SUPPRESS)


#cut

q.parts['Part-
29'].DatumPlaneByPrincipalPlane(offset=((chain_stays_small_length_z+distanc
e_chain_stays_mid_bracket)-stays_edge_connector_length/2),

    principalPlane=YZPLANE)


q.ConstrainedSketch(gridSpacing=34.34, name='__profile__',

    sheetSize=1373.82, transform=

    q.parts['Part-29'].MakeSketchTransform(

    sketchPlane=q.parts['Part-29'].datums[2],

    sketchPlaneSide=SIDE1,

    sketchUpEdge=q.parts['Part-
29'].edges.findAt((((chain_stays_small_length_z+distance_chain_stays_mid_br
acket)-stays_edge_connector_length/2),

    (chain_stays_long_length+chain_stays_small_length_y), 341.0), ),
sketchOrientation=RIGHT,
origin=(((chain_stays_small_length_z+distance_chain_stays_mid_bracket)-
stays_edge_connector_length/2),
(chain_stays_long_length+chain_stays_small_length_y), seat_tube_length)))

q.parts['Part-29'].projectReferencesOntoSketch(filter=

    COPLANAR_EDGES, sketch=q.sketches['__profile__'])

q.sketches['__profile__'].CircleByCenterPerimeter(center=(

    0.0, 0.0), point1=(-29.0820288150608, 34.34))

q.sketches['__profile__'].vertices.findAt((-29.082029,

    34.34))

q.sketches['__profile__'].geometry.findAt((42.797543,

    -13.905765))

q.sketches['__profile__'].CoincidentConstraint(
```

```
    addUndoState=False, entity1=
    q.sketches['__profile__'].vertices.findAt((
    -29.0820288150608, 34.34), ), entity2=
    q.sketches['__profile__'].geometry.findAt((42.797543,
    -13.905765), ))
q.parts['Part-29'].CutExtrude(flipExtrudeDirection=ON,
    sketch=q.sketches['__profile__'], sketchOrientation=
    RIGHT, sketchPlane=q.parts['Part-29'].datums[2],
    sketchPlaneSide=SIDE1, sketchUpEdge=
    q.parts['Part-
29'].edges.findAt((((chain_stays_small_length_z+distance_chain_stays_mid_br
acket)-stays_edge_connector_length/2),
(chain_stays_long_length+chain_stays_small_length_y), 341.0),
    ))
del q.sketches['__profile__']
mdb.models['Model-1'].rootAssembly.features['Part-28-1'].resume()



mdb.saveAs(pathName=caeName)


####end####
```

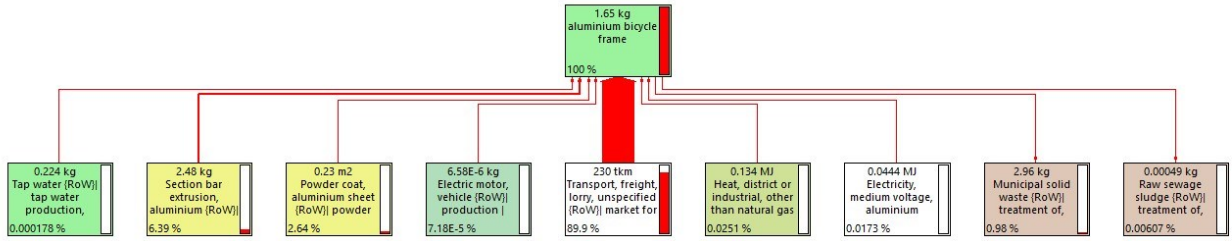
8.3 Network diagram for LCA of different bicycle frame model

8.3.1 Network diagram of selective Impact catagories of Charecterization from LCA for 1.89 kg bicycle frame:

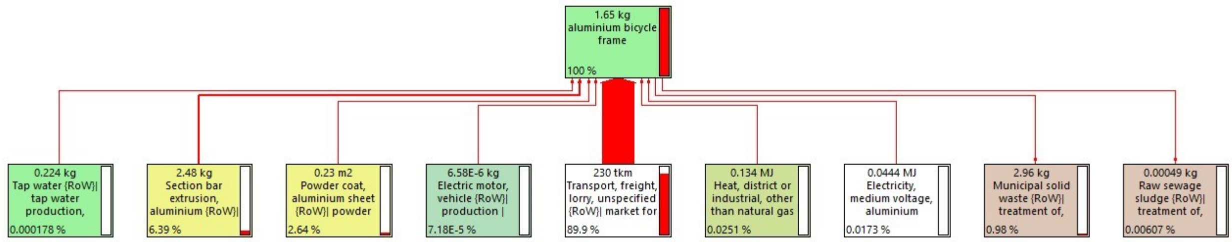
Global warming:



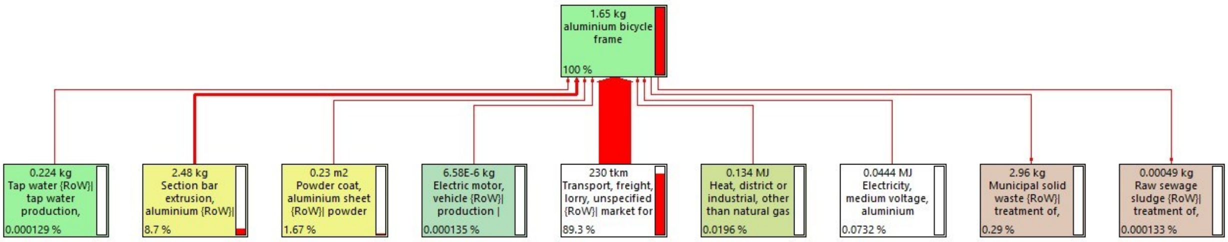
Stratospheric Ozone depletion:



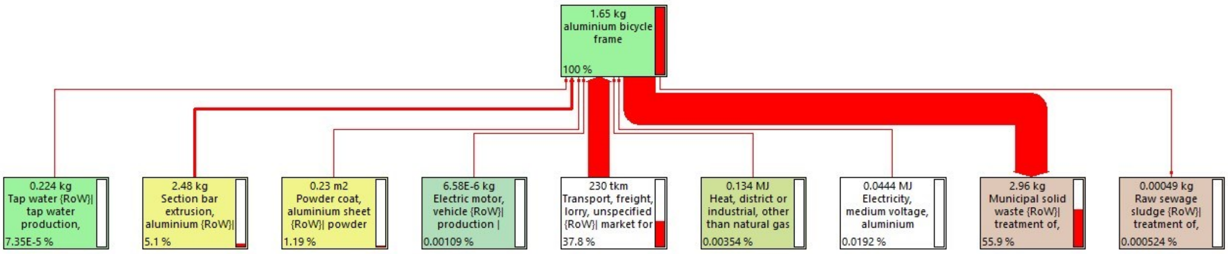
Terrestrial ecotoxicity:



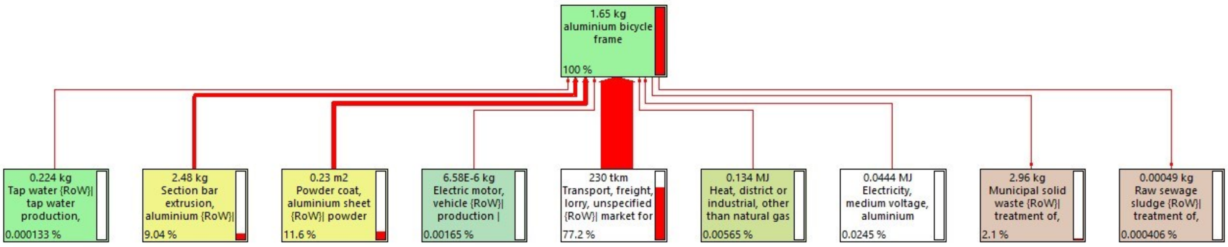
Terrestrial acidification:



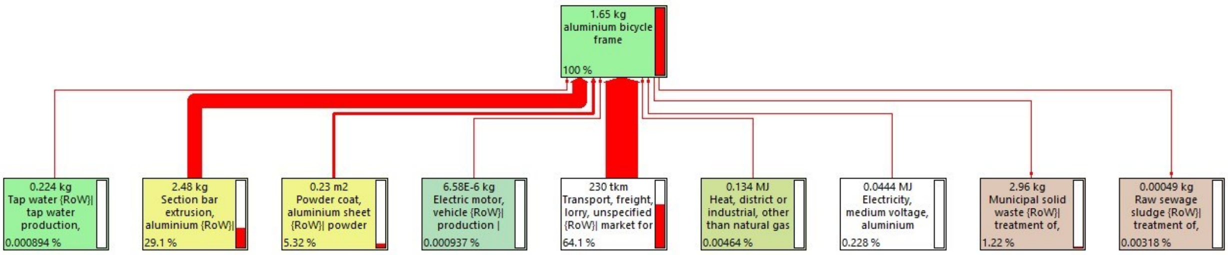
Marine Ecotoxicity:



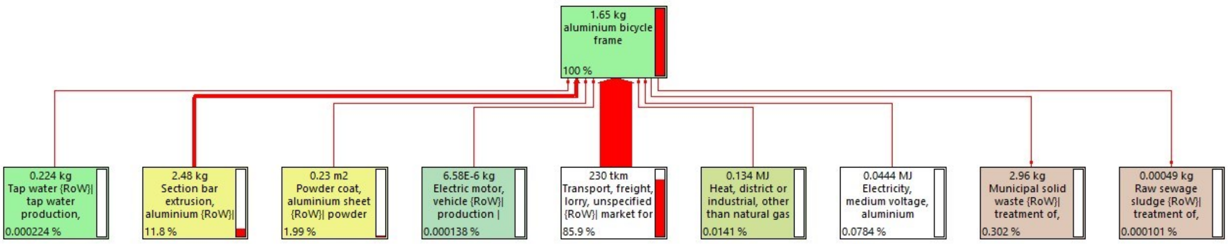
Human Carcinogenic Toxicity:



Freshwater eutrophication:

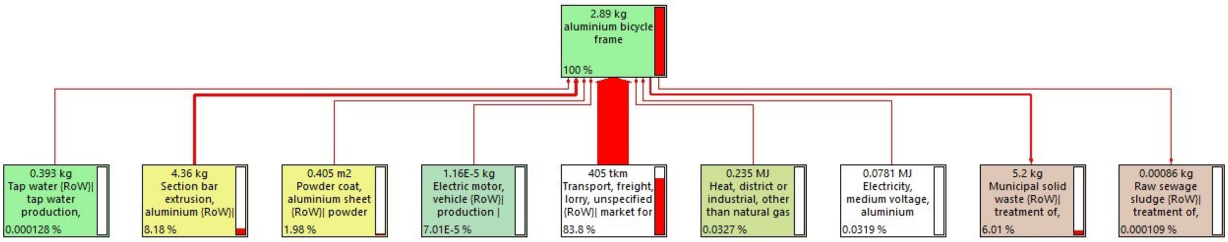


Fine particulates matter formation:

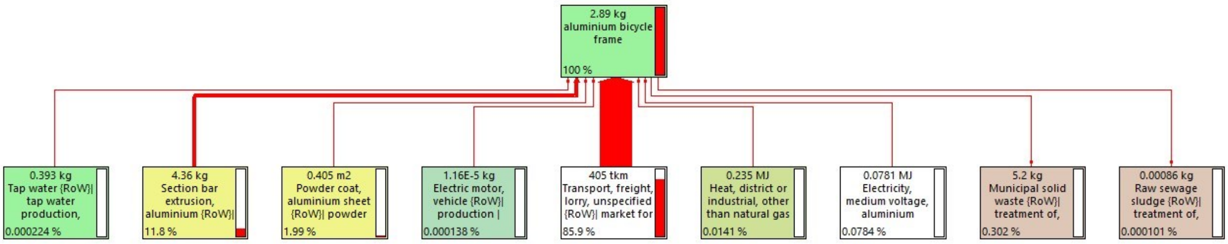


8.3.2 Network diagram of selective Impact catagories of Charecterization from LCA for 2.89kg bicycle frame :

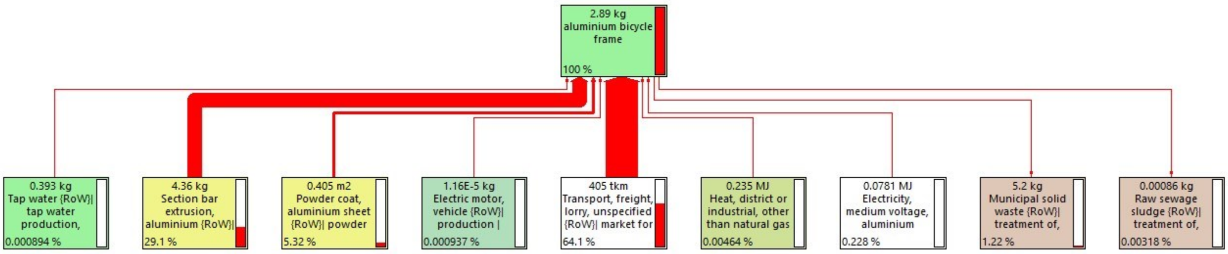
Global warming:



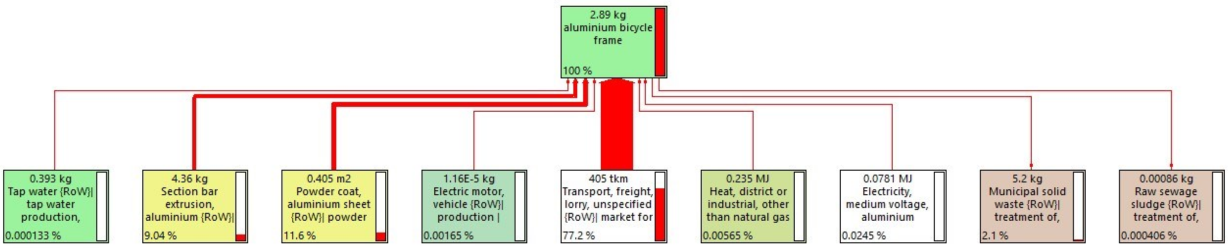
Fine particulates matter formation:



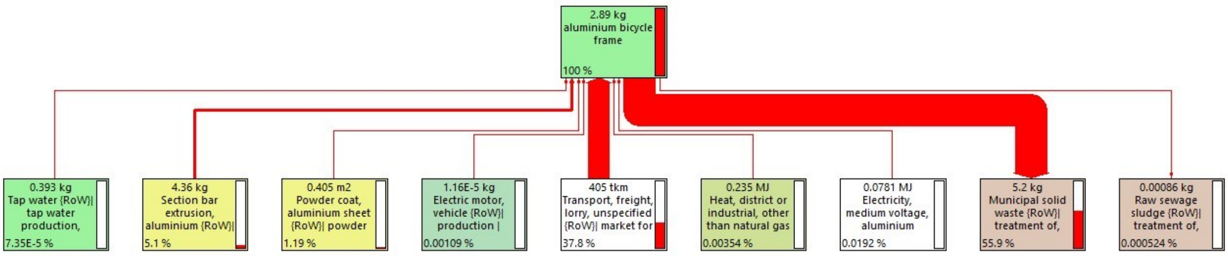
Freshwater eutrophication:



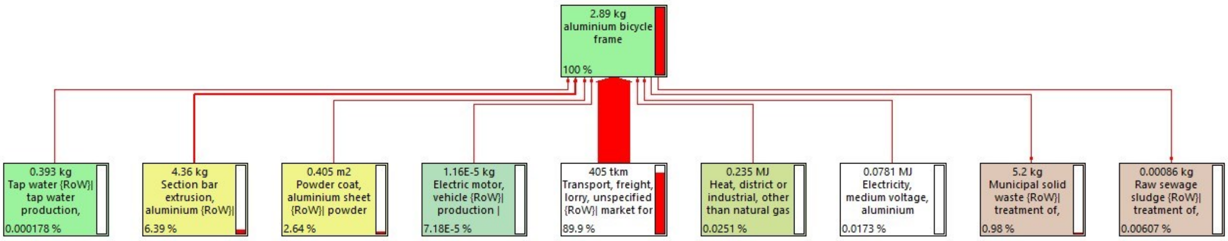
Human carcinogenic toxicity:



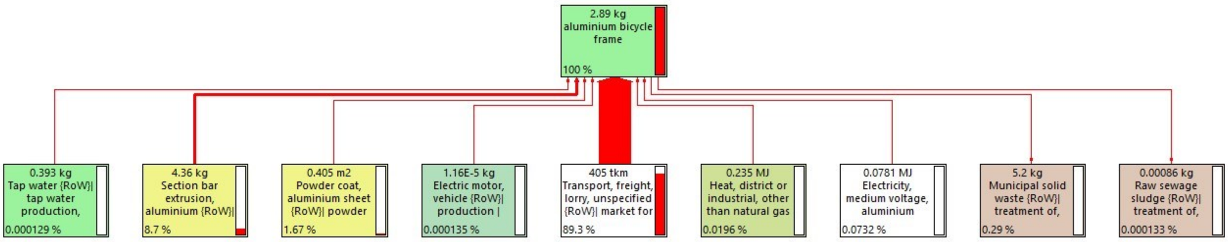
Marine Ecotoxicity:



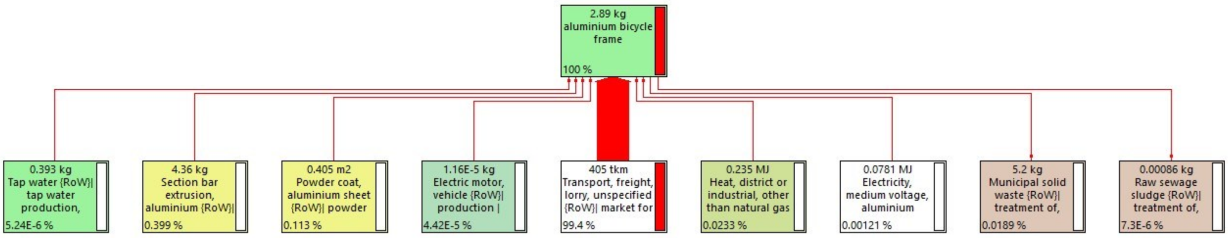
Stratospheric ozone depletion:



Terrestrial acidification:

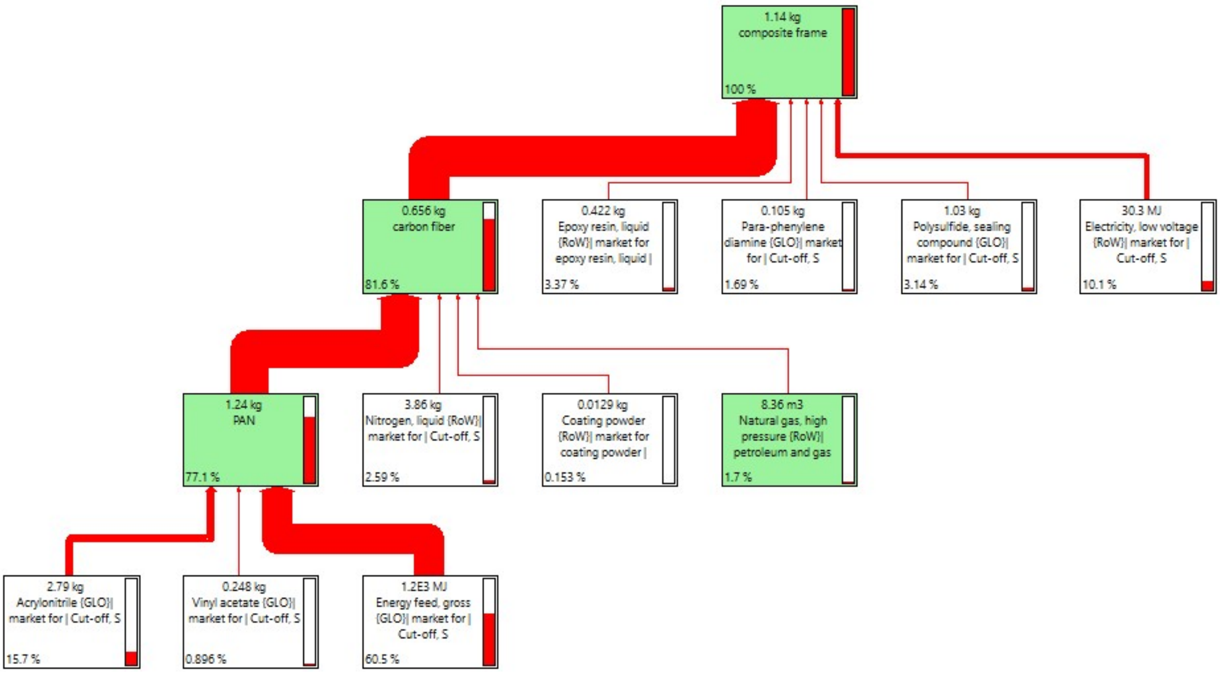


Terrestrial ecotoxicity:

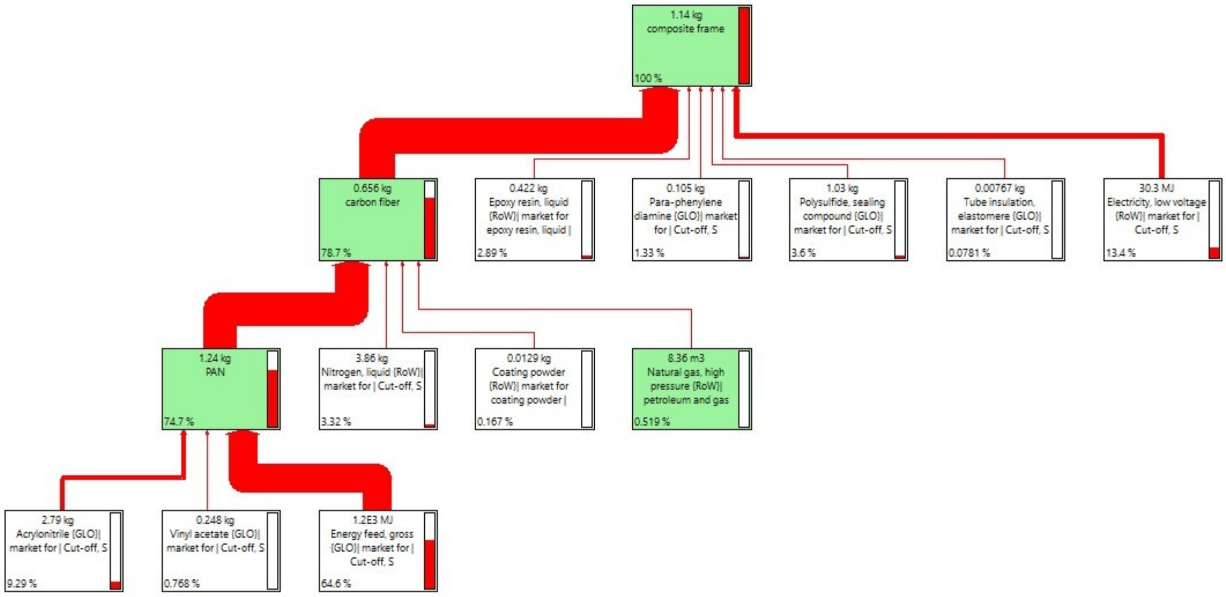


8.3.3 Network diagram of selective impact categories of characterization for 1.14kg Four layers Carbon-epoxy reinforced composite frame

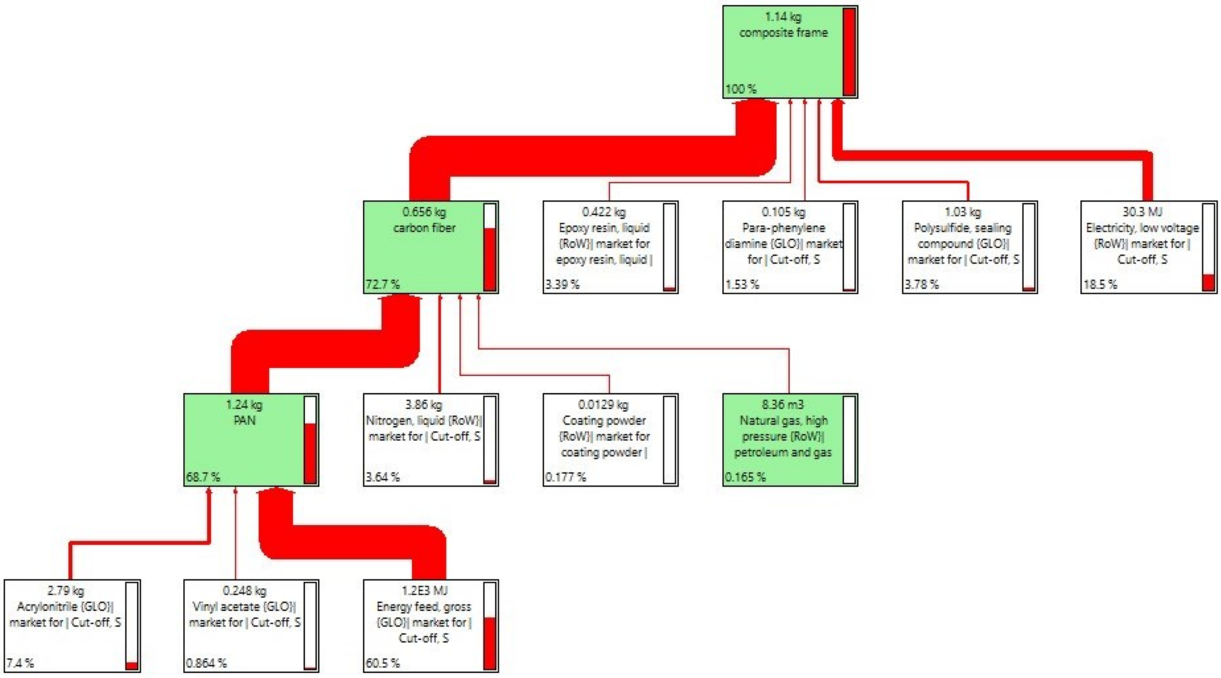
Global warming:



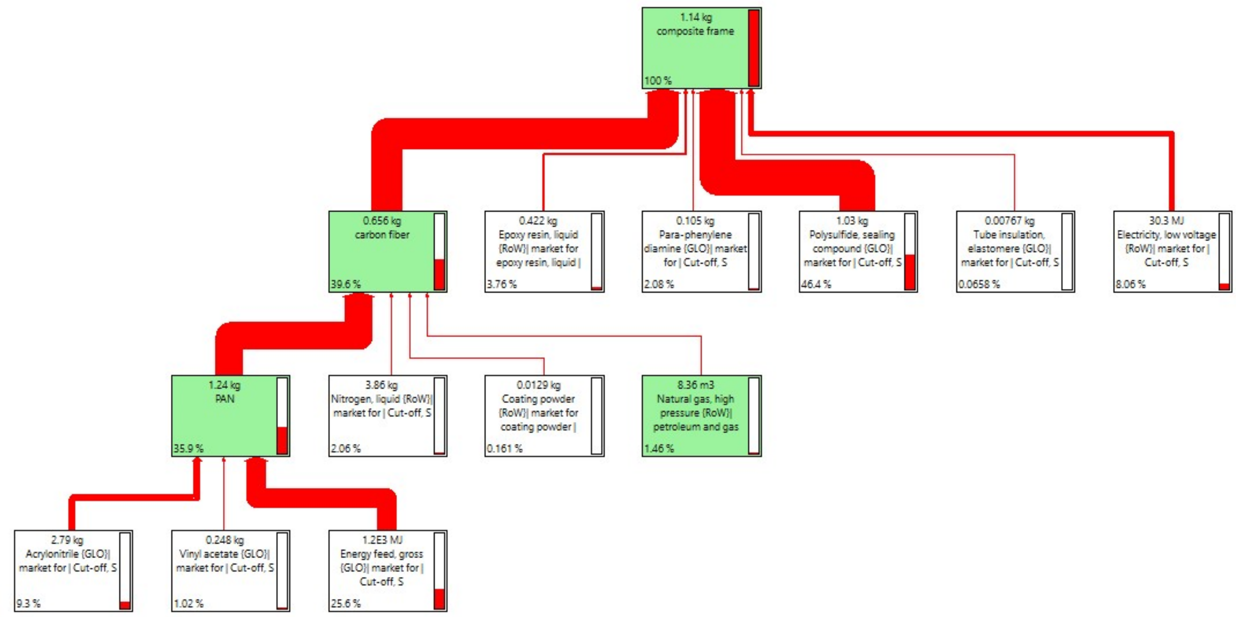
Fine particulates formation:



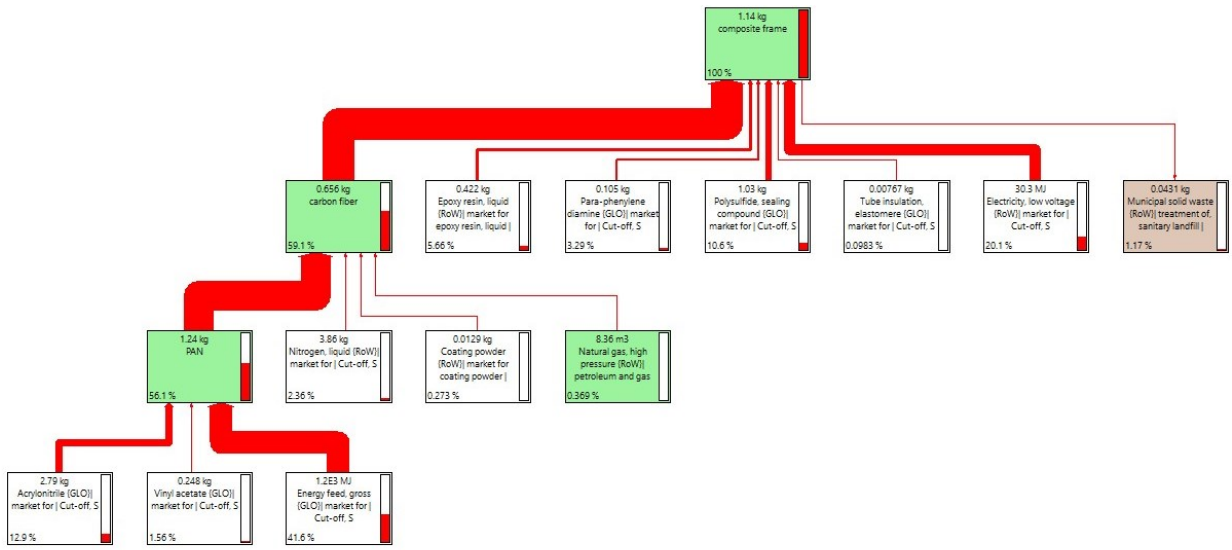
Freshwater Eutrophication:



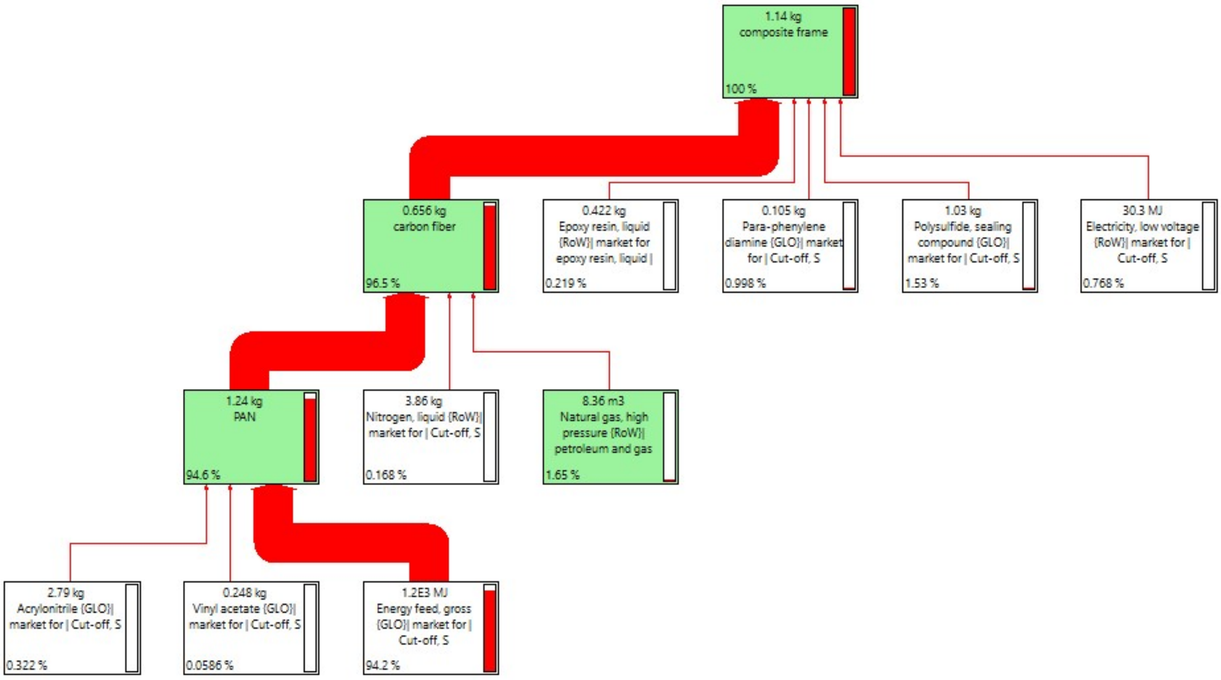
Human Carcinogenic Toxicity:



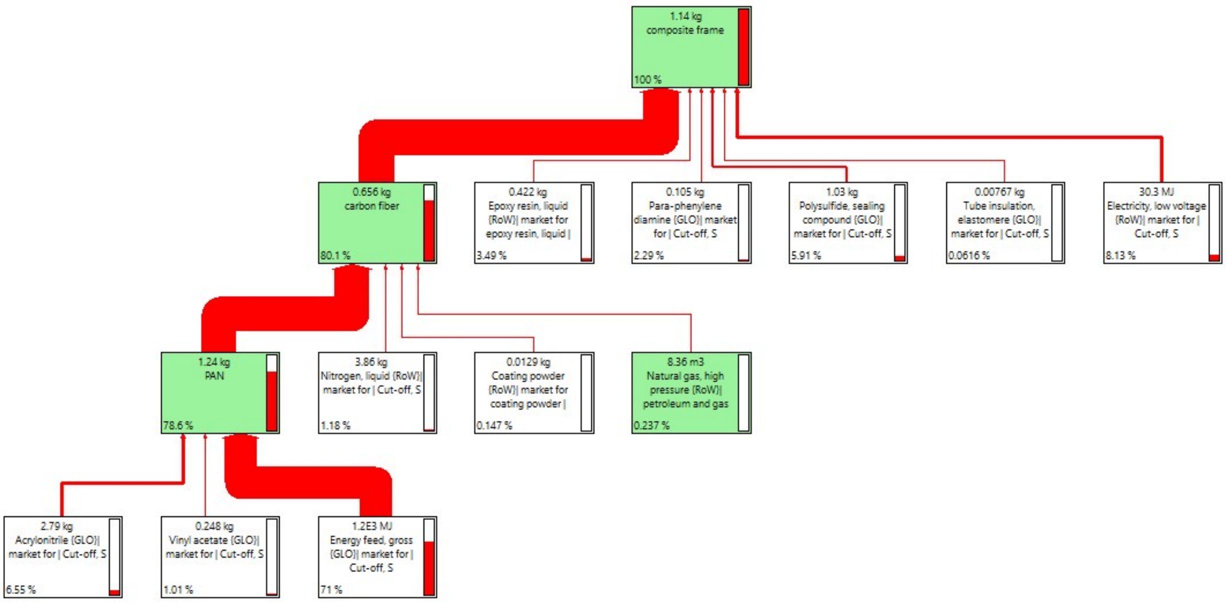
Marine Ecotoxicity:



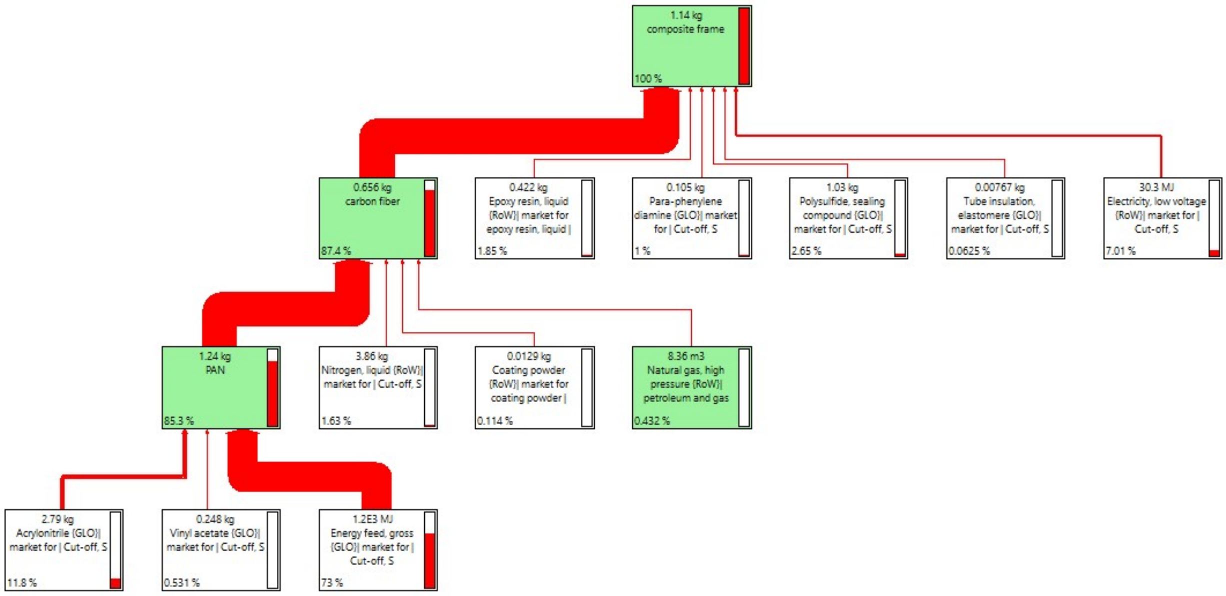
Stratospheric ozone depletion:



Terrestrial ecotoxicity:



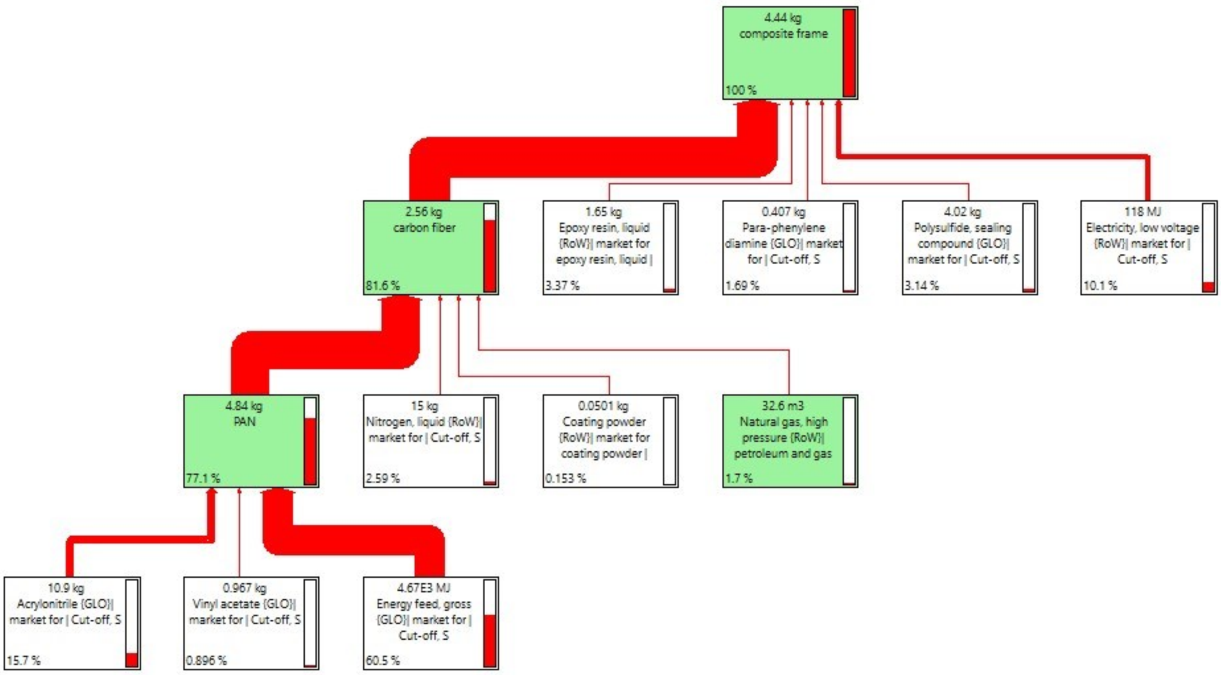
Terrestrial acidification:



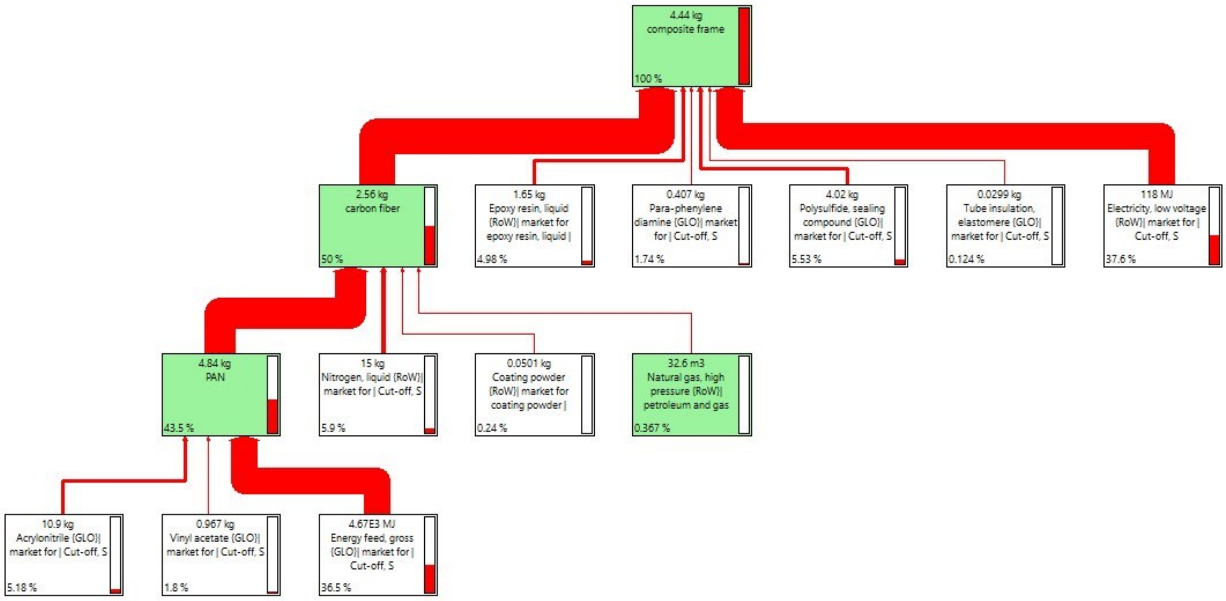
8.3.4 Network diagram of selective impact categories of characterization for 4.44kg Eight layers Carbon fiber-epoxy reinforced composite frame

8.3.5 :

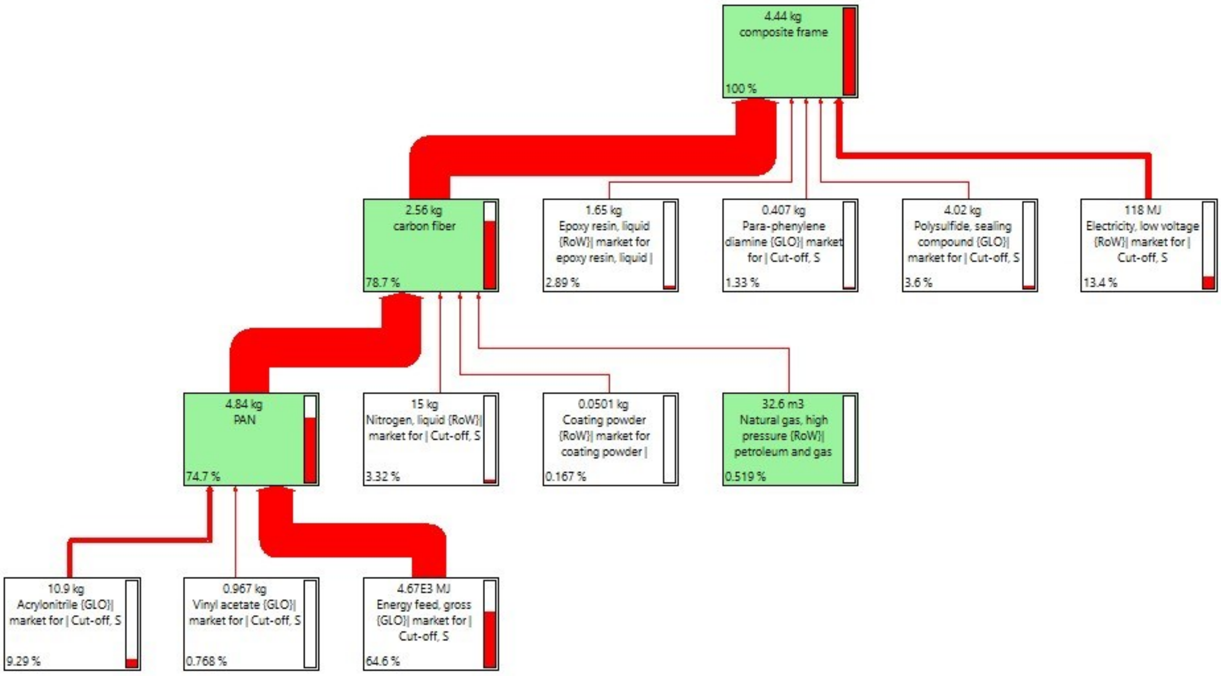
Global warming:



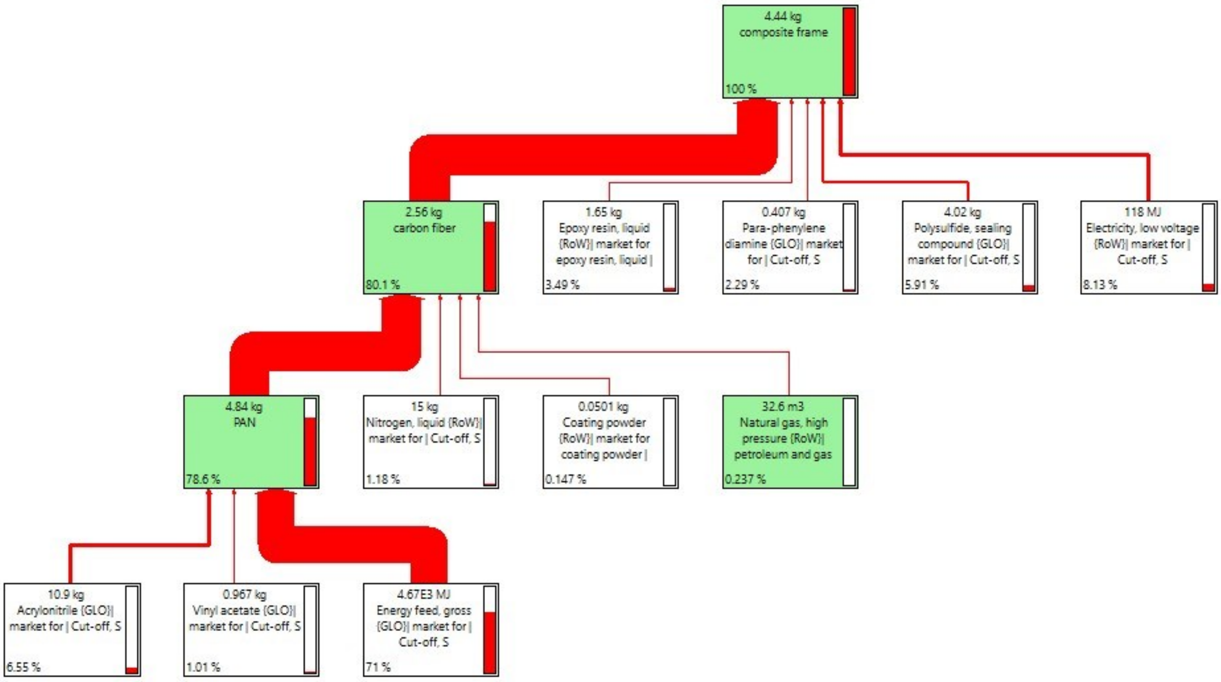
Ionizing radiation:



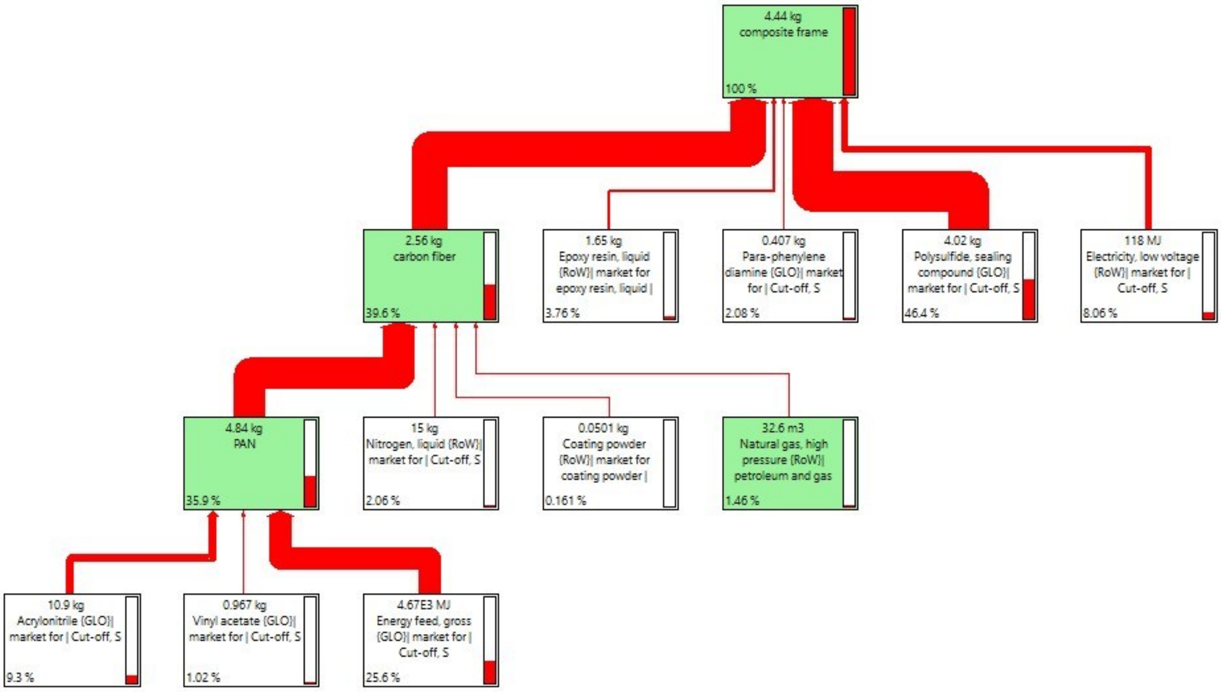
Fine particulate formation:



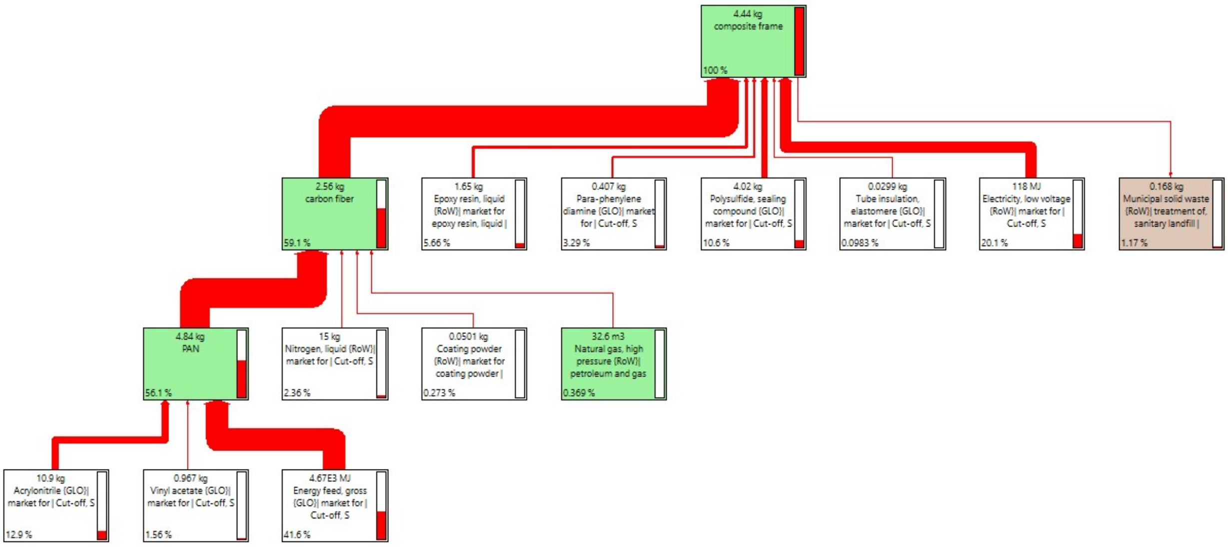
Terrestrial ecotoxicity:



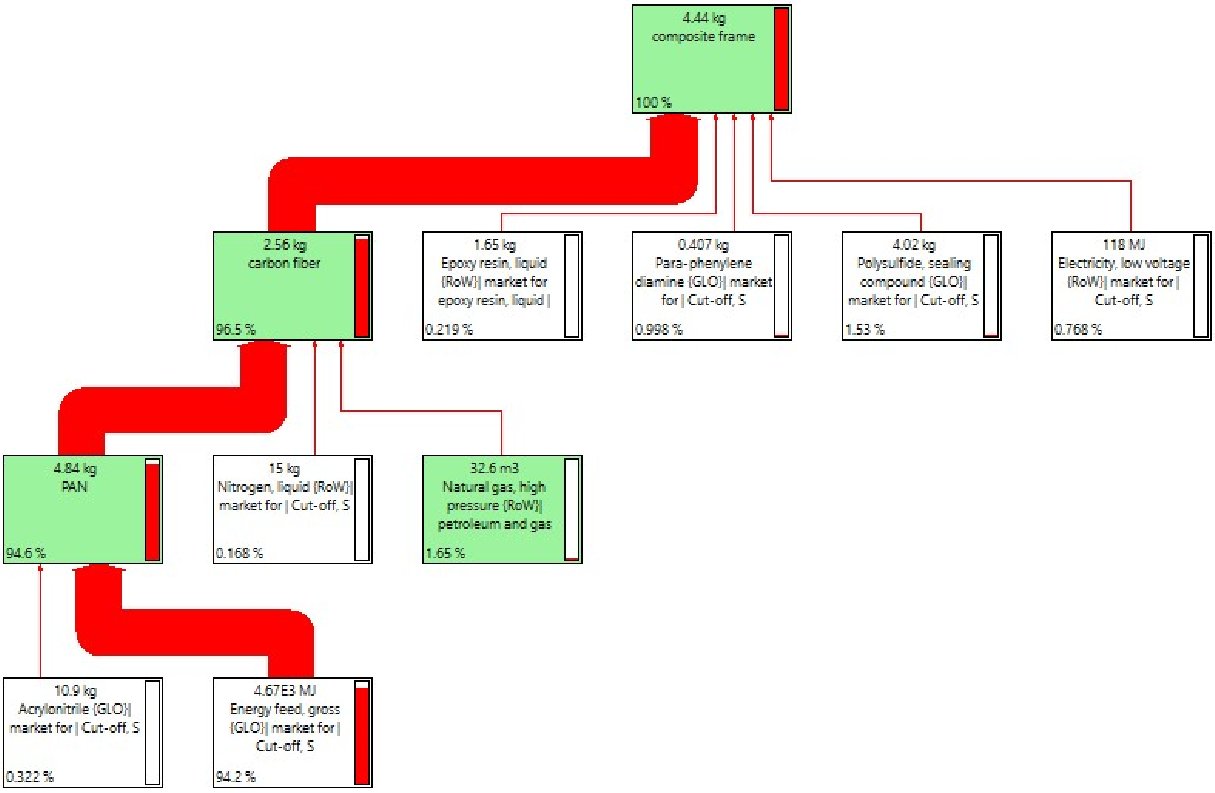
Human carcinogenic toxicity:



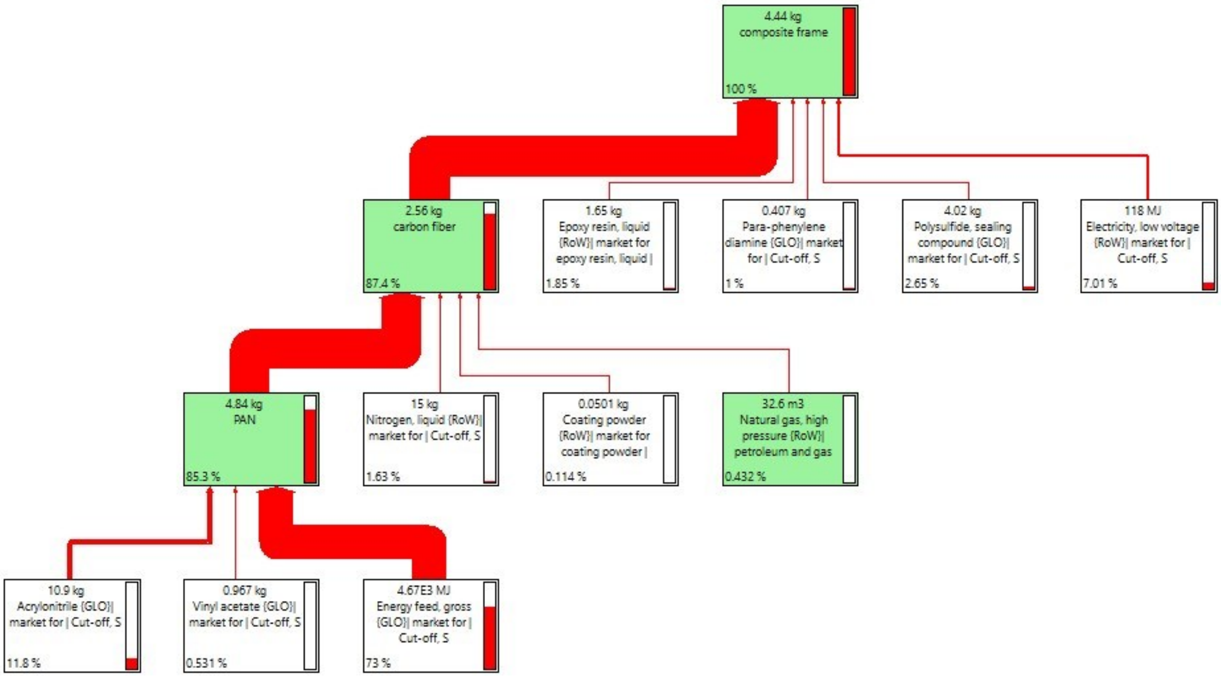
Marine Ecotoxicity:



Stratospheric Ozone depletion:

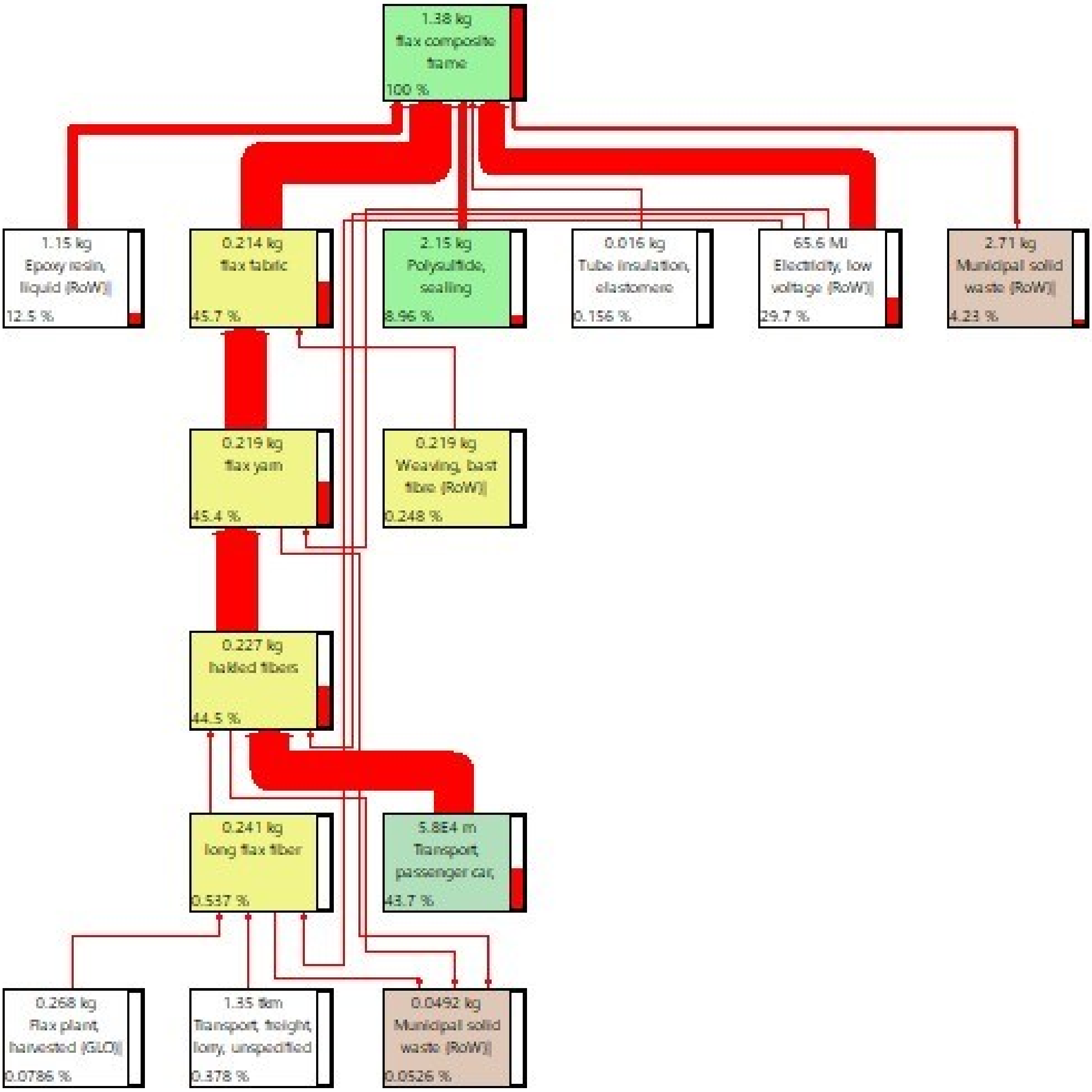


Terrestrial acidification:

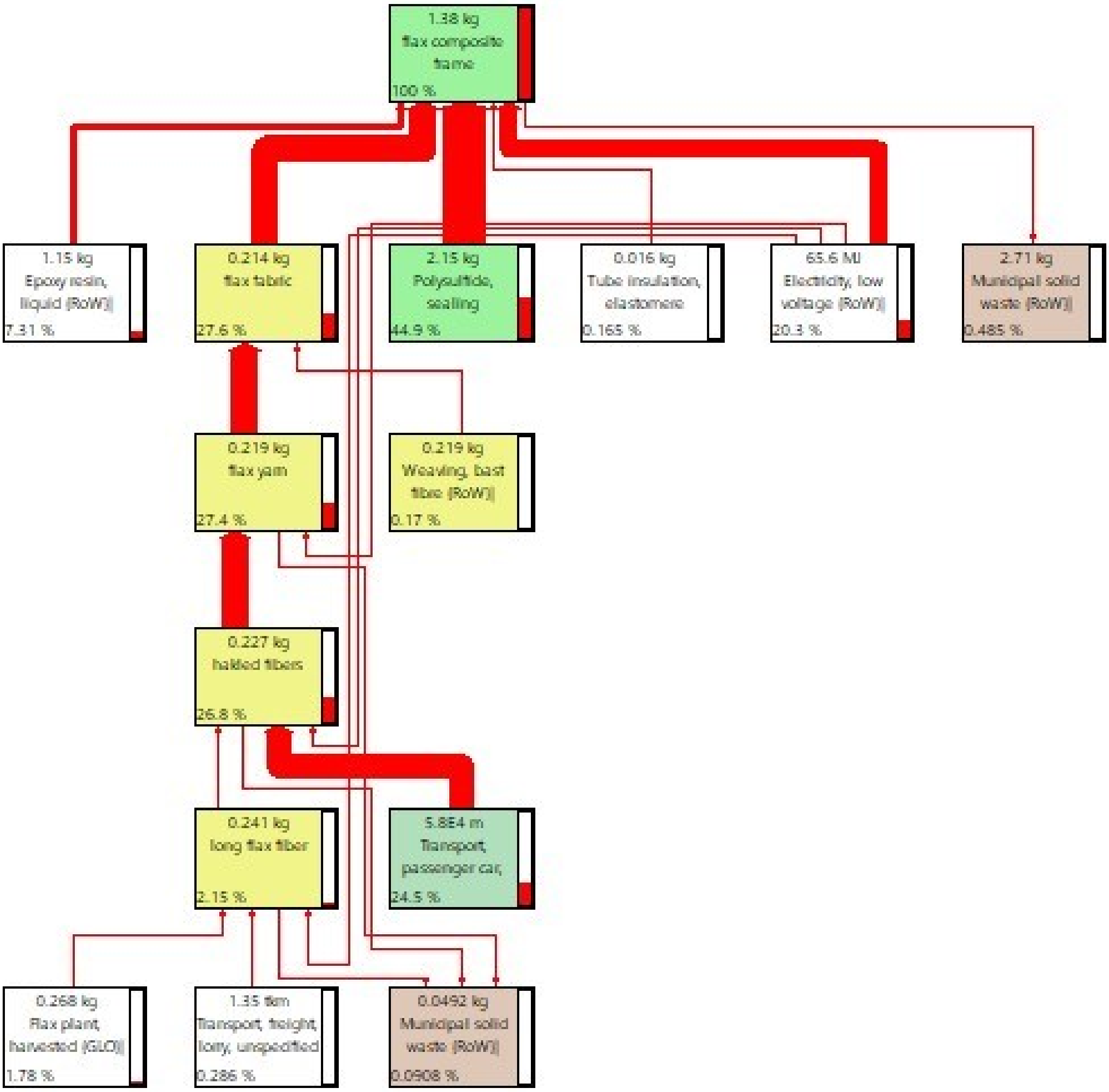


8.4 Network diagram of selective impact categories of characterization for 1.38kg Four layers Flax-epoxy reinforced composite frame:

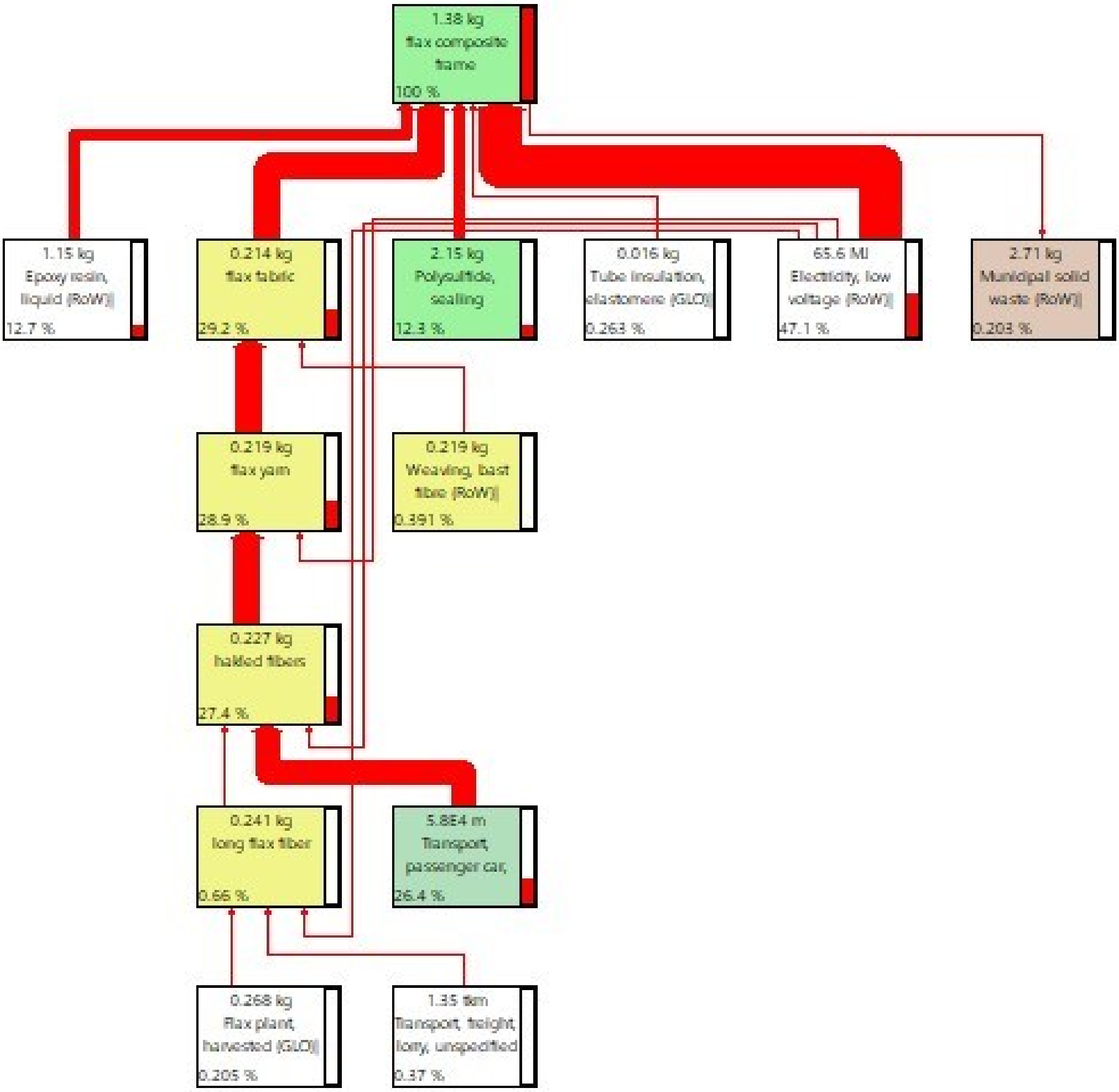
Global Warming:



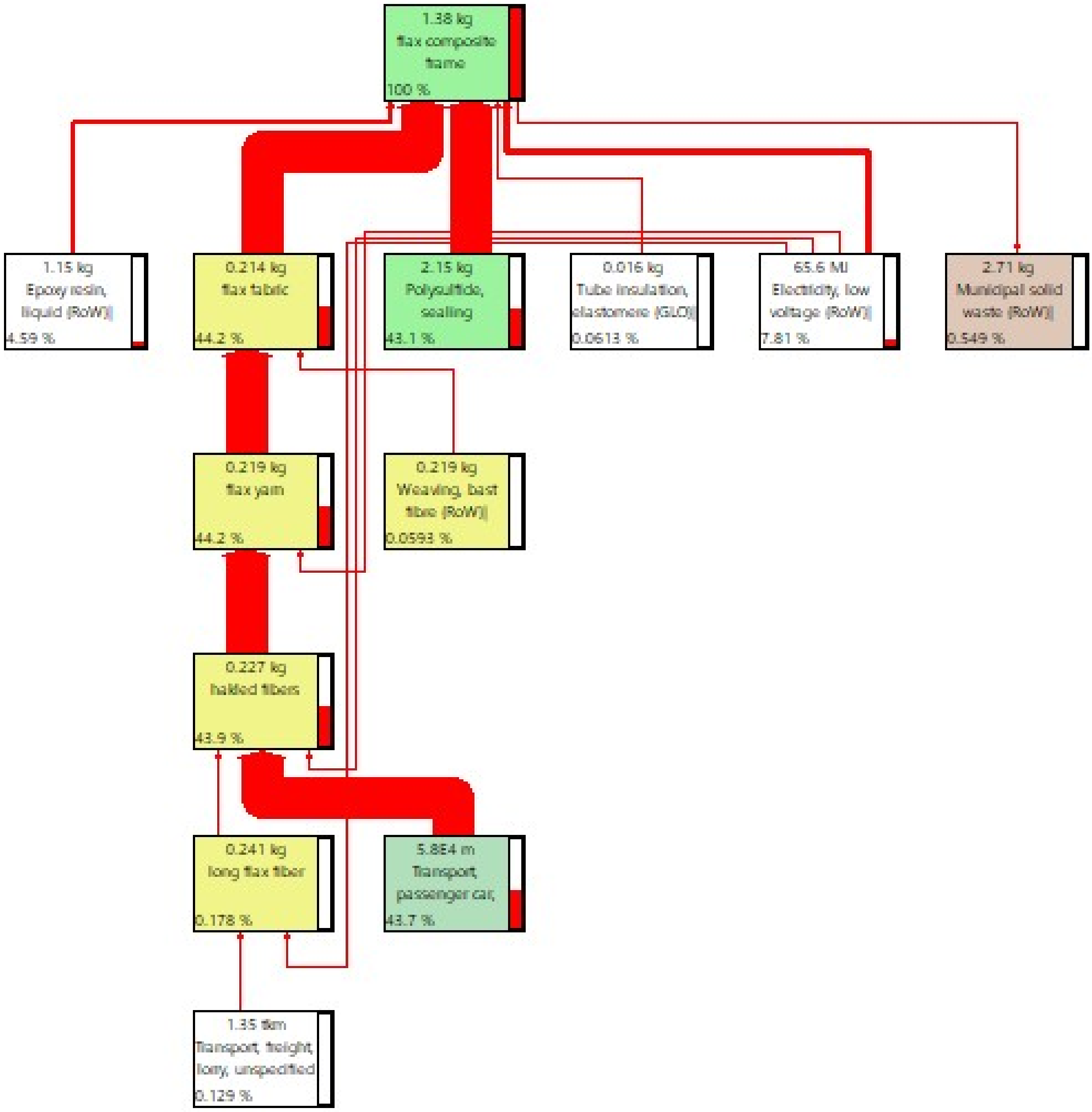
Stratospheric ozone depletion:



Fine particulate matter formation:

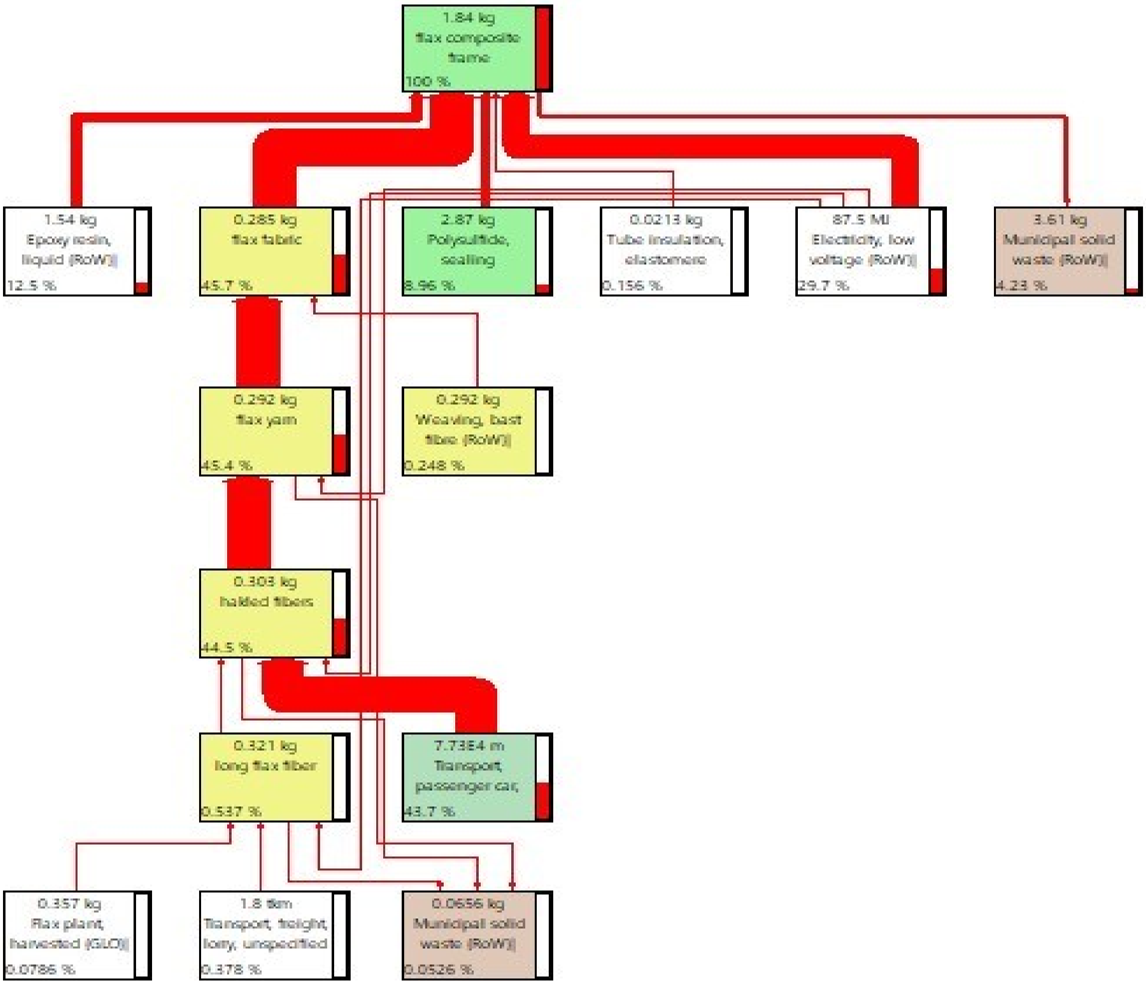


Human Carcinogenic Toxicity:

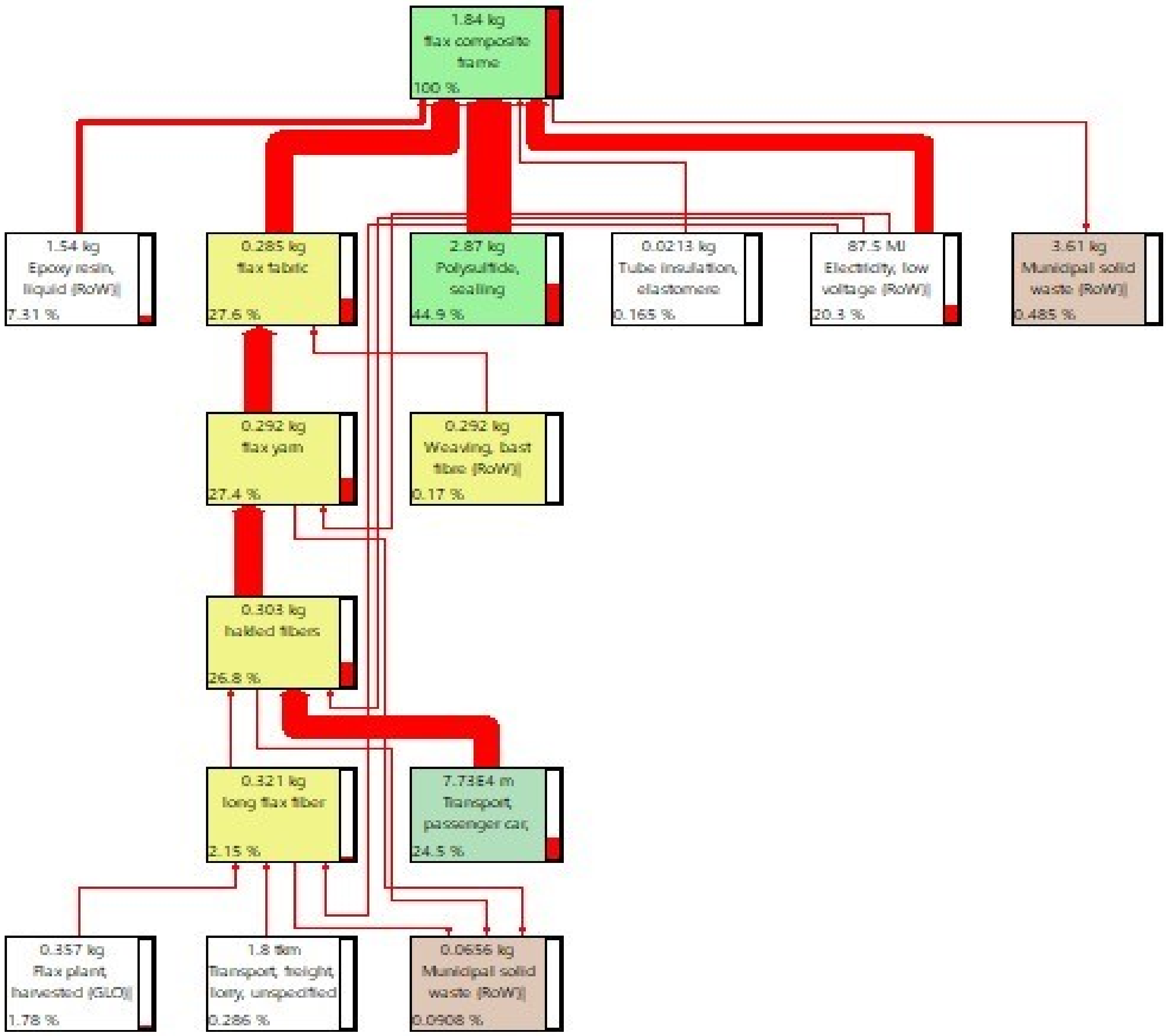


8.4.1 Network diagram of selective impact categories of characterization for 1.84kg Eight layers Flax-epoxy reinforced composite frame

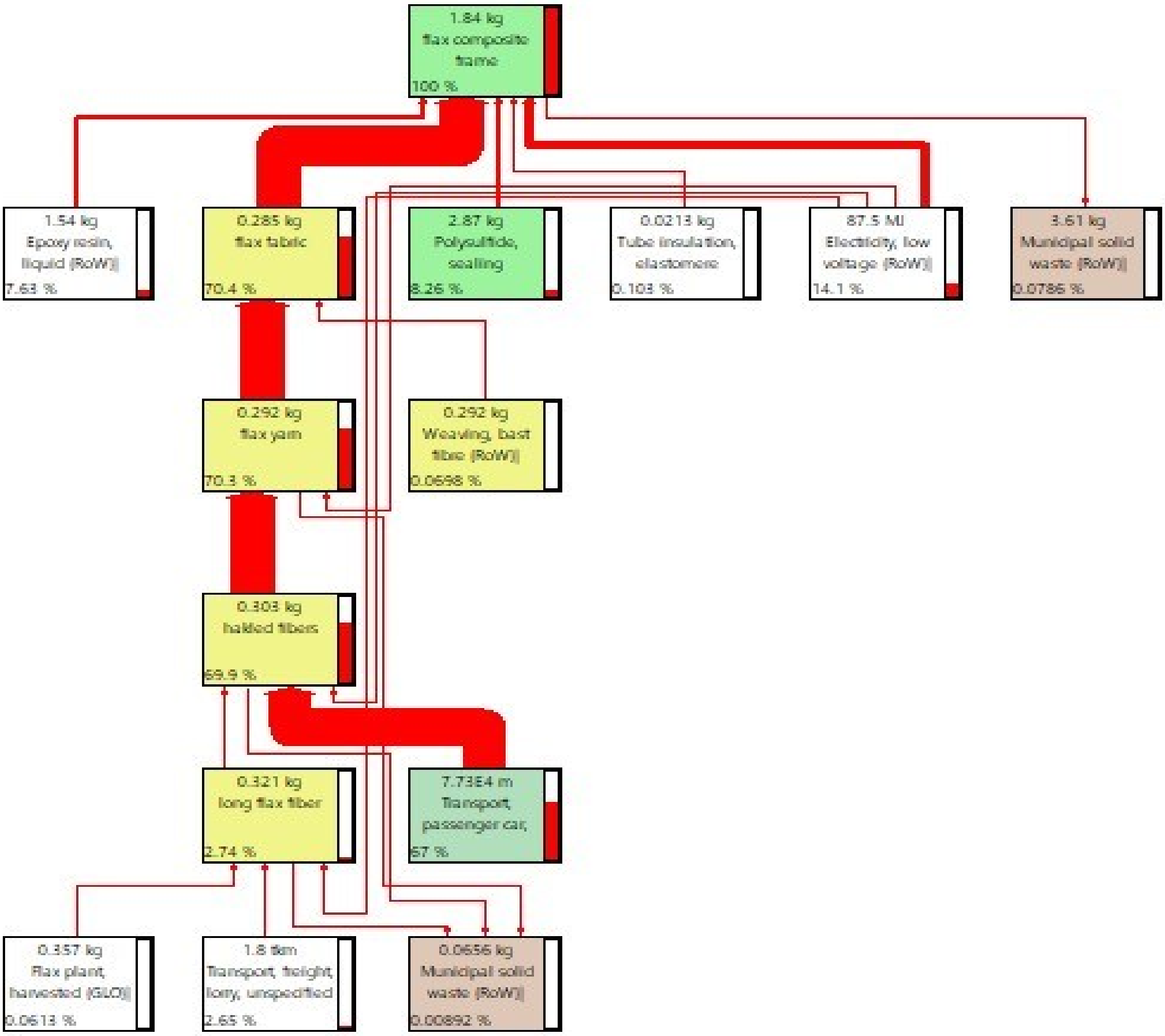
Global warming:



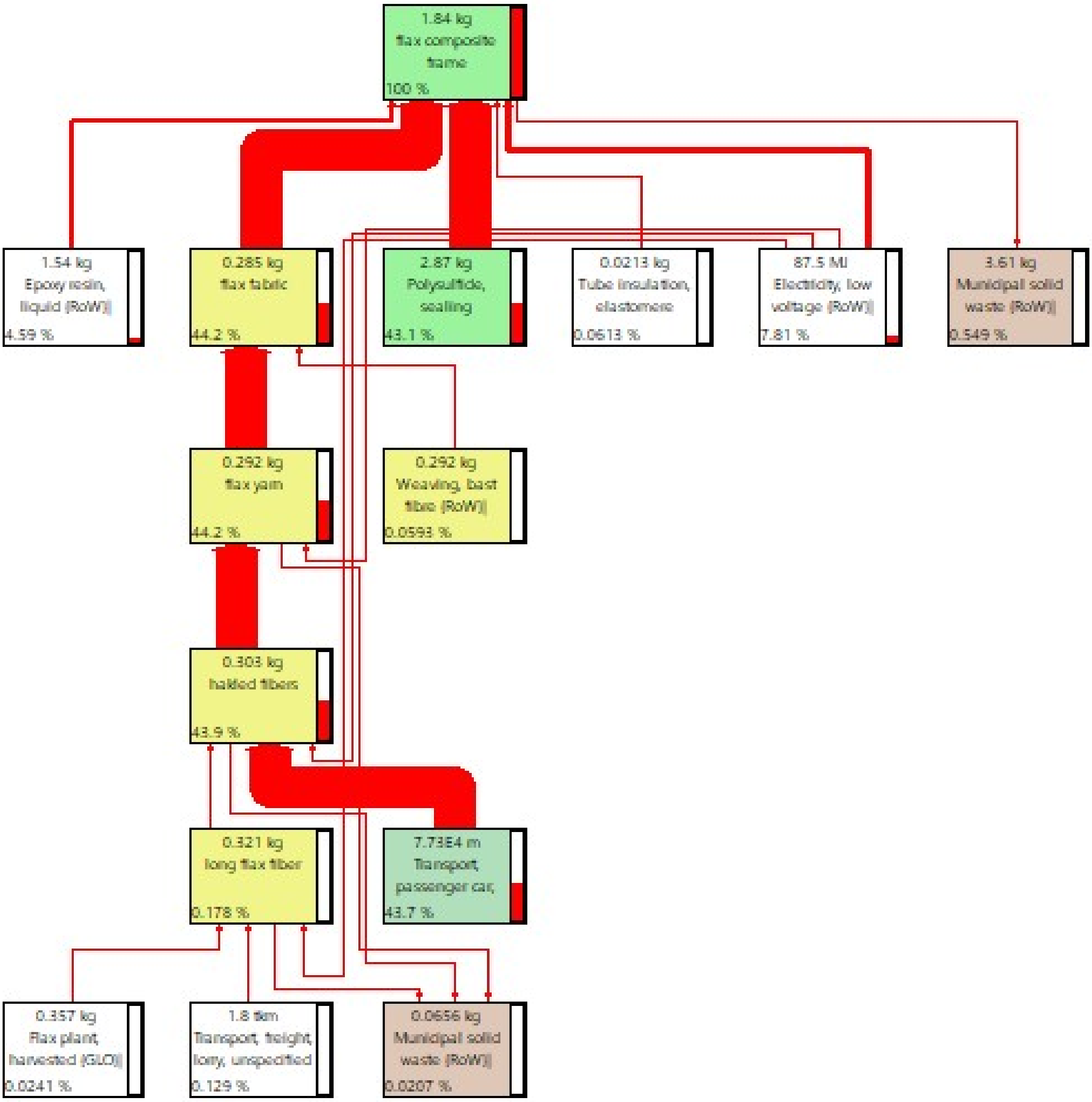
Stratospheric ozone depletion:



Terrestrial ecotoxicity:



Human carcinogenic toxicity:



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