Sustainability assessment of a non-pneumatic tire produced with fused filament fabrication

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Thesis to obtain the Master of Science Degree in

Mechanical Engineering

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November 2024

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Dedicated to my father who always supported me, my mother and brothers, and the whole family and friends.

Acknowledgments

I would like to thank my supervisors Professors Inês Ribeiro and Manuel Sardinha for giving me the opportunity to work and develop this theme, and for their support and guidance throughout this experience. I would like to thank all my friends and university colleagues who accompanied me during these years at Instituto Superior Técnico. I would also like to thank my entire family and friends, including Father Tiago, and especially my parents and siblings for being my main support and my biggest fans, who have always been there throughout my academic journey.

Resumo

Esta tese analisa o impacto ambiental de pneus de bicicleta não pneumáticos (NPTs) produzidos através da fusão de filamento (FFF), com ênfase na sustentabilidade e no desempenho. Os pneus pneumáticos tradicionais, apesar de amplamente utilizados, apresentam desafios como furos, desgaste e problemas de fim de vida devido a materiais não biodegradáveis. Os NPTs, fabricados com poliuretano termoplástico (TPU) reciclável através de manufatura aditiva, oferecem uma alternativa promissora que reduz a necessidade de manutenção e o impacto ambiental.

O estudo realiza uma Avaliação do Ciclo de Vida (LCA) para analisar o impacto ambiental dos NPTs em várias etapas — da extração de matérias-primas ao fim de vida útil — utilizando normas ISO e o software SimaPro. As variáveis principais incluem configurações de material único vs. bi-material e designs de peça única vs. multi-peça. Os resultados mostram que os NPTs reduzem o desperdício, simplificam a reciclagem e eliminam a manutenção relacionada com a camara de ar. Os designs de bi-material e multi-peça demonstram vantagens em eficiência de recursos.

A durabilidade e a reciclabilidade dos NPTs posicionam-nos como alternativas sustentáveis aos pneus tradicionais. Os resultados demonstram que os NPTs são sustentáveis e podem transformar a indústria de pneus ao reduzir significativamente o desperdício, melhorar a reciclabilidade e apoiar práticas ambientalmente responsáveis. A tese conclui que, embora os NPTs tenham um grande potencial para reduzir os impactos ambientais na fabricação, pesquisas adicionais são necessárias para otimizar sua aplicação em diversos contextos.

Palavras-chave: Avaliaçao de ciclo de Vida, LCA, TPU, Pneu não pressurizado, NPT, FFF

Abstract

This thesis examines the environmental impact of non-pneumatic bicycle tires (NPTs) produced with fused filament fabrication (FFF), emphasizing sustainability and performance. Traditional pneumatic tires, while widely used, present challenges such as punctures, wear, and disposal issues due to non-biodegradable materials. NPTs, using recyclable thermoplastic polyurethane (TPU) in additive manufacturing, offer a promising alternative that reduces maintenance and environmental burdens.

The study conducts a Life Cycle Assessment (LCA) to analyze NPTs' environmental impact across various stages—from raw material extraction to end-of-life—using ISO standards and SimaPro software. Key variables include single- vs. bi-material configurations and single-piece vs. multi-piece designs. Findings reveal that NPTs reduce waste, simplify recycling, and eliminate air-related maintenance. The bi-material, multi-piece designs demonstrate advantages in resource efficiency.

NPTs' durability and recyclability position them as sustainable alternatives to traditional tires. Findings demonstrate that sustainable NPTs could transform tire manufacturing by significantly decreasing waste, enhancing recyclability, and supporting environmentally friendly practices. The thesis concludes that, while NPTs show strong potential for reducing environmental impacts in manufacturing, further research will support their optimization for diverse applications.

Keywords: Life cycle assessment, LCA, TPU, Nonpneumatic tire, AM, FFF,

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Nomenclature

AM	Additive Manufacturing
E-bike	Electrical Bicycle
EoL	End of Life
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
NPT	Non pneumatic tire
PLA	Polylactic Acid
PT	pneumatic tire
PU	Polyurethane
SLS	Selective Laser Sintering
TPU	Thermoplastic Polyurethane

Chapter 1

Introduction

1.1 Motivation and Topic Overview

In recent years, there has been a global shift toward sustainable transportation, with bicycles emerging as one of the most eco-friendly mobility solutions, especially in urban environments. This growing trend aligns with the need for greener alternatives to fossil fuel-powered vehicles, as cities aim to reduce pollution and improve public health. However, traditional pneumatic tires, which are commonly used in bicycles, come with several inherent challenges. These include frequent maintenance due to punctures, air pressure fluctuations, and general wear and tear. Such issues are not only inconvenient to cyclists but also negatively impact the overall lifecycle costs of maintaining a bicycle.

Additionally, the environmental impact of discarded pneumatic tires is significant. The materials used in conventional tires are often non-biodegradable, and their disposal presents a long-term environmental burden. Recycling these tires is complicated by their composite structure, which typically includes multiple layers of rubber, metal, and synthetic materials. As a result, a considerable portion of used tires ends up in landfills, exacerbating the waste management problem.

Recent advances in additive manufacturing (AM), especially fused filament fabrication (FFF), offer a promising alternative in the form of non-pneumatic tires (NPTs) enabling the creation of new tires with more complex geometries. NPTs eliminate the need for pressurized air, reducing maintenance requirements and potentially improving the longevity of the tire. Moreover, the use of recyclable materials in FFF-produced NPTs can significantly reduce waste and environmental impact.

This thesis explores the sustainable design, production, and environmental impact of NPTs for bicycles, manufactured through FFF. Emphasis is placed on examining how different design configurations, material selections, production processes, and end-of-life (EoL) options influence the overall sustainability of these tires.

1.2 Objectives

This research aims to investigate additive manufacturing technology and materials for NPT production, while also focusing on the design and contribution to the development of a functional prototype specifically tailored for bicycles. A key part of the study is the comprehensive Life Cycle Assessment (LCA), which will assess the environmental impact across various stages, including material production, manufacture and end-of-life. Additionally, the thesis seeks to identify the design parameters that have the greatest influence on the overall sustainability of the NPT, providing insights into how design choices affect the tire's environmental performance.

1.3 Thesis Outline

This thesis is subdivided into six main chapters as follows:

- Chapter 1 introduces the motivation, objectives and an overview of the topic.
- Chapter 2 presents a review of the literature on non pneumatic tires, additive manufacturing, and sustainability in the context of the tire industry
- Chapter 3 details the methodology followed and the decision making towards the non pneumatic tire case studies
- Chapter 4 presents the case studies, their experimental procedure and the Life Cycle Assessment for each one, including its findings
- Chapter 5 concludes the study, summarizing the key findings and offering suggestions for future research.

Chapter 2

Literature Review

2.1 Non-pneumatic tires

Non-pneumatic tires (NPTs) represent an innovative evolution in tire design, offering a range of benefits over traditional pneumatic tires. While pneumatic tires have long dominated the market due to their durability and performance, NPTs address critical challenges such as puncture resistance, load-bearing capacity, and sustainability. Advances in material science and manufacturing techniques, particularly in polymers and additive manufacturing, have significantly improved the feasibility of these tires. This chapter will delve into the historical development of NPTs, key advancements their structural and material composition, production methods, and potential applications, with a focus on the role of sustainable practices in shaping the future of this technology.

2.1.1 The history behind

The search for alternatives to traditional pneumatic tires has a history that dates back to the early 20th century. Although pneumatic tires have dominated the market due to their efficiency and durability, the idea of a tire that did not require pressurized air to support the vehicle's weight has been explored for more than a century [1] [2].

The first concepts of non-pneumatic tires (NPTs) began to emerge in the early 1900s [2]. In 1914, Papadopoulos patented a resilient tire that used internal springs to support the load, one of the earliest known examples of a tire that dispensed an air chamber [3].

In the following decades, various approaches to airless tires were developed, but none of these early designs matched the efficiency of pneumatic tires in terms of comfort and durability [1] [2].

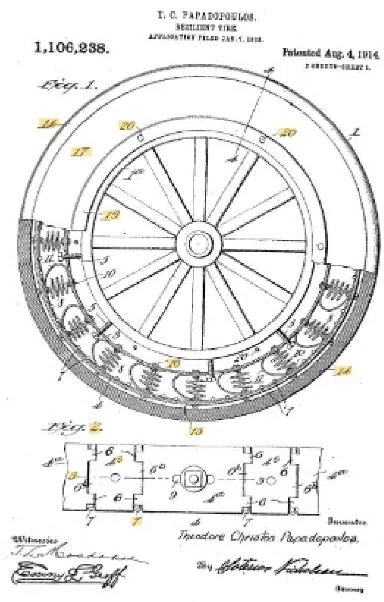


Figure 2.1: Resilient tire concept, registered by Papadopoulos in 1914 [3]

The renewed interest in non-pneumatic tires began to gain momentum in the 1980s, driven by the need to reduce vehicle weight and improve material efficiency. In 1983, General Motors Corporation challenged the industry to develop lighter and more efficient spare tire systems, which resulted in the development of new tire concepts, including those that did not require air [1]. Additionally, a more comprehensive historical analysis of the challenges and innovations associated with non-pneumatic tires was discussed by Araújo and Morera (2021), who highlighted the initial attempts and difficulties faced during the transition to airless technologies [4].

In recent decades, there have been significant advances in non-pneumatic tire technology. A key milestone was the development of the Tweel™ by Michelin in 2005, which combined a solid tread with a flexible spoke system, eliminating the need for pressurized air and becoming commercially available on July 2012 [5]. This concept was followed by other innovative models, such as the Uptis™, also by Michelin, which further improved the design and functionality of NPTs [6].

a) b)

Figure 2.2: a) Tweel™ by Michelin in 2005 and b) Uptis™ by Michelin in 2019 [5, 6]

Despite the advances, large-scale production of non-pneumatic tires still faces significant challenges. Among them are the difficulty in evenly distributing weight, ensuring durability under different usage conditions, and predicting tire failure mechanisms [2]. In addition, the need for specific standards to test and validate these tires, which differ substantially from traditional tires, represents another obstacle to widespread adoption [1] [2].

Recent literature also highlights the importance of emerging technologies, such as additive manufacturing (AM), which can enable the production of NPTs with complex and customized geometries to meet different performance and sustainability requirements [2]. These innovations could revolutionize the way tires are designed and manufactured, paving the way for more efficient and eco-friendly solutions.

2.1.2 Materials used in Non pneumatic tires

The materials used in non-pneumatic tires are selected based on their ability to provide the necessary mechanical properties, such as flexibility, strength, and energy absorption. As highlighted in an article published in 2023 by M. Sardinha et al., the primary materials used in NPTs are polymers, particularly thermoplastic polyurethanes (TPUs) [2]. TPUs are valued for their combination of elasticity and durability, allowing them to endure significant deformation while maintaining their structural integrity [7]. This makes them ideal for the repetitive stresses encountered in tire applications.

In addition to polymers, other materials such as metal alloys, composites, and shape memory alloys (SMAs) are utilized in specific NPT designs, particularly where enhanced strength or unique deformation characteristics are required [2]. Yaoji Deng categorizes these materials based on their functional roles within the tire, such as providing a rigid framework or enabling adaptive deformation under load. For example, SMAs are used for their ability to return to a predetermined shape after deformation, which is beneficial in maintaining tire performance under varying conditions [8].

The choice of material is then dictated by the intended application of the NPT. For instance, in heavy-duty vehicles where load-bearing capacity is paramount, materials with high strength and rigidity are prioritized. Conversely, for passenger vehicles, where comfort and energy efficiency are critical, materials that offer a balance between flexibility and durability are preferred. Table 2.1 presents various materials and the corresponding features and functions [8].

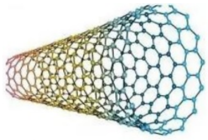
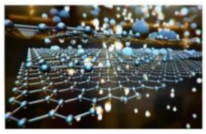
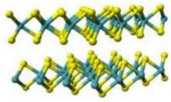
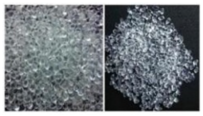
Designation	Features	Functions	Figure
Aramid pulp	High modulus and strength; excellent thermal and chemical stability; dimensional stability and toughness	Increase tread strength and abrasion resistance	
Carbon nanotubes	High thermal conductivity; High strength; High conductivity	Reduce the rolling resistance of the tread; improve the strength and thermal stability	
Graphene	Thinnest; Lowest resistivity; Highest heat conductivity; Highest electron mobility	Give rubber outstanding mechanical properties and multifunctional properties	
Molybdenum disulphide	Minimum coefficient of friction	Improve the strength and abrasion resistance of tires	
Polyurethane	Long service life; High tear strength; Good shock absorption	Good shock absorption function	
Glass fiber	Low density; Good toughness; High chemical stability; High temperature resistance	Improve the strength and service life	

Table 2.1: Materials of non pneumatic tires [8]

2.1.3 Categorization of Non Pneumatic Structures

The structural design of NPTs is as critical as the materials used, with different geometric configurations playing a key role in determining how the tire performs. NPT structures are primarily categorized into two main types: spoke-based designs and cellular or honeycomb structures [2]. Later design versions that do not fill into any of the previous categories have been discovered and are also discussed below [8].

Spoke-Based Designs: These structures typically consist of radial spokes that connect the inner hub to the outer tread. The spokes, often made from flexible materials, are designed to deform under load, providing a cushioning effect similar to that of pneumatic tires. The design and arrangement of these spokes is crucial in determining the tire's ability to distribute stress evenly and maintain consistent contact with the ground. Such designs are favored in applications where a balance between stiffness and flexibility is essential, such as in passenger vehicles and certain military vehicles [8].

Multi-hole Structures: These structures are characterized by a repeating pattern of cells, often in a honeycomb-like configuration, which provides a high strength-to-weight ratio. These geometric designs are tailored to optimize specific performance characteristics, such as load distribution, rolling resistance, and durability. Cellular structures are particularly advantageous in applications where minimizing material weight without sacrificing performance is crucial, such as in lightweight vehicles and electric scooters [8].

Convex type: The convex tyre is a conceptual non-pneumatic tire characterized by its innovative, adaptable design for various road and weather conditions. These designs focus on adaptability, weather resistance, and terrain-specific performance, aiming for enhanced grip, durability, and flexibility [8].

Solid Type: The solid type tire represents a unique category of non-pneumatic tires, characterized by advanced designs that focus on innovative materials and functionality. This type leverage advanced materials like PU and 3D printing technology to fabricate tires with complex structures, innovative features such as real-time adaptability, and environmentally conscious designs [8].

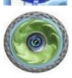
Category	Designation	Illustration	Structural features	Advantages	Disadvantages	Application
Spoke type	Tweel		Annular shear zone; Flexible polyurethane spokes	High grip; Low rolling resistance; Low noise; Abrasion resistance; Good shock absorption	Unclear fire and bullet proof performance	Lunar rover
	Uptis		Hollowed out design	High grip; Large lateral stiffness; Good shock absorption	Poor driving comfort; Loud noise	Chevrolet EC
Multi-hole type	Honeycomb tyre		Honeycomb-like spokes	Uniform mass distribution; Large bearing capacity; Good shock absorption; High strength; Low noise	Easy to insert sundries; Stress concentration	Armored vehicle
	Lunar rover tyre		Spiral steel wire mesh structure	Can adapt to harsh environment; High strength	Poor handling stability; Poor vibration damping	Lunar rover
Convex type	reCharge		Adjustable tread	Can be customized; Energy conservation and environmental protection; intelligence	Complex structure; High cost	Car
	Tiltread		Three independent parts	Good adaptability; High grip	Complex structure; High cost	Car
Solid type	Eagle360		Sphere; Coral-like texture	Suitable for different roads and weather; 360°steering; High grip	Require special vehicles	Special vehicles
	Oxygene		Live moss grows in the tyre wall	Energy storage; Durable; Lightweight; Environment protection	Complex structure; Still a concept	Car

Figure 2.3: Comparison of main non-pneumatic tires [8]

The categorization of these structures extends to the specific mechanical behaviors they facilitate. For instance, honeycomb structures can be designed with varying cell sizes and shapes to achieve different levels of stiffness or flexibility. The use of advanced manufacturing techniques, such as additive manufacturing, has enabled the creation of increasingly complex cellular structures, allowing for greater customization and optimization of NPT, hence the latter design categories presented [2] [8].

2.1.4 NPTs production methods

Traditional tire molding techniques, such as compression molding, filament winding, and centrifugal casting, involve numerous types of equipment, intricate processes, high energy consumption, and low yield. Non-pneumatic tires, with their complex support structures, are not suitable for these conventional molding methods. Consequently, improving manufacturing technology for non-pneumatic tires is a crucial challenge that must be addressed to promote their widespread use. Currently, injection molding, centrifugal casting, and 3D printing are the primary methods employed for molding non-pneumatic tires [8].

Injection Molding Technology

Injection molding technology is a well-established manufacturing process known for its efficiency, precision, and automation capabilities. It offers several advantages, including short forming cycles, complex shape capabilities, high-quality products, and mechanization. However, traditional injection molding methods have limitations when it comes to molding non-pneumatic tires, as the two-step process of plasticizing and injection does not align with the complexities of these tires [8].

To address these issues, one-step injection technology has been developed, allowing simultaneous plasticizing, injection, and dosing. This advancement streamlines the process, improving efficiency. The optimization of injection molding technology for non-pneumatic tires has been a target of research, with focus on factors like gate position and quantity [9], finite element analysis [10], and the influence of injection molding parameters on tire properties [11].

Centrifugal Casting Technology

Centrifugal casting is particularly suited for non-pneumatic tires, especially those primarily composed of polyurethane (PU) [12] [13]. The process leverages the low viscosity and excellent flowability of PU to create tires through simple liquid-phase processing. A centrifugal casting machine mixes raw materials and injects them into a manifold, where centrifugal force propels them into the mold cavity. The result is a solid and dense skin layer on the outer surface of the tire, with uniformly distributed minute bubbles throughout the material, creating a microporous elastomer layer. This method ensures that the tire has suitable density and acceptable static and dynamic balance.

Compared to other molding methods, centrifugal casting offers the advantage of producing tires with considerable strength and stiffness, eliminating the need for traditional curing equipment, thereby reducing production costs. Several studies like the one performed by Bert Bras and Austin Cobert have investigated the environmental impact of non-pneumatic tires produced via centrifugal casting, particularly focusing on Michelin Tweel tires, which consist of treads, hubs, and PU spokes. The process involves internal mixing, extrusion, and vulcanization for treads, hub casting, and PU spoke manufacturing, with the entire assembly cured to bond all components together [14].

Additive Manufacturing

Additive manufacturing, also known as 3D printing technology, has revolutionized tire production, enabling the creation of complex structures without the need for traditional molds. This technology has opened up possibilities for complex surface and internal tire structures, enhancing product design diversity and flexibility [15] [16].

Fused Filament Fabrication Technology

Fused Filament Fabrication (FFF) is the most widely used 3D printing technology and due to its simplicity, ease of maintenance, and cost-effectiveness. It involves bonding filaments horizontally and vertically, with the bonding force generated by the rapid transformation of printing material from a molten to solid state. However, the filament-to-filament bonding strength is relatively weak, which can result in defects in the mechanical properties of products [17–20]. Researchers such as Jun Wang have explored the application of FFF to 3D-printed non-pneumatic tires, understanding that it may reduce the stiffness of these tires compared to simulations, and adjustments are necessary to maintain accurate performance predictions [21]. On another article published by Suvanjumrat, FEA has been used to compare the vertical stiffness of FFF printed samples with actual non-pneumatic tires, validating the feasibility of constructing complex spoke shapes using FFF [22]. Figure 2.4 shows the process utilized by Suvanjumrat to obtain the NPT samples that later were compared.

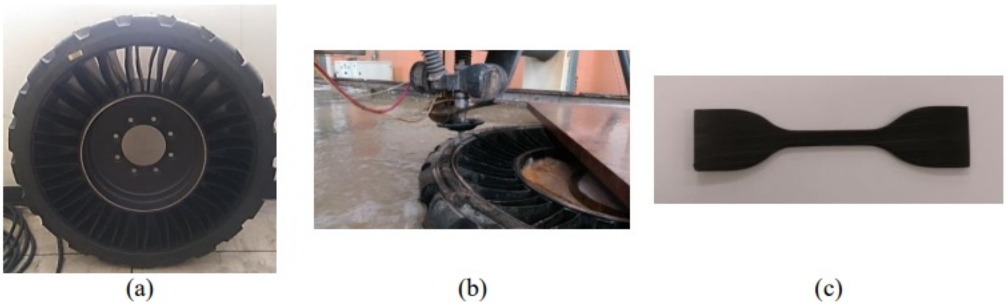


Figure 2.4: a) TWEEL NPT, b) the extraction of spokes using waterjet cutting technique, and c) a waterjet cut specimen [22]

Selective Laser Sintering Technology

SLS is a 3D printing method that employs an infrared laser beam as an energy source for sintering a powder material [23]. It is particularly suited for producing complex tire structures without the need for support structures. However, SLS technology has drawbacks, including low product accuracy, rough surfaces, and expensive equipment with high maintenance costs. Nevertheless, SLS technology is applied in the production of non-pneumatic tires, particularly when highly efficient, complex structures are required [23, 24].

As a high-speed molding technology, 3D printing technology has transformed the tire manufacturing industry by allowing rapid tire production for laboratory and track testing. Researchers can now efficiently conduct experimental tests, construct complex support structures for non-pneumatic tires, and study their mechanical properties, while being offered the versatility to create non-pneumatic tires with multiple materials and various designs, and gradually providing more molding options.

2.1.5 Mechanical Characteristics and Behavior of NPTs versus Pneumatic Tires

The comparison between non-pneumatic tires (NPTs) and traditional pneumatic tires reveals critical insights into their mechanical characteristics and behavior, highlighting both the advantages and challenges associated with NPTs.

Structural Design and Deformation

NPTs differ fundamentally from pneumatic tires due to their unique structural designs, which directly impact their deformation characteristics under load. Pneumatic tires rely on an inflated air chamber to distribute loads and absorb shocks, which allows them to adapt to various surfaces and impacts efficiently. In contrast, NPTs use a solid or cellular structure, often made of composite materials, to perform the same functions. This structural difference leads to variations in how each tire type deforms under stress [25].

Rugsaj et al., which developed the NPT presented in figure 2.5, developed 3D finite element models of non-pneumatic tires featuring different spoke shapes, utilizing a hyper-elastic primary structure model. The analysis revealed that the vertical stiffness, maximum local stress, and mass of the spokes are influenced by the thickness of the spokes [26].

Figure 2.5: Picture taken from the NPT developed by Rugsaj et al. [26]

Aboul-Yazid developed a quasi-static 2D analytical model to investigate how spoke structure and shear plies impact contact pressure, vertical tire stiffness, and stress. The findings indicate that the shape of the spokes significantly influences the performance of tires without compound rings [27].

It is important to notice that while NPTs can maintain their shape and function without the need for inflation, their deformation behavior under load is more complex and requires careful design optimization to match or exceed the comfort and performance of pneumatic tires.

Durability and Puncture Resistance

One of the primary advantages of NPTs over pneumatic tires is their resistance to punctures. Since NPTs do not rely on pressurized air, they eliminate the risk of blowouts and punctures, which are common issues with pneumatic tires. This characteristic makes NPTs particularly suitable for military, construction, and agricultural vehicles, where pavement conditions are often adverse and prone to punctures.

H. X. Fu et al. examined the fatigue performance of NPTs with mesh flexible spokes and proposed a method for predicting their fatigue life. They analyzed how structural parameters affect the fatigue life of these tires. Using the Thomas crack model, they estimated the fatigue life of a non-pneumatic tire with mesh flexible spokes by employing strain energy density as the fatigue life characterization parameter. The actual driving distance for a mesh flexible NPT was approximately 23,900 km [28].

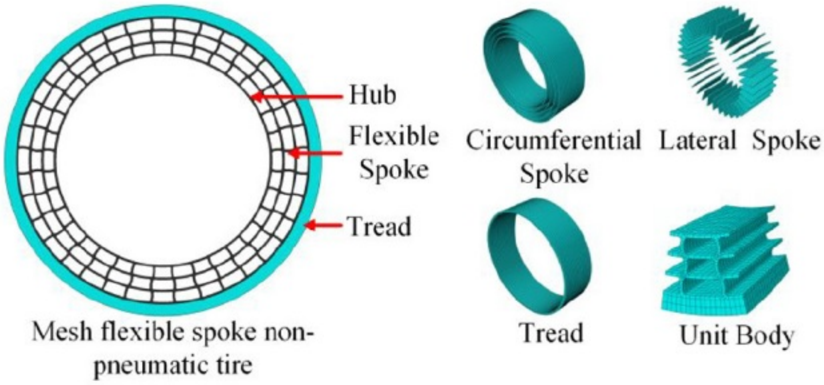


Figure 2.6: Structure of non-pneumatic tire with mesh flexible spokes studied by H. X. Fu [28]

Not only the structure, but the pavement conditions also plays an important role and Sriwijaya working with Hamzah, studied how road inclination affects the stress distribution in non-pneumatic tires with flexible spokes. Their findings indicated that the equivalent stress distribution in flexible spokes increases with pavement inclination. Excessive road inclination was found to accelerate the failure of flexible spokes in non-pneumatic tires[29].

Has seen previously with the H. X. Fu research, the durability is influenced by the structure. The same was observed by Jaehyung Ju et al. that investigated how the structural parameters of honeycomb tires affect their fatigue performance. They designed honeycomb supports at six different angles and applied various structural parameters to the flexible spoke structure for verification. By comparing and analyzing the local stresses of honeycomb supports with different angles under a uniaxial load, they found that honeycomb tires with larger unit angles exhibit lower local stress and enhanced fatigue resistance [30].

However, this increased durability comes with trade-offs. The same review from Sriwijaya and Hamza research, notes that the solid or semi-solid structure of NPTs can lead to increased rolling resistance, which may result in higher energy consumption and reduced fuel efficiency when compared to pneumatic tires. This is particularly important in applications where fuel efficiency and speed are critical[29].

Energy Efficiency and Rolling Resistance

Rolling resistance is a critical factor in determining a tire's energy efficiency, as it directly affects the amount of energy required to move the vehicle.

The rolling resistance of NPTs is generally higher than that of pneumatic tires, primarily due to their solid structure. In contrast, pneumatic tires, with their air-filled chambers, are designed to minimize rolling resistance through optimal inflation pressure, which allows for smoother and more energy-efficient driving. The challenge for NPT developers is to innovate designs and materials that can reduce rolling resistance while maintaining the inherent benefits of NPTs, such as puncture resistance and durability.

A study by Clemson University discovered that using multi-cell geometry and PU materials significantly reduces the elastic hysteretic loss and shear modulus of elastomers in non-pneumatic tires. This, in turn, effectively lowers the rolling resistance of the tres [31, 32].

Veeramurthy created a finite element model of the Tweel tire to analyze how spoke thickness, shear band thickness, and shear modulus affect energy loss. The findings revealed that increasing the shear band thickness and shear modulus of the shear layer reduces the tire's rolling resistance, significantly impacting its performance [33].

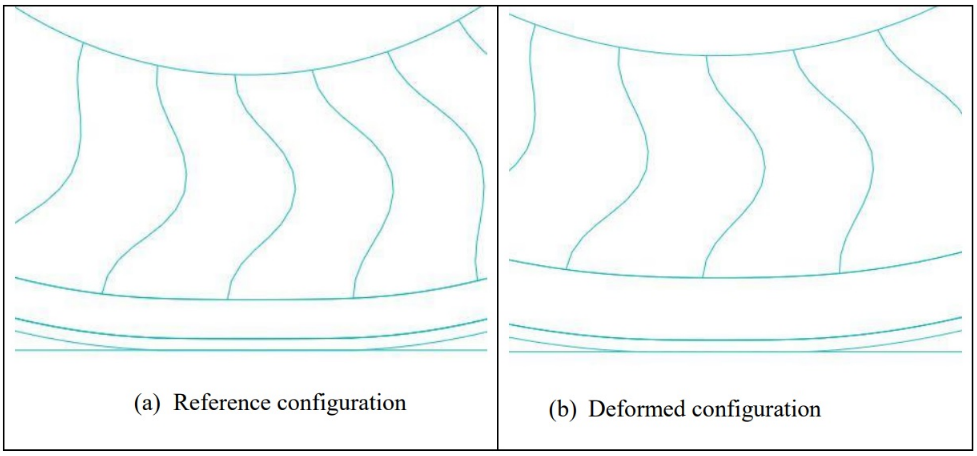


Figure 2.7: Deformation of Reference configuration Vs Optimized configuration obtained by Veeramurthy for a vertical load of 4000N [33]

Xiaochao Jin examined the rolling resistance of a honeycomb tyre. Their analysis revealed that the rolling resistance increases with both the mass of the honeycomb structure and its angle, while maintaining the same load-carrying capacity [34].

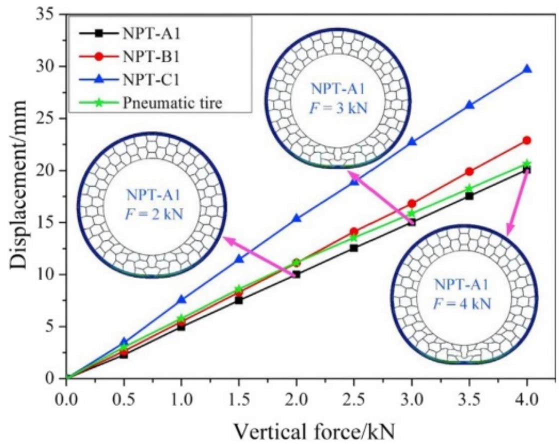


Figure 2.8: Rolling resistance of non-pneumatic tires under different vertical forces obtained by Xiaochao Jin [34]

The optimization of rolling resistance remains a significant challenge in the development of NPTs, with ongoing research focused on finding the right balance between durability and energy efficiency, with this having a significant consideration for the automotive industry, where reducing rolling resistance is crucial for improving vehicle efficiency and reducing emissions.

Load-Bearing Capacity and Safety

NPTs are designed to bear loads without relying on air pressure, which fundamentally changes their load-bearing characteristics. Unlike pneumatic tires, which can adjust their load distribution through inflation, NPTs must rely on their structural design to handle varying loads.

To better understand how both tires behave under the same stress, R. Rugsaj et al. conducted tests to measure the vertical stiffness of Michelin Tweel tires and compared the results with those of similarly sized pneumatic tires [35]. They tested five positions along the tire's circumference, applying vertical loads of 4, 16, 18, 20, and 22 kN to determine the vertical stiffness of the NPTs. The force–displacement relationship from these tests at various loads is illustrated in figure 2.12 a). The vertical stiffness of non-pneumatic tires is compared to that of pneumatic tires, with the results illustrated in figure 2.12 b). The findings indicate that NPTs exhibit greater vertical stiffness than traditional pneumatic tires [35].

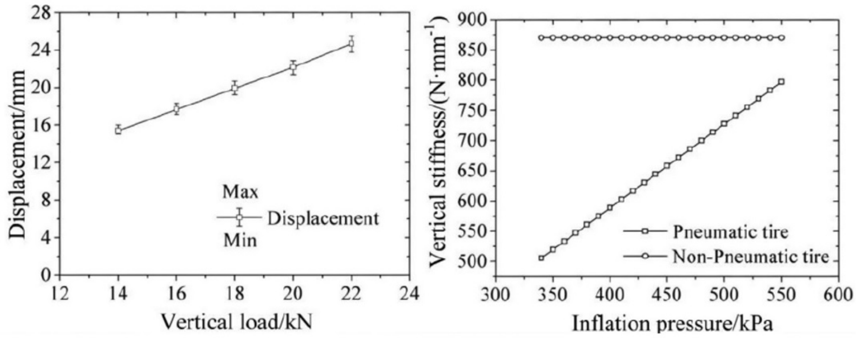


Figure 2.9: a) Force–displacement relationship of NPT b) vertical stiffness of NPT and PT [35]

William Rutherford found that spoke thickness had the most significant effect on the mass and vertical stiffness of Tweel tires [36]. Ganniari-Papageorgiou investigated the maximum stress, contact pressure, maximum vertical displacement, and absorbed energy during loading using a parametric finite element model and found that the density, thickness, and internal angle of the honeycomb structure significantly affect the vertical stiffness [37].

While NPTs can be engineered to support heavy loads, their performance in this area is highly dependent on the specific materials and design used, making one of the main challenges in NPT design achieving a balance between load-bearing capacity and other performance factors such as ride comfort and handling .

Safety is another critical aspect where NPTs differ from pneumatic tires. The absence of air pressure in NPTs eliminates the risk of sudden deflation, which is a common cause of accidents with pneumatic tires. However, NPTs must be carefully designed to avoid issues such as excessive heat buildup, which can compromise their integrity over time.

2.1.6 Applications

Non-pneumatic tires (NPTs) hold promise for various applications, each leveraging their unique characteristics to address specific needs. While NPTs are still in the development and research phase for some applications, they have already found their place in a range of industries [2].

Military Applications:
In challenging environments like military and mining operations, where rugged road surfaces and severe impacts compromise the durability of pneumatic tires, NPTs have gained significant attention for their superior load-bearing capacity and endurance at low speeds, enhancing vehicle performance in these demanding conditions. [38].

Aerospace and Lunar Exploration:
NPTs have been used for lunar rovers and space exploration vehicles. Their robust construction and ability to withstand harsh conditions make them a suitable choice for extraterrestrial missions. NASA, for instance, developed superelastic NPTs for lunar exploration. These tires can withstand the challenging lunar terrain and the demanding conditions of space missions. This application showcases the versatility of NPTs in extreme environments [39].

Off-Road Vehicles:
In all-terrain and utility task vehicles, NPTs find applications in agriculture and other off-road industries. Their low-maintenance nature and ability to handle rugged terrains make them ideal for farm equipment and utility vehicles that need to operate in challenging environments [40].

Forklift Vehicles:

Forklifts, commonly used in warehousing and logistics, can benefit from NPTs. The durability and load-bearing capacity of NPTs make them suitable for such industrial applications. These tires are well-suited for environments where punctures and maintenance downtime can be costly [41].

Bicycles:

NPTs have made inroads in the bicycle industry. Companies like Bridgestone and Tannus® Tires have introduced NPTs for bicycles. These airless bicycle tires offer reduced maintenance needs and a longer lifespan, appealing to cyclists who want a hassle-free riding experience [42].

Wheelchairs:

NPTs have been applied in wheelchairs. This application, dating back to 1989, is a testament to the durability and reliability of NPTs. Wheelchair users benefit from tires that require minimal maintenance and offer a smooth ride [43].

Golf Carts and Trailers:

Commercial solutions for golf carts, trailers, and lawnmowers have embraced NPTs. These applications highlight the versatility of NPTs in low-speed, utility vehicles where reliability is crucial [44].

While NPTs are still in the process of development and optimization for some applications, they have already made significant strides in various industries. From military and aerospace applications to off-road vehicles and bicycles, NPTs offer a durable, low-maintenance solution that addresses specific needs in a range of sectors. As technology and materials continue to evolve, NPTs are likely to find even broader applications in the future.

2.2 Additive Manufacturing with TPU

One of the primary advantages of AM lies in its ability to create complex geometries and customized products with reduced material waste. Unlike traditional manufacturing methods, AM doesn't require cutting tools or auxiliary materials, making it a resource-efficient approach. The process also facilitates lightweighting and functional improvements in products, resulting in items that are not only more environmentally friendly but often more cost-effective as well. Furthermore, AM's ability to shorten the manufacturing steps and supply chain can reduce resource expenses related to transportation and storage, contributing to its potential ecological benefits [45]. Recently, thermoplastic polyurethane (TPU) has become increasingly important in various industrial fields, particularly in replacing traditional thermoset elastomers. In the tire industry, TPU materials are favored over rubber for manufacturing high-performance tires due to their good elasticity and thermoplastic processing capabilities [46].

2.2.1 Thermoplastic Polyurethane

Thermoplastic polyurethanes (TPU) is a linear segmented block polymer that undergoes microphase separation due to the thermodynamic incompatibility between their polar hard segments and relatively nonpolar soft segments [47, 48]. The hard segments (HS), typically derived from diisocyanates and small molecule chain extenders (such as diamines or diols), provide good mechanical strength. In contrast, the soft segments (SS), formed by oligomeric diols, offer flexibility and elastic behavior [49, 50].

By adjusting the ratio of soft to hard segments and their structural morphologies, the material properties of TPU can be customized [51]. This customization results in unique performance characteristics, including excellent wear resistance, high tensile strength, good chemical resistance, and machinability.

Additionally, TPU materials offer simple processing technology, low rolling resistance and high mechanical properties. Tires made from TPU materials benefit from low energy consumption, high load capacity, and long service life [46, 52, 53].

An investigation developed between Shandong Linglong Tire and the Beijing University of Chemical Technology led to first 3D printed TPU tire , using FFF, illustrated in figure 2.12 [54].

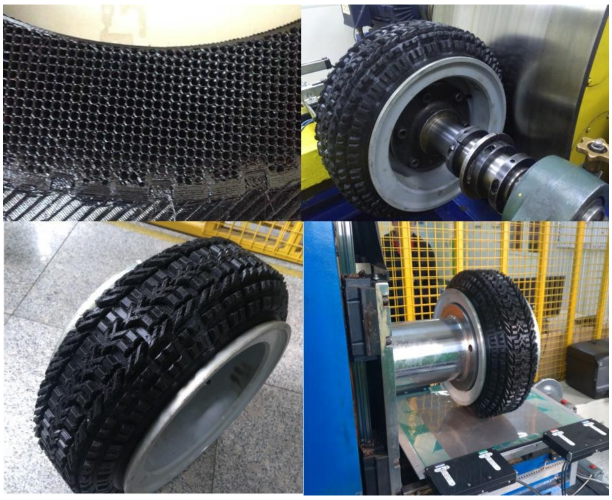


Figure 2.10: China's first 3D printed TPU tyre with FFF - 2017 [54]

2.2.2 TPU in SLS

In a project developed by Zoltan Major, two cylindrical specimen configurations, hollow cylindrical (HC) and bulk notched cylindrical (BNC) specimens, were manufactured in the selective laser sintering process for the polymer TPU [55].

As results, they concluded that the printing orientation induces a distinct anisotropy of the mechanical behavior. This anisotropy is less pronounced for the tensile modulus values and moderate for the yield stress or tensile strength values. The main influence was observed in the failure strain [55].

While the hollow cylindrical specimen represents an ideal uniaxial stress state, a smooth notch (R=1 mm) was introduced in order to generate a weak multi-axial stress state. The influence of the notch is clearly visible in the stress-strain curves of the TPU specimens [55].

The macroscopic stress concentration effect is interacting with the anisotropy effect. The lowest monotonic tensile strength values were observed for notched specimen printed perpendicular to the loading. Somewhat surprisingly, the hollow cylindrical specimens revealed lower fatigue strength values in this printing direction than the notched specimens but with a minor difference.

These values, that are shown in figure 2.11 have shown very unambiguously the effects of the macroscopic stress concentration and the weak interfaces between the layers perpendicular to the loading directions [55].

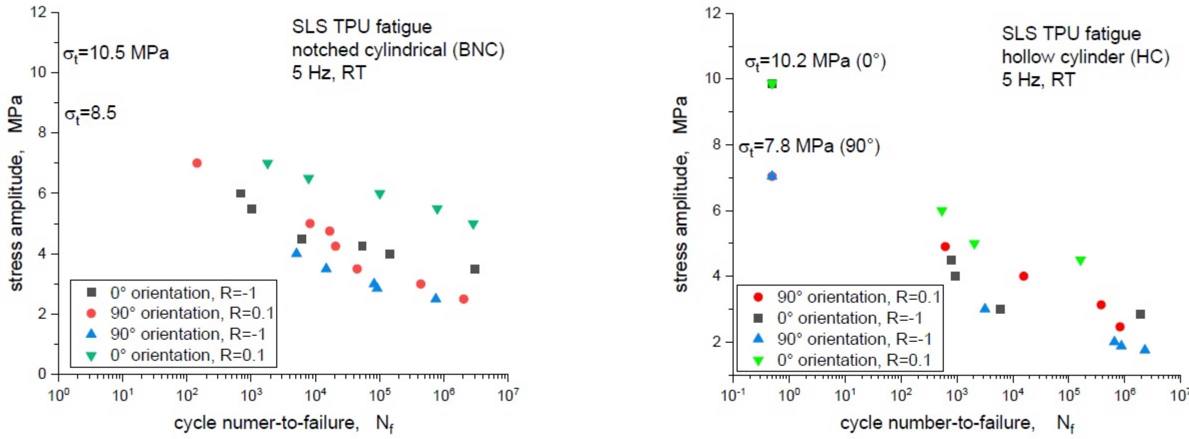


Figure 2.11: Wöhler curves for the SLS TPU material; (a) bulk notched cylindrical specimens (BNC); (b) hollow cylindrical (HC) [55]

2.2.3 TPU in FFF

In a study developed by Jun Wang et al, thermoplastic polyurethane (TPU) materials were used to investigate the impact of FFF, on the performance of non-pneumatic tires. The rheological analysis of TPU materials indicated that as the shear rate increased, the shear viscosity decreased progressively. For the 3D printing process to remain stable within the shear rate range associated with FFF, a minimum printing temperature of 195℃ was required [46].

Comparing the wear resistance of TPU to other common rubber materials, TPU demonstrated significantly better wear resistance than natural rubber (NR), butadiene rubber (BR), and styrene butadiene rubber (SBR). Further analysis of the FFF process parameters revealed that higher infill percentages improved the mechanical performance of the 3D-printed samples. The optimal performance was achieved at a printing temperature of 210℃ with a 100 percent infill rate [46].

In addition, leveraging these optimized FFF process parameters, non-pneumatic tires were successfully manufactured. The three-dimensional stiffness of the printed tires was evaluated, and by adjusting material performance in the simulation, the actual stiffness of the 3D-printed non-pneumatic tire was aligned with the simulation results [46].

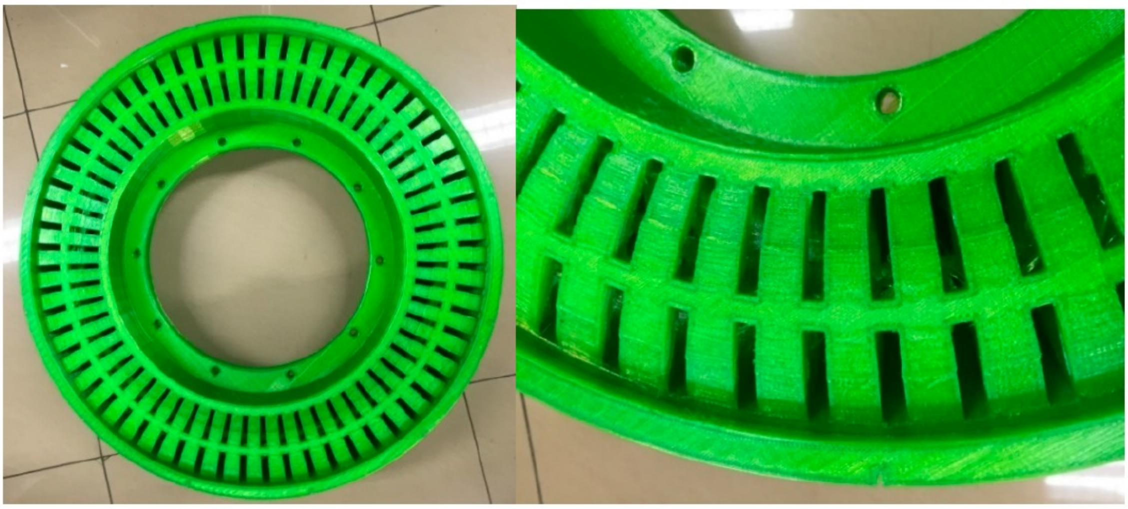


Figure 2.12: FFF NPT based on TPU material by Jun Wang et al. [46]

2.3 Sustainable assessment

The rapid growth of the automobile and transportation industries has led to a significant increase in the number of waste from tires. The accumulation of these waste has resulted in severe environmental pollution worldwide, as the rubber materials, which make up the majority of tires, are not biodegradable or recyclable. In contrast, TPU materials offer a more sustainable alternative, as they can be recycled and reused, significantly reducing the environmental impact of waste produced [46]. When all usefull life is over, TPUs can also be incinerated to recover energy [56].

Not only the choice in more sustainable materials can have a positive impact on the environment, but also the manufacturing process utilized, namely AM.

2.3.1 Ecological performance of AM

Additive Manufacturing (AM), encompassing processes like FFF, holds significant potential for enhancing ecological performance in manufacturing. By fabricating products layer by layer, AM can bring about various benefits, including reduced resource consumption and a diminished cradle-to-gate environmental footprint when compared to traditional manufacturing methods.

Some of the advantages of AM with regard to sustainability encompass lightweighting and functional improvements, which result in products requiring fewer resources and being more environmentally friendly. Additionally, AM processes can eliminate the need for cutting tools, fluids, or auxiliary materials, leading to reduced waste and the opportunity for feedstock reuse, aligning with the principles of a circular economy. Moreover, AM simplifies manufacturing steps and supply chains, which can lower resource costs in terms of transportation and storage [57, 58].

However, there is an ongoing debate about the consistency of AM's ecological benefits, with concerns such as the extra energy required for feedstock production, the continued use of cutting tools and fluids in post-processing, energy inefficiencies in certain AM methods, and the heightened energy demand associated with long build times, which led to the rose of concepts like the eco-design for AM (Eco-DfAM) where ecologic concerns are also take into account [59, 60].

2.3.2 NPTs contribution towards sustainability

The sustainability of NPTs encompasses various aspects throughout their life cycle, from production to end-of-life disposal, making it a significant driver in the development of NPTs with several key considerations.

Firstly, during the production phase, NPTs present opportunities for reduced energy and material consumption, with a optimized design. This is in contrast to traditional pneumatic tires, which have complex manufacturing processes and consume substantial resources. Some tire manufacturers are even exploring the use of recycled materials in NPT production [61]. This approach has the potential to decrease resource exploration, reduce land waste occupation, and minimize emissions associated with both tire manufacturing and disposal.

The environmental impact of conventional PTs, with their susceptibility to punctures and uneven wear due to improper air pressure, results in many tires being discarded prematurely. NPTs aim to address this issue by offering more robust and long-lasting solutions. Kannan P. et al. [61] and Bras B. et al. [14] compared the environmental impact of PTs and NPTs, proving the potential for NPTs to reduce vehicle fuel consumption and, thus, their overall environmental footprint.

NPTs also have an advantage in recycling. The simplicity of the materials used in NPTs, often composed of a single and easily recyclable material like thermoplastic polyurethane (TPU), simplifies the recycling process [62]. This streamlined composition, in contrast to the complexity of PTs, contributes to more efficient resource recovery and reduces the exploration of new resources. Traditional PTs consist of a complex blend of natural and synthetic rubber, steel, carbon black, and various additives, making them economically challenging and complex to recycle. The vulcanization process used to create traditional rubber tires further complicates recycling [63].

Solving the problem of waste tire disposal is crucial for environmental sustainability. Although landfilling and burning tire waste have been banned in many countries due to pollution concerns, they are still the most common method of waste tire disposal [62]. Alternative solutions include using shredded tire rubber in products like rubberized asphalt, concrete, and playground mats [64]. However, these methods are insufficient to address the vast quantities of waste tires generated each year. Promising techniques such as de-vulcanization are still in the early stages of development [62, 64].

Regarding materials, there is also a growing emphasis on biodegradability, emphasized by the small parts of tire structures shed during their operational lifespan, contributing to environmental contamination [65, 66]. Research performed by My HY and Jing X, shows efforts to improve the biodegradability of materials like thermoplastic polyurethane without compromising the mechanical properties [67].

2.3.3 Life Cycle Assessment

Life Cycle Assessment (LCA) has become a critical tool in understanding the environmental implications of manufacturing technologies, especially within the context of AM and, more specifically, FFF. With AM being increasingly recognized for its material efficiency, particularly in comparison to subtractive manufacturing processes, LCA offers a structured way to evaluate the broader environmental impacts across each stage of a product's lifecycle [68]. This chapter will discuss LCA within the context of FFF and the tire industry exploring the main questions raised by previous studies regarding the methods and assumptions that define LCA's role in evaluating AM's and tires sustainability.

LCA for FFF

Methodology

The LCA framework used to evaluate FFF widely adheres to international standards ISO 14040 and ISO 14044, ensuring consistency and comparability across studies. Within these guidelines, LCA for FFF involves several key stages. First, the goal and scope definition phase establishes which part of the FFF process is under analysis, identifying what parts of production (such as material sourcing or transportation) are included. This stage is followed by the life cycle inventory (LCI) phase, which records energy consumption, material input, and emissions output throughout the identified stages. The LCI phase provides critical input for the life cycle impact assessment (LCIA) stage, where environmental impacts are translated into quantitative terms like Global Warming Potential (GWP). Lastly, the interpretation phase synthesizes the data to draw conclusions about FFF's environmental impact (Sola et al., 2024).

Studies using this methodology demonstrate the versatility of LCA in examining various aspects of AM. For example, Tagliaferri et al. used LCA to compare FFF with other AM methods, such as SLS and Multi-Jet Fusion, revealing that different methods entail unique environmental impacts depending on material type and energy consumption [69]. The LCIA step often exposes the energy intensity of AM, a challenge many researchers acknowledge is central to improving AM's overall environmental performance [70].

Equipment and Assumptions

LCA studies on FFF use diverse types of equipment to examine the ecological implications across varying scales and capabilities. Desktop FFF printers, such as the Prusa i3 [71], are often studied for small batch productions due to their accessibility and energy consumption profiles, while larger, industrial-grade systems, like the Arburg freeformer [72], provide data on more intensive manufacturing processes. The chosen equipment greatly influences energy consumption rates, as each printer's heating requirements and power needs vary significantly [73]. The use of energy and assumptions around its source—renewable or fossil-based—are critical in understanding each machine's environmental load. For example, Kreiger and Pearce (2021) demonstrated that switching to a renewable energy mix could considerably reduce FFF's CED (Cumulative Energy Demand) when compared to traditional electricity sources [74].

Various assumptions must also be made to complete LCAs, such as the level of infill required in printed parts, which impacts material use, energy needs, and print time. Garcia et al. (2021) showed that reducing infill decreases the environmental burden by reducing both material consumption and printing energy, but this can only be done when lower structural strength is acceptable [70]. Moreover, LCAs often assume uniform energy consumption across print sessions, even though energy use may fluctuate depending on the material, print orientation, and settings specific to each machine. Such assumptions, though necessary for standardizing data, contribute to the variance in findings across different LCA studies [75].

Key findings

Recent Life Cycle Assessment (LCA) studies highlight several key points regarding the environmental impact of Fused Filament Fabrication (FFF). Energy consumption is a major concern, as FFF requires substantial energy for heating materials and maintaining temperatures, leading to a higher energy demand compared to other additive manufacturing methods [69]. Optimizing energy efficiency and utilizing greener energy sources are essential strategies for reducing FFF's environmental footprint (Sola et al., 2024) [68].

In terms of material efficiency, FFF generates less waste than traditional methods like CNC machining by building objects layer by layer. However, energy-intensive post-processing can offset these benefits [75]. Furthermore, while FFF is well-suited for small batches and complex designs, it is less efficient for high-volume production, where injection molding is superior due to lower energy use per unit [70]. The cost of materials in FFF can also be higher than in traditional processes [73].

To improve sustainability, using bio-based or recycled materials can significantly reduce emissions and enhance waste management. Integrating recycled content into FFF feedstocks supports circular economy goals and can lower the overall environmental impact associated with FFF [68].

LCA for tires

Research in tire life cycle assessment (LCA) reveals several key findings across different stages. In the production phase, tire manufacturing is identified as resource and energy intensive, namely processes like vulcanization, requiring materials such as natural and synthetic rubber, carbon black, and metals. This phase significantly contributes to global warming potential (GWP) and resource depletion. During the use phase, the environmental impact is generally highest due to fuel consumption linked to rolling resistance on automotive industry. As a result, reducing rolling resistance has become a priority for designers aiming to minimize the life-cycle emissions of CO2. When it comes to end-of-life (ELT) management, techniques such as recycling, material recovery, and pyrolysis show notable reductions in environmental impact by reclaiming valuable materials and decreasing waste [76].

In addition to these findings, there are several assumptions common in tire LCA studies that can influence the interpretation of results. Most studies rely on mass-based functional units (FU), like per kilogram or tonne of tires, while some adopt distance-based units, such as per 100,000 kilometers driven [76].

System boundaries are another important factor, Many studies tend to omit transportation impacts because they are considered minor compared to the production and use phases. Furthermore, some studies exclude recycling benefits in their end-of-life analyses, which can affect the overall impact reporting. The use of system expansion for recycled materials is encouraged to accurately reflect the environmental savings gained from incorporating recycled tire content [76].

Figure 2.13 presents a comparison of different models of tires in terms of LCIA results.

Authors (year)	Object	Description of improvement in new models	Life distance (km)	Impact category	Results (old/new)	Unit	System boundary
Saur et al. (1997)	A passenger tires	Silicon dioxide is added to replace carbon black as filler	40,000	GWP	2340/ 2,302#	kg CO_2 eq	Production and use stages
Krömer et al. (1999)	A passenger tire	Substituting silica for part of carbon black as filler	50,000	GWP	623.25/ 564.15	kg CO_2 eq	Whole life cycle except ELT stage
Krömer et al. (1999)	A passenger tire	Substituting polyester for rayon as textile fabric	50,000	GWP	623.25/ 625.17	kg CO_2 eq	Whole life cycle except ELT stage
Bras and Cobert (2011)	A passenger tire	The new model is an airless one-piece wheel-and-tire combination with a rubber tread bonded to a wheel hub with polyurethane spokes	67,620	GWP	533.1/ 520.4	Pt	Whole life cycle
La Rosa et al. (2015)	A tire	Using recycled waste tires in mixture with virgin rubber (75% rate)	–	GWP	3384.4/ 846	kg CO_2 eq	Production stage
Sun et al. (2017)	A passenger tire	Silicon dioxide is added to replace part of the carbon black as filler	60,000	GWP	843/713	kg CO_2 eq	Whole life cycle
Lin et al. (2017)	An electric bicycle tire	Replacing carbon black with graphene (100% rate)	–	GWP	4.56/3.49	kg CO_2 eq	Production stage
Eranki and Landis (2019)	A passenger tire	Replacing natural rubber and synthetic rubber with guayule (100% rate)	112,654–128,748/ 128,748–144,841	GWP	641/564	kg CO_2 eq	Whole life cycle
Lonca et al. (2018)	A truck tire	4% recycled content 10% recycled content	125,000–245,000 116,250–227,850	Ecosystems	−4.60* −4.65*	% %	Whole life cycle except transportation stage

Figure 2.13: Comparison of different tires in terms of LCIA results [76]

Lin et al. studied the environmental impact of replacing carbon black with graphene on a eletric bicycle tire and obtained an improvement for the carbon footprint measured in kg CO2 eq. of 2,07, obtaining a final result of 3,49 kg CO2 eq [77].

Chapter 3

Methodology and Implementation

This chapter presents the overall methodology for this dissertation, along with the materials, equipment and software used to perform both the laboratory experimental procedure and the environmental analysis.

3.1 Overall methodology

The methodology used in this dissertation, present on Figure 3.1, began with the literature review necessary to investigate NPTs comprehensively and understand the sustainability behind NPTs produced by FFF. Then, it was determined the specific type of bicycle for which the case study NPT would be designed.

Figure 3.1: Methodology implemented to approach the dissertation

Furthermore, two main parameters in study were chosen to understand their impact in NPT's sustainability: the number of materials used in a tire (single material or bi-material) and the number of parts that make up a tire (a single one with larger dimensions or several identical parts that are assembled post-production).

Various case study were then produced in the laboratory using FFF and the information regarding energy consumption of the printers, the printed material weight, the residues weight resulting from production and the filament used were measured, as well as the values presented by the printer slicer software, PrusaSlicer 2.8.1.

These values were subsequently applied in the SimaPro model for further analysis and evaluation within the context of the Life Cycle Assessment (LCA). For that, some of the life cycle phases, with the utmost interest to assess, were chosen.

At last, a sensitivity analysis was performed on the LCIA considering different sub-parameters such as the variation of the mass, the variation on the percentage of each material and on the variation of the EoL scenario.

3.2 Identification of bike and NPT

This section provides a detailed overview of the process behind the product concept generation, including the steps and considerations that led to the final case study choices. Additionally, it discusses the assumptions made during the development process, clarifying why certain factors, such as material properties, design constraints, or manufacturing methods, were prioritized over others. By examining these choices and assumptions, this chapter aims to provide a comprehensive understanding of how the product concept evolved and the rationale behind each key decision.

3.2.1 E-bike

In line with the path towards a sustainable future, the tire is assumed to be developed for an electrical bicycle (E-bike), which according to a study performed by Tom McCarran and Nicole Carpenter, can be divided onto 5 different categories [78]. The standard bike also known as ”commuter” bike, is the predominant bicycle that can be found in a city environment and the chosen type for the case study tires. This type of bike is known for its simplicity, characterized by not having a suspension, not having fat tires and having a standard wheel base. Because of these features, the loads to which a commuter e-bike is typically subjected are lower than those encountered by other e-bike categories, such as mountain bikes, fat tire bikes, or cargo bikes, which are designed for more intensive use and higher-impact conditions.

Figure 3.2: Standart/commuter bicycle [79]

The four case study tires have a non-pneumatic design, meaning its performance relies on a combination of its geometry and the materials used.

3.2.2 Non-pneumatic design

Geometry design

The design of the NPT's geometry, especially in the area corresponding to the spokes, will influence the NPT performance, particularly in terms of stifness. From the environmental impact and LCA study perspective, the design of the geometry influences 2 stages in the LCA: the Product Stage, which is impacted by the mass inputs and the Use stage, by influencing the performance and maintenance required for the tire.

However, regarding the Use Stage, the FFF NPT is assumed to have a lifespan comparable to that of a standard pneumatic bicycle tire. Although this assumption may not be 100% correct, determining its validity requires comprehensive material characterization and extensive product testing. Consequently, this assumption implies that if the lifespan of the tire is half that of a conventional pneumatic tire (PT), the associated impact and cost values would effectively double. Conversely, if the tire is expected to last twice as long as a PT, the final calculated impact or product cost would be halved. To address uncertainties surrounding durability, this study seeks to remove lifespan and maintenance considerations from the overall assessment and therefore, leaving the use phase of the product out of the scope of the project.

Since the use stage is outside the scope of the project, the design of the geometry depends exclusively on the mass of the chosen geometry.

With this in mind, it is essential to understand the impact of different geometries on the final mass and for that, four different geometries, based on the work of Tomé [80], were printed and can be seen in Figure 3.3.

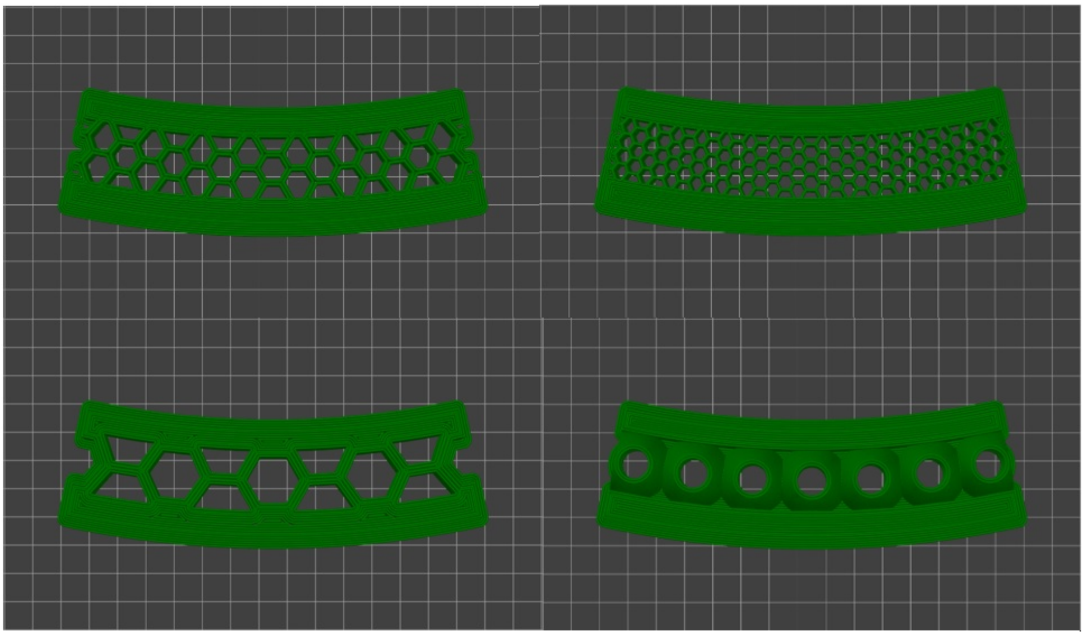


Figure 3.3: Different geometries printed: top left - Geometry A, top right - Geometry B, bottom left - Geometry C and bottom right - Geometry D

The corresponding mass for each geometry provided by PrusaSlicer 2.8.1. is presented in Table 3.1, as well as the average value and the standard deviation.

Geometry	Part Mass (g)
A	109,60
B	115,52
C	108,82
D	112,78
Average Value	111,68
Standart deviation	2,67

Table 3.1: Mass obtained from PrusaSlicer 2.8.1 for each geometries

Since the value obtained for the standard deviation has a corresponding percentage value of 2,39%, it is reasonable to conclude that the design of the geometry has a meaningless impact on the LCA results.

Materials

Thermoplastic Polyurethane

Given the large deformations expected in some features of the tire, the primary material used is an elastomer, which can endure significant deformation without major changes to its internal structure. Specifically, a thermoplastic elastomer like TPU is chosen due to its compatibility with the FFF method.

TPU offers a combination of excellent wear resistance, high tensile strength, and good chemical resistance, making it an ideal material for tires that must withstand rigorous conditions. Its properties ensure that tires made from TPU not only deliver superior elasticity and durability but also benefit from low rolling resistance, high load capacity, and long service life, making it a preferred material in the tire industry over traditional rubber. Additionally, TPU's thermoplastic nature facilitates easier processing and recycling, further enhancing its suitability.

The TPU utilized for manufacturing the NPT case studies was Flexfill TPU 92A, from fillamentum [81], shown in figure 3.4.

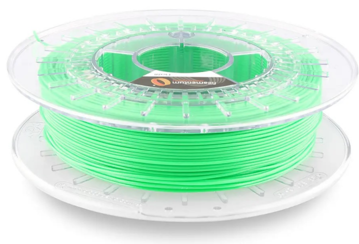


Figure 3.4: Fillment spoll of TPU92A from fillamentum [81]

Since the material data sheet did not present energy recycling values, its properties shown in table 3.2 were considered for later comparison with the properties of different TPU variants present in Ansys

Granta Material Data software [82], where the same energy recycling values are presented.

Flexfill TPU 92A properties	Typical Value	Test Method	Test Condition
Material density	1, 20 g/cm3	ISO1183 1	-
Tensile strength	49MPa	DIN 53504	at break
Tensile stress	7, 5MPa	DIN 53504	100% elongation
	16MPa	DIN 53504	300% elongation
Hardness	92 Shore A	ISO 7619	-
	22 Shore D	ISO 7619	-
Tear strength	85kN/m	ISO 34-1	
Elongation at break	600%	DIN 53504	-
Abrasion	30 mm	ISO 4649	-

Table 3.2: Flexfill TPU 92A properties obtained from the material data sheet [81]

The correspondent material in Ansys Granta Material Data software [82] with the same properties than the one from fillamentum, and from which the energy recycling values were considered is named TPU (Ester, aromatic, Shore A70).

Polylactic Acid

The secondary material was selected based on three main guiding criteria. The first criterion, focused on sustainability, aimed to ensure that the material chosen would positively contribute to the overall sustainability of the bi-material NPT tire. The second criterion was to identify a material that through its distinct properties from TPU, could potentially enhance the mechanical properties of the tire, improving its performance. Lastly, the third criterion emphasized compatibility with TPU to support the viability of the bi-material tire design.

Having said criteria in mind, the chosen material to compose the bi-material tire alongside with TPU was the polylactic acid, PLA.

PLA is known for being a more sustainable material compared to TPU, as it is biodegradable and produced from renewable sources [82]. Additionally, it's life cycle has a lower environmental impact, with reduced CO2 emissions and better performance in terms of recycling and composting, making PLA an eco-conscious choice for the project [56].

PLA also offers superior stifness compared to TPU, as shown by the values of elastic modulus (E) in table 3.3, making it suitable for the area of the tire that requires most dimensional precision and strength, such as the contact zone with the interior rim mounting area, as it is evidenced in the example of figure 3.5, with PLA assuming a blue color. TPU, on the other hand, can be used in the areas that demand more flexibility and elasticity like the spoke area and the shear band area, thus balancing the properties of both materials for optimal performance [56] [83] [84] [85].

	PLA	TPU
σ (uts)	58 MPa	49 MPa
E	**3,5 GPa**	0,06 GPa
ξ	3,6%	**600%**

Table 3.3: TPU and PLA Mechanical properties [81] [82]

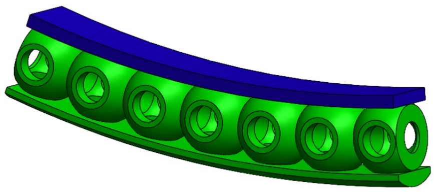


Figure 3.5: Tire modular part with PLA (blue) on mounting rim area and TPU (green) on the spoke and shear band area

Complying with the third criteria, previous studies have already demonstrated the viability of PLA and TPU combinations in bi-material structures, as highlighted in the article published by Alicja Zur. et. al. In the article, the combination of PLA and TPU has proven effective across various geometries and applications, showcasing the proven compatibility between the two materials, which provides confidence in this choice for the project [85].

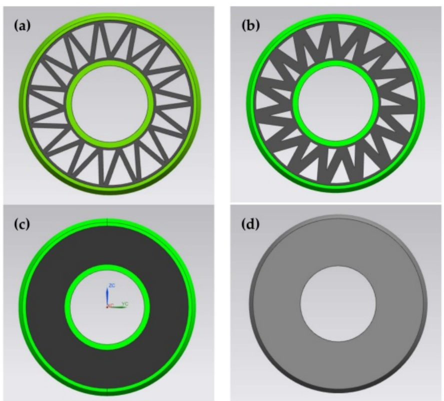


Figure 3.6: TPU (grey) - PLA (green) structures studied by Alicja Zur. et. al. [85]

These three factors justify the combined use of PLA and TPU, ensuring a balance between sustainability, mechanical performance, and compatibility.

Fused Filament Fabrication

At the laboratory, single material TPU NPT case studies were manufactured with FFF in two different 3D printing machines.

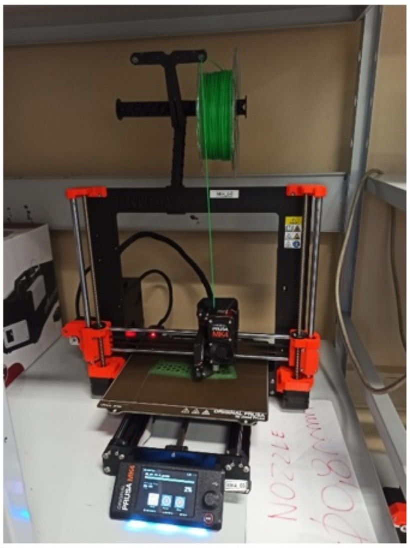
The first one, an industrial printer shown in figure 3.7 a), was utilized for the production of a single piece tire, that was possible given its capability of printing single piece prototypes up to 1,2 x 1,0 x 0,7m [86]. The industrial printer specifications are also presented in figure 3.7 b).

Industrial Printer	Specifications
Build Volume	1.2 × 1.0 × 0.7m
Print heads	6
Build Platforms	3
Printer Dimensions	1.2 × 1.2 × 0.7m

a) b)

Figure 3.7: a) Industrail 3D printing machine b) 3D Printing machine specifications [86]

The second printing machine is a Prusa MK4 shown in figure 3.8 a), utilized to produce a NPT divided in multiple modular sections that are assembled post production, resulting on the final NPT. The Prusa MK4 specifications are illustrated in figure 3.8 b).



Prusa MK4	Specifications
Build Volume	250 × 210 × 220 mm
Filament diameter	1.75 mm
Layer height	0.05 - 0.30 mm
Max nozzle temperature	290ºC
Max heatbed temperature	120ºC
Power consumption	80 - 120 W
Printer dimensions	500 × 550 × 400 mm

a) b)

Figure 3.8: a) Prusa MK4 printing machine b) Prusa MK4 machine specifications [87]

The two 3D printers consume electricity primarily for three functions: powering electronics, driving motors, and generating heat through heating elements. The electronics, which include LEDs, sensors, and other components, consume minimal energy and represent the machine's idle or baseline consumption. The motors, responsible for the primary movements of the x, y, and z axes and the extruder, use energy to drive these parts during the printing process. Finally, the most significant energy expenditure comes from the heating elements, which include the heated bed that maintains a stable temperature and the extruder that supplies the thermal energy needed to melt and shape the polymer [88] [89].

One of the variables that affects the energy consumption for heating elements, both the nozzle and the build plate, is the material being printed. Each material has specific printing conditions suited to its composition, which optimize the printing performance. The optimum values for PLA and TPU are presented in Table 3.4.

	TPU	PLA
Nozzle Temperature	220-240	210-230
Build Plate Temprerature	50-60	50-60

Table 3.4: Nozzle and Build Plate temperatures for TPU and PLA [81] [90]

Since the temperature range for ideal printing conditions is the same for both materials, the energy spent for the heating elements is assumed to be the same for both materials.

3.3 Identification of main parameters in study

During the research process two key variables with an important impact on the sustainability of the NPT were identified and this chapter will cover them.

The first variable examines the potential impact of employing a bi-material approach, as opposed to utilizing a single material throughout the tire. This inquiry arose from the hypothesis that combining two materials could potentially enhance the tire's performance and resource efficiency.

The second variable explores the possibility of manufacturing the NPT multiple identical parts, so that it can be printed in a regular size commercial 3D printing machine and the implications of modular production. Specifically, the study of this parameter seeks to understand how modularity might affect factors such as material waste and ease of recycling.

The study of these two main variables is then followed by sensitivity analysis on different parameters, from varying the mass to varying the EoL, with the objective to provide a deeper understanding of how design decisions can influence the tire's sustainability, contributing to more informed material and manufacturing strategies.

Single material or Multi Material

A single-material tire represents the most straightforward approach and serves as the baseline for energy consumption measurements in this study. The idea of developing a tire made of a bi-material unveils countless possibilities for improving the tire performance by tailoring material properties for specific functions and enhancing features that with only a single material cannot be achieved. Not only it brings advantages to the tire Use stage performance but also for the tire Production stage, since the FFF post processing surface treatment of the tire can be improved if the material chosen for the print supports (like the skirt or brim approach) differs from the one utilized for the part printed.

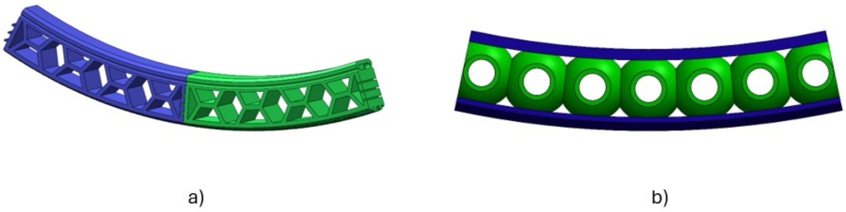


Figure 3.9: Different structural material hypothesis/combinations

However, processing a bi-material on the EoL stage may be followed by adversities regarding the separation of materials and the study of this variable seeks to understand how it impacts the final LCA results. While the machines used in the energy analysis are only capable of processing one material at a time, it is important to highlight that energy consumption during production is likely to remain consistent across different materials, as explained in chapter 3.2.2.

Single piece or Multi Piece

The second main parameter delves in the possibility of printing the tire in modular parts that are assembled post production. This scenario implies a post-production assembly process that wont be addressed in this study. On the other hand, producing a tire in smaller modular parts opens the possibility of printing a NPT tire in a "regular" printer which is within the reach of a greater number of people given the recent commercialization of 3D printing machines.

Not only becomes accessible to more people but it also brings numerous advantages on the Production Stage by substantially saving material, time and energy whenever a print fail happens. Printing failure is a phenomenon associated with FFF and as several different causes such as layer shift, detachment from the build plate, under or over extrusion, warping, among others.

Although print failures were not considered for the LCA analysis due to the difficulty in parameterizing the percentage of print failures that are likely to occur, the probability of them occurring associated with the potential gains from reducing their negative impact, since the modular part has a fraction of the full tire material, cannot be disregarded.

Ultimately, the study of this parameter will seek to determine whether the multi-piece approach offers tangible benefits in terms of energy efficiency and its contribuition to sustainability.

3.4 Life Cycle Assessment Methodology

LCA is an efficient and comprehensive tool to estimate the life cycle environmental impacts of products and services [91]. Life Cycle Assessment (LCA) can be applied across the entire life cycle of a product. This begins with the extraction of raw materials, followed by their transportation, processing, manufacturing, and the transportation of the finished product, as shown in Figure 3.10. It also includes the product's use and later disposal, completing what is known as the cradle-to-grave approach. Alternatively, cradle-to-gate is another approach that covers the stages from raw material extraction to product manufacturing and was utilized in chapter 4.5.3 to compare the carbon footprint values obtained in the case studies with literature values. The last approach is called gate-to-gate and focuses solely on a single stage. It was utilized in chapter 4.3.2 to comprehend the EoL results [92].

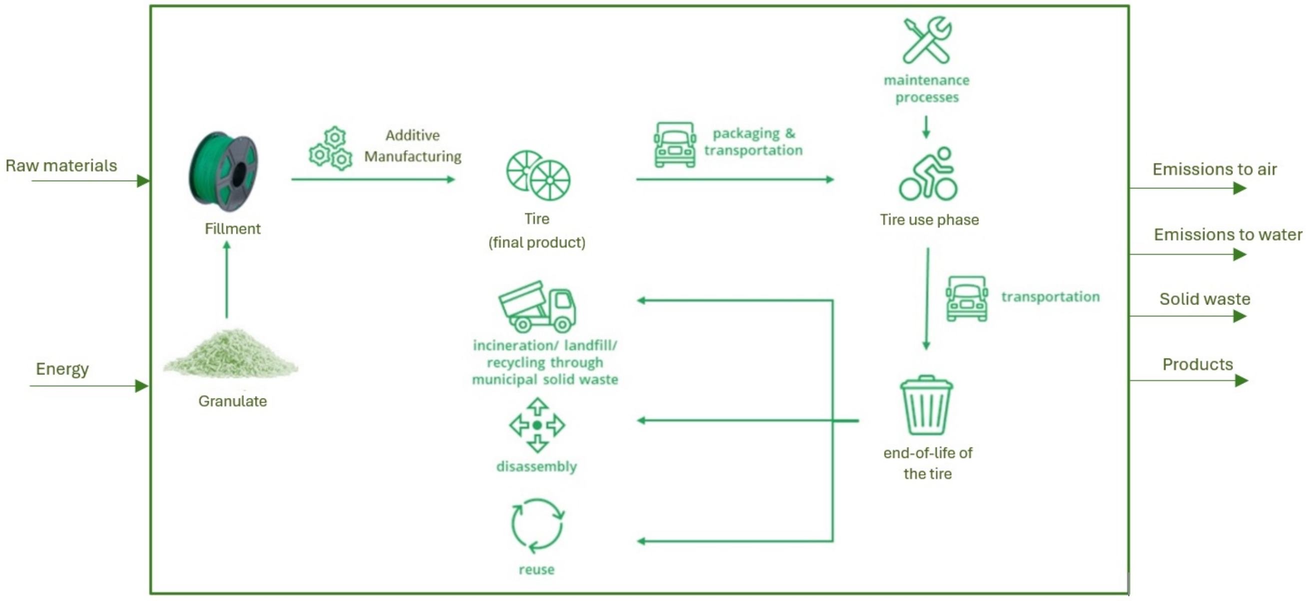


Figure 3.10: Whole life cycle of the bicycle NPT with boundary as indicated by outer dark solid line (adapted from [93])

This dissertation follows the International Organization for Standardization (ISO) 14040 and 14044 standards, which recommends a framework with four stages to implement the LCA method, as presented in Figure 3.11 [94]. In addition, the LCA was performed using the SimaPro v9.6 software and the Ecoinvent database.

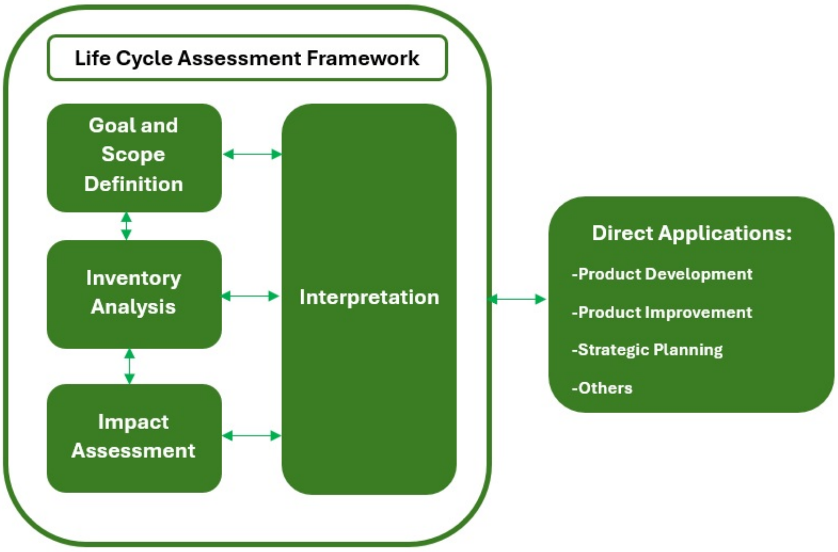


Figure 3.11: Methodology implemented for LCA according to ISO 14040 and 14044 (adapted from [94])

In the first stage, goal and scope definition, it is essential to establish several key elements, including the goal and purpose, system boundaries, target audience, functional unit, reference flow, and the type of environmental impacts to be analyzed [95].

The second stage, inventory analysis, also known as life cycle inventory, involves gathering data and quantifying the inputs and outputs associated with a product throughout its life cycle, in a process used in SimaPro which is described in Figure 3.12 [93]. The inventory utilized contained fundamentally data obtained directly from the literature, from the experimental setup and from Ecoinvent library.

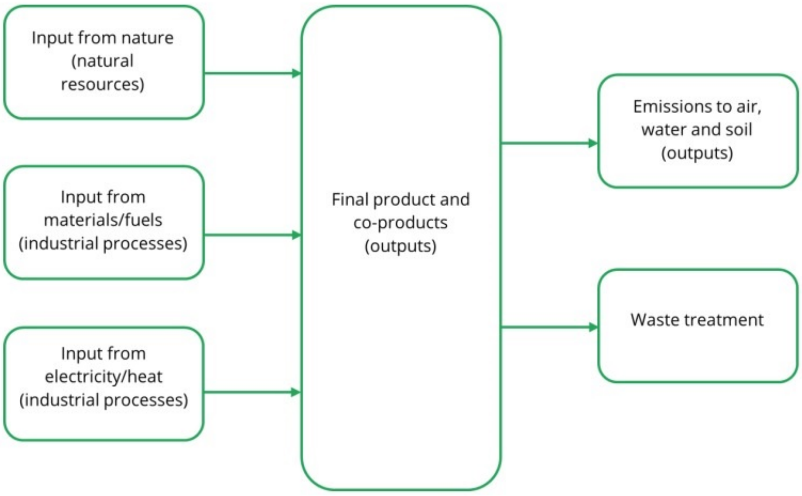


Figure 3.12: SimaPro inventory processes [93]

The impact assessment phase, or life cycle impact assessment, translates the data from the previous stage into potential environmental impacts and estimates the resources utilized. This phase follows the methodology outlined in Figure 3.13, beginning with the selection of impact categories, followed by classification and characterization [96].

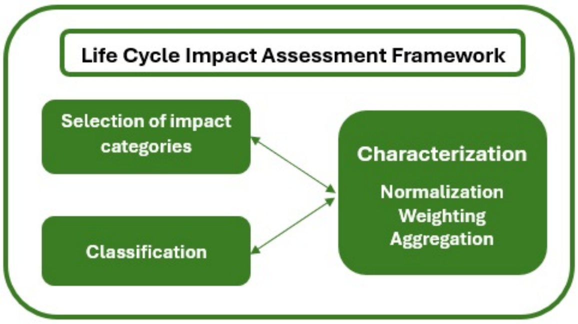


Figure 3.13: Methodology implemented for the impact assessment (adapted from [95])

In the classification step, inputs and outputs are assigned to the selected impact categories [94], while in the characterization step, results are converted into indicator outcomes.

The ReCiPe 2016 impact assessment method was used in this study. ReCiPe 2016 consists of two sets of impact categories: midpoint, by categorizing impacts by specific environmental concerns (problem-oriented) and endpoint, that focuses on overall damage by classifying impacts into broader categories (damage-oriented). Midpoint and endpoint are both available in three perspectives: individualist (I), hierarchist (H), the one used in this dissertation, and egalitarian (E). [93, 94]

At the midpoint level, 18 impact categories are addressed. At the endpoint level, most of these midpoint categories are multiplied by damage factors and aggregated into three endpoint categories: Human Health (HH), Ecosystems (EC), and Resources (RS), illustrated in the figure 3.14 [97].

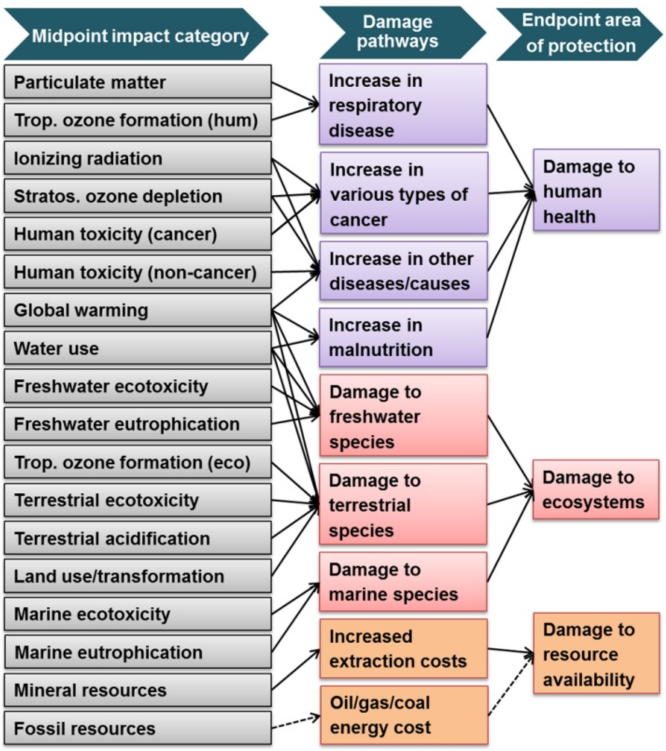


Figure 3.14: Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection [97]

The ReCiPe Midpoint (H) V1.13/Europe Recipe H was chosen to compute 18 impact categories, while the ReCiPe Endpoint (H) V1.13/Europe ReCiPe H was chosen to consolidate these into the three endpoint categories.

This process results in normalized, weighted, and aggregated scores for each endpoint and lastly, the interpretation phase involves analyzing the previously determined results, including insights on environmental impacts, potential improvements, and other considerations [95, 98].

Chapter 4

Life Cycle Assessment

In this chapter four case studies will be introduced with their respective experimental setup, analyzed and discussed through sensitivity analysis, in order to understand how the two main variables impact the tires life cycle.

4.1 Case study: Single Material and Single Piece

4.1.1 Experimental Setup

The tire and corresponding structure, illustrated in Figure 4.1, was produced by fused filament fabrication and the build orientation chosen for the tire was lying flat on the build plate.

Figure 4.1: a) Single Piece and Single Material Tire b) corresponding structure

When considering tire sizes, it is essential to evaluate scenarios with mass and energy ranges that encompass the majority of bicycle tires. For the purpose of the analysis, this study will focus on a commuter bike tire with a mass of 0.9 kg, serving as a representative case for assessment tasks, but further analysis will approach scenarios with different masses. The considered baseline value of 900 grams utilized for the case studies is an average value of the mass of the different prints produced, that were estimated by the software PrusaSlicer 2.8.1.

A detailed analysis of the bicycle tire market reveals that a commuter bicycle tire weights typically range from 700 to 1200 grams, as evidenced by the company LIGHT BICYCLE [99], showing values that are in-line with the average mass value chosen for the case studies. Despite the fact that such tires do not fit under the NPT category, it is important that the value utilized for the case studies belongs to the same range of values, so that the impact of other variables such as the materials chosen or the production method may be analysed. This approach allows a more comprehensive evaluation of the two main variables impacting the tire sustainability.

In addition, Table 4.1 presents some considerations regarding dimensions, mass and material.

Tire specifications	Values
Outer diameter	700 mm
Inner diameter	622 mm
Thickness	21 mm
Mass	900 g
Material	Flexfill TPU 92A fillament

Table 4.1: Tire components considerations for the SM and SP case study

The processes considered to manufacture this component, are presented in Figure 4.2. The manufacturing stage plan included two steps, material extrusion where TPU granulate is transformed into TPU filament and fused filament fabrication where the tire is produced.

Figure 4.2: Processes considered for manufacturing stage

Since the extrusion process was not conducted in the laboratory, the values obtained for the energy consumption of the extruder machine were taken from Filastruder data sheet [100]. The extruder machine and its specifications are illustrated in figure 4.3.

a) b)

Figure 4.3: a) Filastruder extrusion machine b) Filastruder specifications [100]

For the fused filament fabrication, the large scale printer shown in Figure 3.7 in chapter 3.2.2 was utilized and the instant power was measured while a tire with a mass of 0.8 kg was printed. The measured values can be seen in figure 4.4.

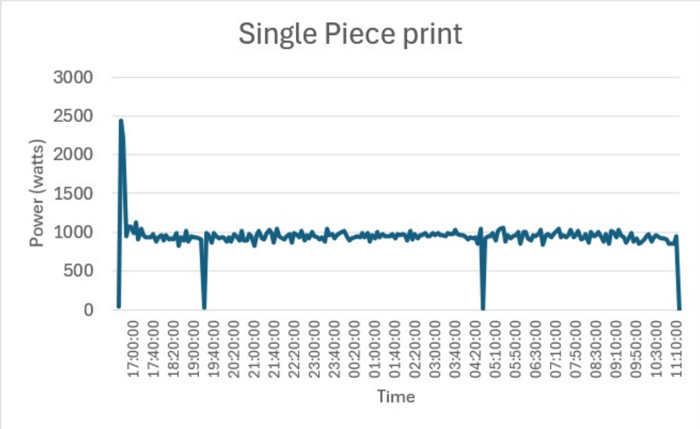


Figure 4.4: Energy consumption for the Large scale Printer

With the values measured, it is possible to obtain the average power output, and multiplying it by the time the print took, the energy consumption for printing a 0.8 kg tire is obtained. At last, considering the case study tire has a mass of 0.9 kg, the energy consumption value for the case study is obtained.

Average power output	944,02 W
Time	19h30min
Energy consumption 0,8 kg tire	18,4 kWh
Energy consumption 0,9 kg tire	20,7094 kWh

Table 4.2: Energy consumption for the single tire piece print

To perform the environmental analysis, in section 4.1.2, the phases considered were the raw material phase, the manufacturing phase and EoL phase.

4.1.2 Life Cycle Assessment

Goal and scope definition

The goal is to analyse and comprehend the environmental impact in the life cycle of a bicycle NPT of two main variables in study, the number of parts and the number of materials that compose the tire. The functional unit for comparison is a tire.

In Figure 4.5, the LCA scheme presents the cradle-to-grave system boundary selected for the environmental assessment. The life cycle stages considered for the NPT tire were raw material, manufacturing (extrusion and FFF), and recycling as the EoL scenario.

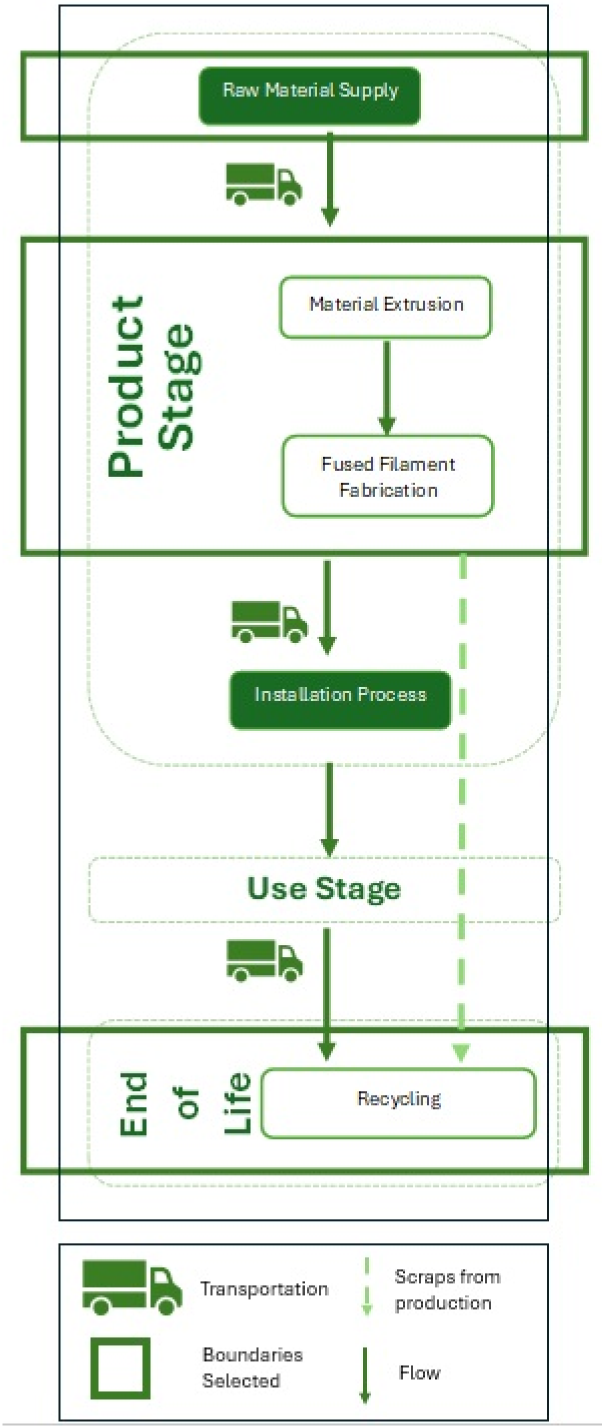


Figure 4.5: System selected for the tire case study environmental analysis

On the product stage, the value considered for the scraps of production were all attributed to the FFF method, resulting in a 0% waste from the extrusion process. The value of 0,7% attributed to the waste in the FFF manufacture technique was obtained directly from the printing software and correspond to the supports, in particular brim/skirt, as it can be seen is figure 4.6. As mentioned in chapter 3.2.2 the print fails, which are a phenomenon that happens with frequency were not take into account on this LCA study.

Figure 4.6: Skirt/Brim percentage attributed to waste in production

It is also important to highlight that, as stated and justified in chapter 3.2.2, the use stage is out of the scope of the project.

Additionally, the transportation stages were negligible, with the associated impact being significantly reduced when compared with the other phases and keeping in mind the that local of production is thought to be the home of the user.

In terms of EoL, TPU is a recyclable material but its reuse incurs certain trade-offs. The material may degrade, resulting in altered properties such as reduced strength and shorter service life.

Since TPU is a recyclable material, a percentage of 90% was considered for recycling, giving a 10% margin for TPU that is not in conditions to be recycled and therefore is considered for incineration.

Inventory analysis

Figure 4.7 presents in detail, the inventory considered to perform the LCA, with data collected from the literature.

		Processes and materials	Ecoinvent	Value	Unit	Ref
Product Stage	Raw material	Thermoplastic Polyurethane	Polyether polyols, short chain {RER}| market for polyether polyols, short chain | APOS, U	0,460	[Kg]	[103]
			Methylene diphenyl diisocyanate {RER}| market for methylene diphenyl diisocyanate | APOS, U	0,2903	[Kg]	[103]
			1,4-butanediol {GLO}| market for 1,4-butanediol | APOS, U	0,154	[Kg]	[103]
		Thermoplastic Polyurethane granulate processing energy	Electricity, medium voltage {GLO} market group for | APOS, U	0,194	[kWh]	[101]
	Manufacturing	Extrusion	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	0,7	[kWh]	[100]
		Fused Filament Fabrication	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	20,7094	[kWh]	a)
			Recycling Thermoplastic Polyurethane, scraps from production, {PT} market for recycle Thermoplastic polyurethane | APOS, U	0,0063	[Kg]	[82]
EoL		Recycling	Electricity, medium voltage {GLO} market group for | APOS, U	11,00	[kWh]	[82]
		Incineration	Waste polyurethane {GLO}| treatment of waste polyurethane, Incineration | APOS U	-	-	[101]

Figure 4.7: Stages and processes from the Ecoinvent v3.10 database for the NPT SP SM and a) Obtained from Experimental procedure [101]

TPU is not available in the Ecoinvent database and was created considering the chemical composition of the materials and the energy values for the corresponding structure. Since polyurethane was present on the library, and TPU belongs to a family of PU, PU was used has a model material to create TPU. PU is formed by a reaction between an isocyanate prepolymer (which is a diisocyanate) and a polyol (also called long-chain diol), the two materials already presented on Simapro Ecoinvent library under the names ”Methylene diphenyl diisocyanate” and ”Polyether polyols”, respectively [102] [103] [104] [105].

The difference between PU and TPU lies on the chain extender or short-chain diol, a third element that integrates the composition of TPU and that is not present on PU. The proportions between polyol (long-chain diol) and the chain extender (short-chain diol) vary and influence the shore value of the final TPU, with the chain extender assuming values in the 5% to 20% interval, while the polyol takes most of the composition with values between 40% and 60%, and at last the diisocyanat has between 30% to 40% of the composition [102] [103] [104] [105].

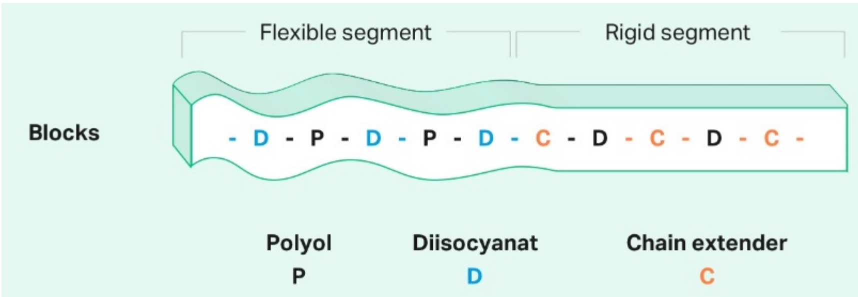


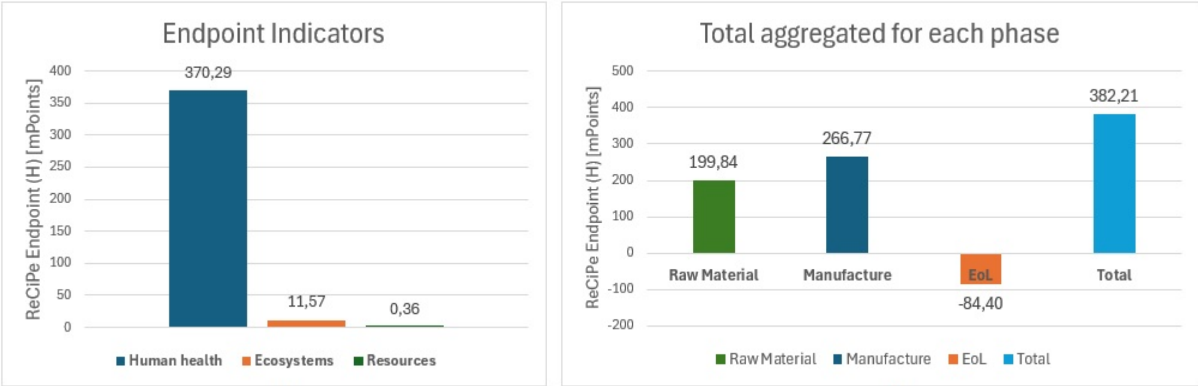
Figure 4.8: TPU chemical composition [105]

The SimaPro software libraries only provide polyurethane in the form of rigid foam, adhesive, or flexible foam. Since the granulate form needed for the manufacturing procedures is not available, it is necessary to create it. In order to do so, another plastic material in the form of granulate, present on the Simapro library, was considered. Polylactic acid, PLA, was the chosen material to obtain the values for the energy consumption utilized to produce the material in the granulate form, since they share common properties, derived the fact that both of them are thermoplastic materials. The values for the processing of TPU in the granulate form, were then approximate by values obtained from PLA in the granulate form.

Regarding the processes included in LCA, when not available in Ecoinvent, they were assessed by considering mainly energy. Lastly, the values used in the production processes, take into consideration the material manufactured and in the End of Life phase, it was considered a recycling rate of 90% for TPU.

Impact assessment and interpretation

For the system boundary selected, Figure 4.9 (a) and Figure 4.9 (b) present the environmental impact of a single piece TPU NPT, for each of the endpoint categories (HH, EC, RS) and as a total (aggregated) for each step, respectively.



a) b)

Figure 4.9: Single Piece and Single Material (SP SM) case study ReCiPe Endpoint analysis

The results show that the Endpoint indicator with highest contribution to the overall score of 382 mPoints is the Human health with a contribution of 96,88%, followed by the Ecosystems indicator with 3,02% and the remaining 0.09% for the Resources.

Figure 4.9 b) presents the contribution of all the processes considered within the system boundaries and their impact on the final Total result. Manufacture stage leads the highest value with a contribution of 266 mPoints, followed by the Raw materials contribution of 199 for a total of 466. The EoL chosen had a relevant impact on the final value since recycling provides a negative impact, managing to settle the total value at 382 mPoints. In chapter 4.3.2, different EoL scenarios will be studied with some adding more points to the final value in contrast with recycling where they get subtracted.

For the midpoint analysis, the results are presented in Table 4.3.

Impact cathegory	Units	Total	Pruduction Stage	EoL Stage
Global warming	kg CO2 eq	8,75	10,30	-1,55
Stratospheric ozone depletion	kg CFC11 eq	0,00	0,00	0,00
Ionizing radiation	kBq Co-60 eq	1,15	1,33	-0,18
Ozone formation, Human health	kg NOx eq	0,02	0,02	0,00
Fine particulate matter formation	kg PM2.5 eq	0,01	0,01	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,03	0,02	0,00
Terrestrial acidification	kg SO2 eq	0,03	0,04	-0,01
Freshwater eutrophication	kg P eq	0,00	0,00	0,00
Marine eutrophication	kg N eq	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	72,92	100,11	-27,19
Freshwater ecotoxicity	kg 1,4-DCB	0,92	1,11	-0,20
Marine ecotoxicity	kg 1,4-DCB	1,20	1,47	-0,28
Human carcinogenic toxicity	kg 1,4-DCB	1,22	1,79	-0,56
Human non-carcinogenic toxicity	kg 1,4-DCB	9,95	14,09	-4,14
Land use	m2a crop eq	0,50	0,64	-0,14
Mineral resource scarcity	kg Cu eq	0,03	0,05	-0,02
Fossil resource scarcity	kg oil eq	0,54	0,63	-0,09
Water consumption	m3	0,15	0,17	-0,02

Table 4.3: Single Piece and Single Material (SP SM) case study ReCiPe Midpoint analysis

At last, the product carbon footprint of the Single Piece and Single Material (SP SM) NPT, measured in kg CO2 eq./tire registered an impact of 8,75.

Mass variation study

The effect of mass variation on the sustainability of NPTs is an important consideration in the tire design. While weight may not be the most critical factor for commuter bicycles, which prioritize service life and reliability, it still influences several key aspects of tire such as durability and energy efficiency.

To understand the impact of the mass variation, five scenarios were built for the first case study, Single Material and Single Piece, that are presented on table 4.4:

Mass (Kg)	Waste (0,7%)	Energy Consumption kWh (extruder)	Energy Consumption kWh (printer)
1,1	0,0077	0,8556	25,31
0,9 (5.1 SP SM)	0,0063	0,7	20,71
0,7	0,0049	0,5444	16,11
0,5	0,0035	0,3888	11,51
0,3	0,0021	0,2333	6,90

Table 4.4: Inventary for the mass scenarios conducted

Although the variables and assumptions made for case study 4.1 were all maintained in order to be possible to compare it with these mass scenarios, it is important to mention that the energy values for the extruder and for the 3d printing machine were calculated based on the average consumption energy value of each machine, respectively.

The results from the LCIA obtained are shown in figure 4.10 and detailed in table 4.5.

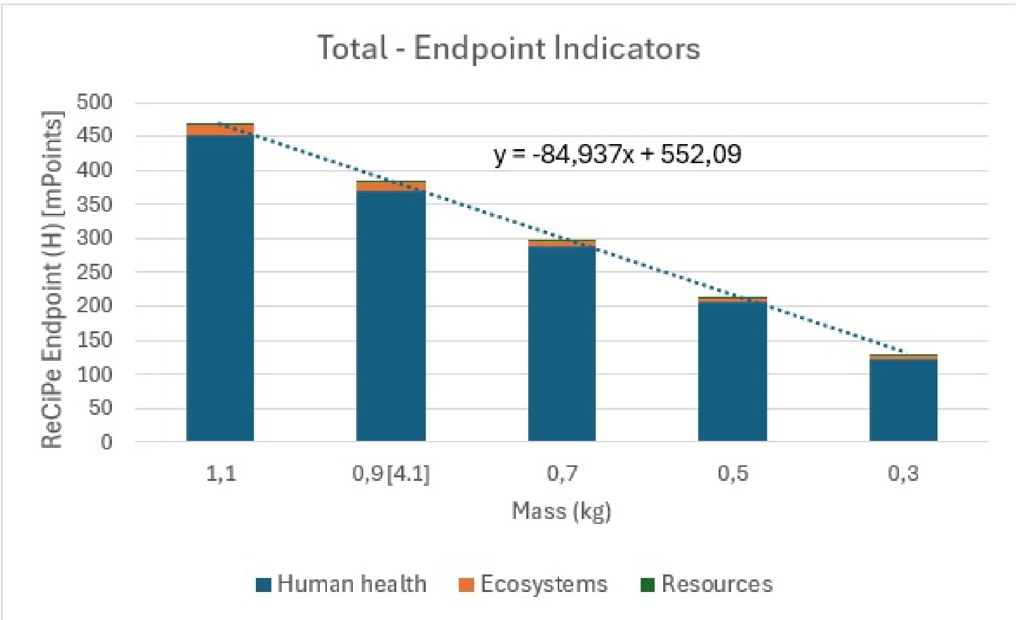


Figure 4.10: ReCiPe Endpoint results on different mass scenarios

Mass kg	Total mPoints	Human health	Ecosystems	Resources
1,1	467,15	452,57	14,13	0,44
0,9 [4.1]	382,21	370,28	11,56	0,36
0,7	297,27	288,00	8,99	0,27
0,5	212,34	205,71	6,42	0,19
0,3	127,40	123,42	3,85	0,12

Table 4.5: ReCiPe Endpoint results on different mass scenarios

To understand the results, it is essential to emphasize that the input parameters used were proportional across all different scenarios, as shown in table 4.5.

The results ended up reflecting a proportional relationship between mass and the ReCiPe Endpoint results, confirming that optimizing the structure and design of the tire by reducing the mass, leads to a lower impact on human health, ecosystems, and resources. Scenario with 0.3 kg, which features the lowest mass, proves to be the most sustainable option. On the other hand, Scenario with 1,1 kg, with a mass that is 3.66 times greater, exhibits the highest environmental impact, with a total sum of endpoint indicators also 3.66 times larger. This confirms the linearity in the results, which can be described by the equation 4.1.

$$y = -84,9x + 552,09 \tag{4.1}$$

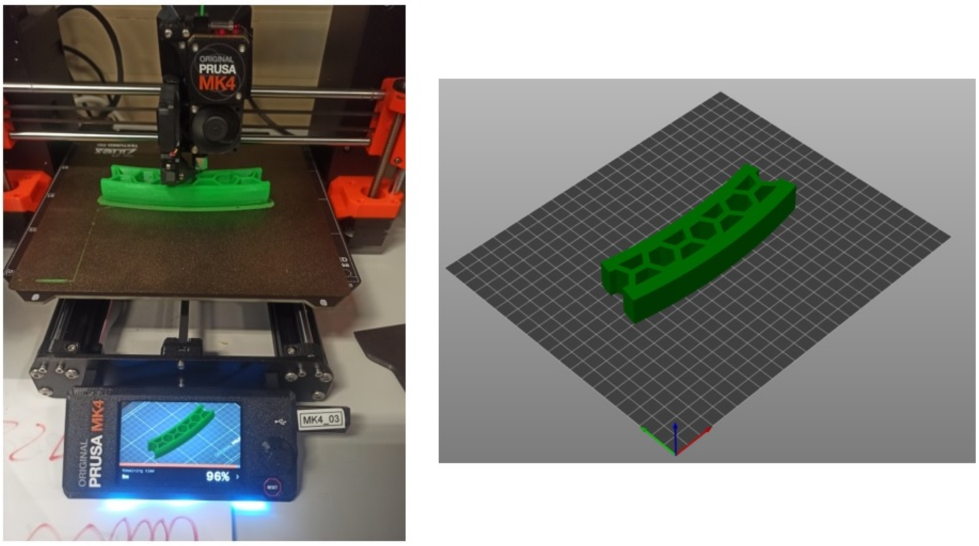
In summary, the proportional linear relationship indicates that for the material considered, TPU, the impact on Human health, Ecosystems and Resources behaves linearly with the mass.

4.2 Case study: Single Material and Multi Piece

4.2.1 Experimental Setup

This case study delves into the scenario where a tire is divided in 15 modular parts and one single part was studied. That tire part, illustrated in Figure 4.11 a), was produced by fused filament fabrication and the build orientation chosen was the same utilized on the previous case study, which was was lying flat on the bed (build plate). In addition, Table 4.6 presents some considerations regarding dimensions, mass, material and rim type.

At last, the results obtained from the LCIA were multiplied by 15 to simulate the values of the production of a full tire and for later comparison to case study 4.1.



a) b)

Figure 4.11: Single Piece and Single Material - Tire part being manufactured

Tire part length	146,60 mm
Tire part width	78 mm
Tire part height	21 mm
Mass	60 g
Material	Flexfill TPU 92A fillament

Table 4.6: Tire part considerations for the SM and MP case study

The processes considered to manufacture this component are the same that were used on the first case study, the material extrusion and the fused filament fabrication.

Although the manufacture processes are the same, on this case study a normal size printer is utilized and therefore, the energy consumption value change. To calculate the energy consumption, the power was measured through out the whole FFF procedure, as it was done in case study 4.1, and the obtained results are presented in figure 4.12.

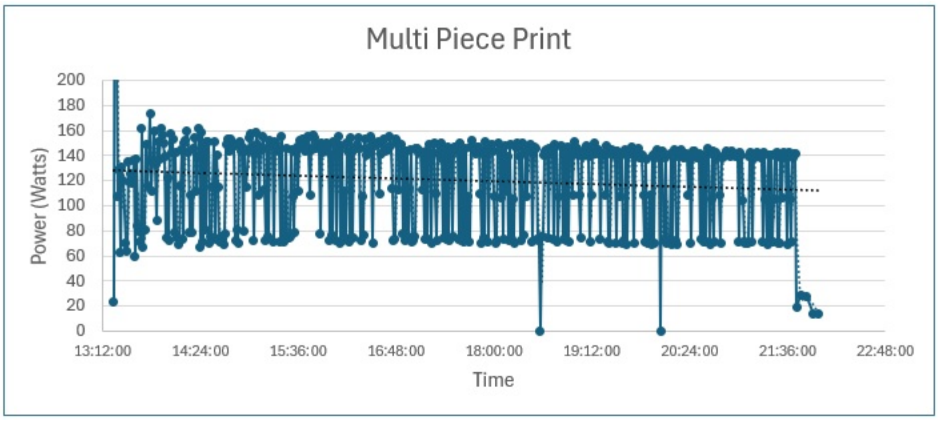


Figure 4.12: Instant power consumption by Pruza MK4 while printing a tire part

The initial spike and higher values registered for the power measured are in line with the initial stage in FFF where the printer heats up the nozzle and requires more energy. Although the slope has a negative value, the interval between 70 watts and 140 watts is preserved and unchanged by the end of the FFF procedure, proving that the longer the FFF procedure takes wont make the energy consumption values reduce.

It is then possible to obtain the energy consumption value for the whole tire part print, has presented in table 4.7.

Average power output	140,34 W
Time	6h40min
Energy consumption	1,216 kWh

Table 4.7: Energy consumption for the tire part print

To perform the environmental analysis, in section 4.2.2, the phases considered were once again the raw material phase, the manufacturing phase and EoL phase.

4.2.2 Life Cycle Assessment

Goal and scope definition

The goal is to analyse the environmental impact through the life cycle of a bicycle TPU non-pneumatic tyre printed in 15 modular parts, analyse the impact of the two main parameters chosen and ultimately, understand if it is more sustainable to print the NPT in one single piece or in smaller parts that can fit in a normal size printer. The functional unit for comparison is a tire, which is made out of 15 modular parts, hence the final results are multiplied times 15.

In figure 4.5 , the LCA scheme presents the cradle-to-grave system boundary selected for the environmental assessment. The life cycle stages considered for the NPT tire were raw material, manufacturing (extrusion and FFF), and recycling as the EoL scenario.

In order to compare the values resulting from the LCIA of this case study with the ones from case study 4.1 (SM SP), assumptions made on this last one regarding lifespan, transportation stages and EoL stages are also valid for this case study.

Inventary

Figure 4.13 presents in detail the inventory considered to perform the LCA, with data collected from the literature. As conducted in case study 4.1, the processes included in LCA, when not available in Ecoinvent, were assessed by considering the respective energy.

		Processes and materials	Ecoinvent	Value	Unit	Ref
Product Stage	Raw material	Thermoplastic Polyurethane	Polyether polyols, short chain {RER}| market for polyether polyols, short chain | APOS, U	0,0306	[Kg]	[103]
			Methylene diphenyl diisocyanate {RER}| market for methylene diphenyl diisocyanate | APOS, U	0,01952	[Kg]	[103]
			1,4-butanediol {GLO}| market for 1,4-butanediol | APOS, U	0,0103	[Kg]	[103]
		Thermoplastic Polyurethane granulate processing energy	Electricity, medium voltage {GLO} market group for | APOS, U	0.0129	[kWh]	[101]
	Manufacturing	Extrusion	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	0,0467	[kWh]	[100]
		Fused Filament Fabrication	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	1,216	[kWh]	a)
			Recycling Thermoplastic Polyurethane, scraps from production, {PT} market for recycle Thermoplastic polyurethane | APOS, U	0,42	[g]	[82]
EoL		Recycling	Electricity, medium voltage {GLO} market group for | APOS, U	0,733	[kWh]	[82]
		Incineration	Waste polyurethane {GLO}| treatment of waste polyurethane, Incineration | APOS U	-	-	[101]

Figure 4.13: Stages and processes from the Ecoinvent v3.10 database for the NPT modular part SM MP and a) Obtained from Experimental procedure [101]

The values used in the production processes, take into consideration the material manufactured and in the End of Life phase, a recycling rate of 90% for TPU was considered once more with the remaining 10% being processed by incineration.

Impact assessment and interpretation

For the chosen system boundary, Figures 4.14 (a) and (b) illustrate the environmental impact of a modular multi-piece TPU NPT. The impact results that have been multiplied by 15, since 15 modular parts are equivalent to a single piece tire, are shown for each endpoint category (HH, EC, RS) and as a total (aggregated) for each step, respectively.

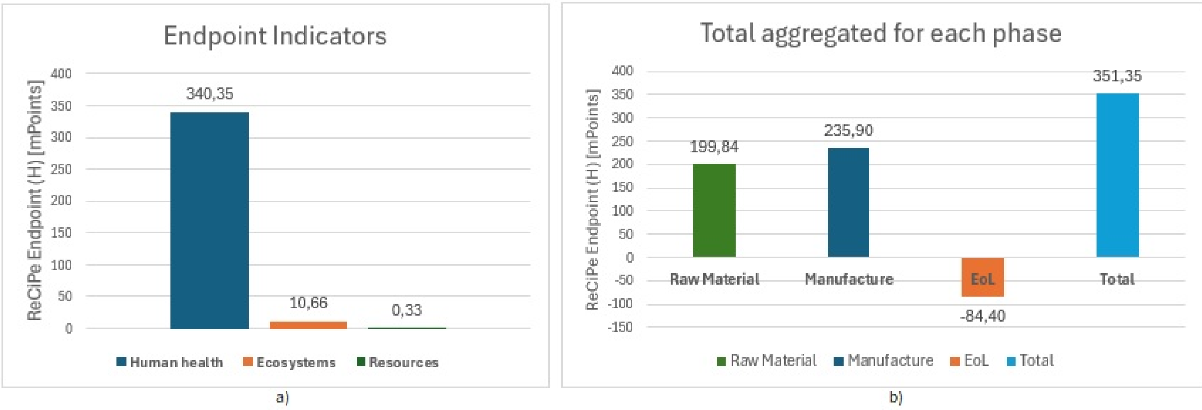


Figure 4.14: Multi Piece and Single Material (MP SM) case study ReCiPe Endpoint analysis

The results in Figure 4.14 (a) indicate that the Endpoint indicator with the highest contribution to the overall score of 351 mPoints is Human Health, contributing 96,87%, followed by the Ecosystems indicator at 3,01%, and Resources at 0,09%.

Figure 4.14 (b) shows the contributions of all processes within the system boundaries and their impact on the final total result. Manufacture has the highest value, contributing 235 mPoints, followed by Raw Materials with 199 mPoints, totaling 435 mPoints. Once again, the chosen End-of-Life (EoL) scenario significantly impacted the final value, as recycling provided a negative impact, reducing the total to 351 mPoints.

For the midpoint analysis, the results are presented in Figure 4.8, with Terrestrial Ecotoxicity having an impact of 66,33 kg 1,4-DCB. Human Non-Carcinogenic Toxicity impact category registred a value of 8,94 kg 1,4-DCB and Global Warming 8,06 kg CO_2 eq.

Impact Cathegory	Units	Total	Production Stage	EoL stage
Global warming	kg CO2 eq	8,06	9,61	-1,55
Stratospheric ozone depletion	kg CFC11 eq	0,00	0,00	0,00
Ionizing radiation	kBq Co-60 eq	1,06	1,23	-0,18
Ozone formation, Human health	kg NOx eq	0,02	0,02	0,00
Fine particulate matter formation	kg PM2.5 eq	0,01	0,01	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,02	0,02	0,00
Terrestrial acidification	kg SO2 eq	0,03	0,03	-0,01
Freshwater eutrophication	kg P eq	0,00	0,00	0,00
Marine eutrophication	kg N eq	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	66,33	93,52	-27,19
Freshwater ecotoxicity	kg 1,4-DCB	0,82	1,02	-0,20
Marine ecotoxicity	kg 1,4-DCB	1,07	1,35	-0,28
Human carcinogenic toxicity	kg 1,4-DCB	1,12	1,68	-0,56
Human non-carcinogenic toxicity	kg 1,4-DCB	8,94	13,08	-4,14
Land use	m2a crop eq	0,46	0,60	-0,14
Mineral resource scarcity	kg Cu eq	0,03	0,04	-0,02
Fossil resource scarcity	kg oil eq	0,50	0,59	-0,09
Water consumption	m3	0,14	0,16	-0,02

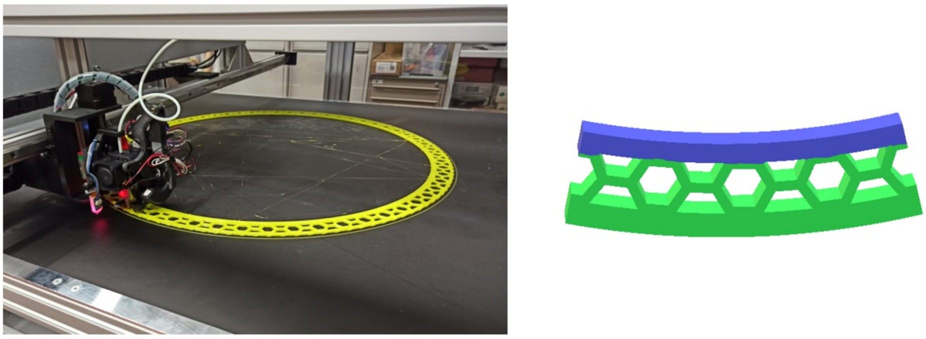
Table 4.8: Multi Piece and Single Material (MP SM) case study ReCiPe Midpoint analysis

Finally, the product carbon footprint of the Multi Piece and Single Material (SP SM) NPT, measured in kg CO2 eq./tire, recorded an impact of 8.06.

4.3 Case study: Multi Material and Single Piece

4.3.1 Experimental Setup

The tire and corresponding structure selected for the multi material case study are illustrated in Figure 4.15. Contrary to case study 4.1 and case study 4.2.1, a 3d model was not printed for the Multi Material and Single Piece case study, since the two FFF machines utilized on this dissertation are not capable of printing with more than one material at a time. Nevertheless, there are printers capable of this feature, printing pieces with different materials at the same time. Figure 4.15 a) illustrates the single material tire being printed, for a better perception of how the single piece and multi material tire, with the help of 4.15 b) would look like. Table 4.9 presents some considerations regarding dimensions, mass and material.



a) b)

Figure 4.15: a) Single Piece (SM) tire being printed b) structure with TPU (green) and PLA (blue)

Tire outer diameter	700 mm
Tire inner diameter	622 mm
Tire Thickness	21 mm
Mass Total	900 g
Mass TPU	764 g (85%)
Mass PLA	136 g (15%)
Main Material	Flexfill TPU 92A fillament
Secondary Material	Polylactic Acid

Table 4.9: Tire components considerations for the SM and SP case study

In accordance with the structure presented 4.15 with PLA (blue) being used for the contact zone with the interior rim mounting area and TPU (green) used for the spoke area and the shear band area, justified in section 3.2.2, the material percentage considered for the PLA is 15% and the material percentage for the thermoplastic polyurethane is 85%.

To perform the environmental analysis, in section 4.3.2, the phases considered were the raw material phase, the manufacturing phase and EoL phase.

4.3.2 Life Cycle Assessment

Goal and scope definition

The goal is to analyse the environmental impact through the life cycle of a bicycle bi-material NPT made out of TPU as the main material (with higher percentage on the tire composition, 85%) and PLA as a secondary material (15%). The LCIA will also allow comprehending if it is more sustainable to print the tire in one single material, or if a bi-material can accomplish better results. Once again, the functional unit for comparison is a tire.

In figure 4.5, the LCA scheme presents the cradle-to-grave system boundary selected for the environmental assessment. The life cycle stages considered for the NPT tire were raw material, manufacturing (extrusion and FFF), and recycling as the EoL scenario.

Since a bi-material NPT was not produced in the laboratory, it is assumed for the production stage that the energy consumption for manufacturing a single material NPT through FFF is the same as the energy that would be consumed to produce a bi-material NPT, as justified in chapter 3.2.2.

Assumptions regarding lifespan and transportation stages were maintained the same, as in case study 4.1 and case study 4.2.1, for later comparison.

For the end of life stage, the recycling percentage presented on case study 4.1 and on case study 4.2.1 is maintained, with 90% of the material being recycled and 10% incinerated.

However, since the MM SP tire is a bi-material and both of the materials are capable of being recycled on their own, there is a need for a process to separate both materials before recycling.

For this process, it is assumed that the materials are easy to separate and that on the ”Design for concept”, the designer plays an important role making sure the tire can be easily recycled. In order for this to be possible, different design configurations would have to be explored, such has printing the TPU and PLA parts separately and then getting them mechanically joined, but such possibilities will not be covered in this dissertation.

This assumption plays an important role directing the scope of the dissertation for the two main variables, multi material and multi piece, and understanding their behavior on the final results.

Nevertheless, on chapter 4.3.2 the possibility where both materials cannot be separated and therefore recycled is also explored and taken into consideration.

Inventory

Figure 4.16 presents in detail the inventory considered to perform the LCA, with data collected from the literature. As conducted in in case study 4.1 and in case study 4.2.1, the processes included in LCA, when not available in Ecoinvent library, were assessed by considering the respective energy. Once again, the values used in the production processes take into consideration the materials manufactured. In the End of Life phase, it was considered a recycling rate of 90% and the remaining 10% go to open burning.

		Processes and materials	Ecoinvent	Value	Unit	Ref
Product Stage	Raw material	Thermoplastic Polyurethane	Polyether polyols, short chain {RER}| market for polyether polyols, short chain | APOS, U	0,391	[Kg]	[103]
			Methylene diphenyl diisocyanate {RER}| market for methylene diphenyl diisocyanate | APOS, U	0,246755	[Kg]	[103]
			1,4-butanediol {GLO}| market for 1,4-butanediol | APOS, U	0,13234	[Kg]	[103]
		Polylactic Acid	Polylactic acid, granulate {GLO}| market for polylactic acid, granulate | APOS, U	0, 135945	[Kg]	[101]
		Thermoplastic Polyurethane granulate processing energy	Electricity, medium voltage {GLO} market group for | APOS, U	0,194	[kWh]	[101]
	Manufacturing	Extrusion	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	0,7	[kWh]	[100]
		Fused Filament Fabrication	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	20,7	[kWh]	a)
			Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | APOS, U	0,0063	[Kg]	[101]
EoL		Recycling	[TPU] - Electricity, medium voltage {GLO} market group for | APOS, U	11,00	[kWh]	[82]
			[PLA] - Electricity, medium voltage {GLO} market group for | APOS, U	4,2	[kWh]	[82]
		Incineration	Waste plastic, mixture {GLO}| treatment of waste plastic, mixture, incineration| APOS, U	-	-	[101]

Figure 4.16: Stages and processes from the Ecoinvent v3.10 database for the NPT MM SP and a) Obtained from Experimental procedure [101]

Impact assessment and interpretation

For the selected system boundary, Figures 4.17 (a) and 4.17 (b) depict the environmental impact of a Single Piece and Multi Material NPT. These impacts are presented for each endpoint category (HH, EC, RS) and as a total (aggregated) for each step.

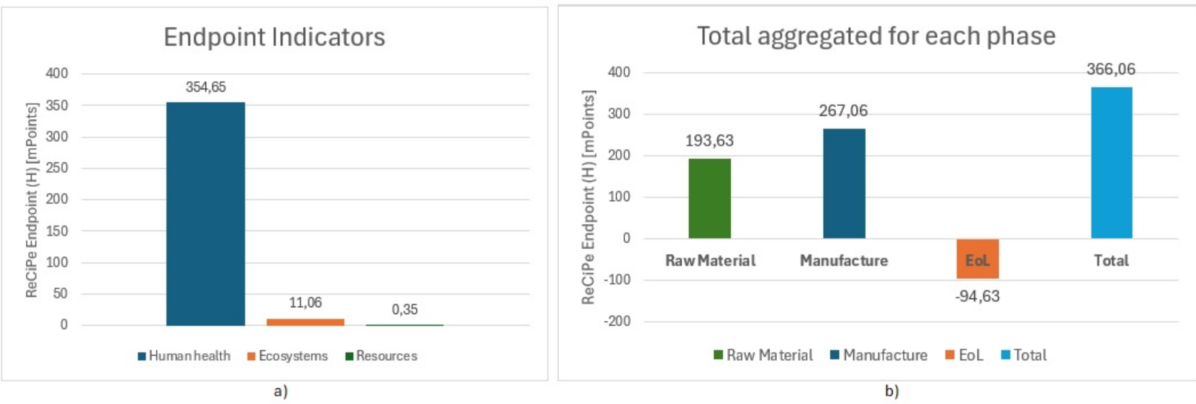


Figure 4.17: Multi Material and Single Piece (MM SP) case study ReCiPe Endpoint analysis

The results in Figure 4.17 (a) show that the Endpoint indicator contributing the most to the overall score of 366,06 mPoints is Human Health, accounting for 96.88%, followed by Ecosystems at 3.02%, and Resources at 0.1%.

Figure 4.17 (b) illustrates the contributions of various processes within the system boundaries and their influence on the total result. Manufacturing has the largest contribution at 267 mPoints, with Raw Materials following at 193 mPoints, leading to a subtotal of 460 mPoints. However, the selected End-of-Life (EoL) scenario significantly reduced the final total, as recycling provided a negative impact of 94, bringing the score down to 366,06 mPoints.

For the midpoint analysis, as shown in Figure 4.10, Terrestrial Ecotoxicity has an impact of 71,96 kg 1,4-DCB, Human Non-Carcinogenic Toxicity of 9,90 kg 1,4-DCB and Global Warming at 8,56 kg CO2 eq.

Impact Cathegory	Units	Total	Production Stage	EoL Stage
Global warming	kg CO2 eq	8,56	10,21	-1,65
Stratospheric ozone depletion	kg CFC11 eq	0,00	0,00	0,00
Ionizing radiation	kBq Co-60 eq	1,13	1,28	-0,15
Ozone formation, Human health	kg NOx eq	0,02	0,02	0,00
Fine particulate matter formation	kg PM2.5 eq	0,01	0,01	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,02	0,02	0,00
Terrestrial acidification	kg SO2 eq	0,03	0,04	-0,01
Freshwater eutrophication	kg P eq	0,00	0,00	0,00
Marine eutrophication	kg N eq	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	71,96	96,73	-24,77
Freshwater ecotoxicity	kg 1,4-DCB	0,92	1,10	-0,18
Marine ecotoxicity	kg 1,4-DCB	1,19	1,45	-0,25
Human carcinogenic toxicity	kg 1,4-DCB	1,20	1,71	-0,51
Human non-carcinogenic toxicity	kg 1,4-DCB	9,90	13,71	-3,81
Land use	m2a crop eq	0,51	0,84	-0,34
Mineral resource scarcity	kg Cu eq	0,03	0,05	-0,01
Fossil resource scarcity	kg oil eq	0,52	0,62	-0,10
Water consumption	m3	0,14	0,17	-0,02

Table 4.10: Multi Material and Single Piece (MM SP) case study ReCiPe Midpoint analysis

Ultimately, the product carbon footprint of the Single Piece and Multi Material (SP MM) NPT, quantified in kg CO2 eq./tire, registered an impact of 8.56.

Material variation study

The effect of varying the material composition between TPU (Thermoplastic Polyurethane) and PLA (Polylactic Acid) was also taken into consideration. While keeping constant the tire mass variable, it is possible to understand how different ratios of these materials impact the environmental footprint of the tire.

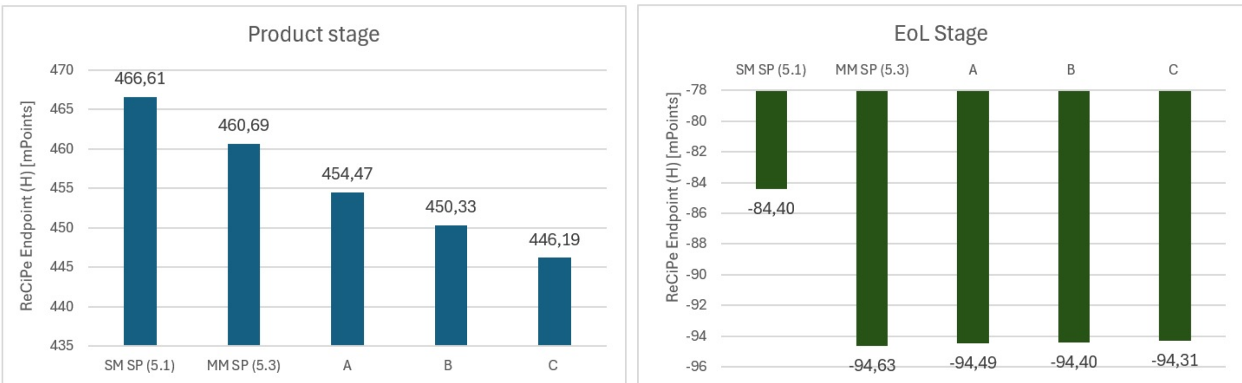
Regarding the materials, TPU provides flexibility and durability, which is the reason why it is always assumed as the main material (with it's percentage never drooping bellow 50%) but is often associated with higher environmental costs in production. Conversely, PLA is bio-based and biodegradable, offering a lower environmental impact but with potential limitations in mechanical performance, relatively to the tire industry. Exploring different combinations of these materials allows for an assessment of whether there is an optimal ratio that minimizes environmental impact.

For the Life Cycle Impact Assessment (LCIA) five different scenarios were created, that are presented in table 4.11.

case study	TPU (%)	PLA (%)	mass (g)
SM SP (5.1)	100	0	900
MM SP (5.3)	85	15	900
A - MM SP	70	30	900
B - MM SP	60	40	900
C - MM SP	50	50	900

Table 4.11: Mass variation scenarios

The results obtained are shown in figure 4.18, organized by the sum of all 3 Endpoint Indicators per case for the Product Stage (a) and for the EoL Stage (b).



a) b)

Figure 4.18: ReCiPe Endpoint results on different material scenarios for a) Product stage and b) EoL stage

At last, figure 4.19 presents the sum of all 3 Endpoint Indicators (Human Health, Ecosystems and Resources) for the whole life cycle boundary system, namely the product stage that encompasses the raw material and manufacture, and the EoL stage, for the five scenarios proposed.

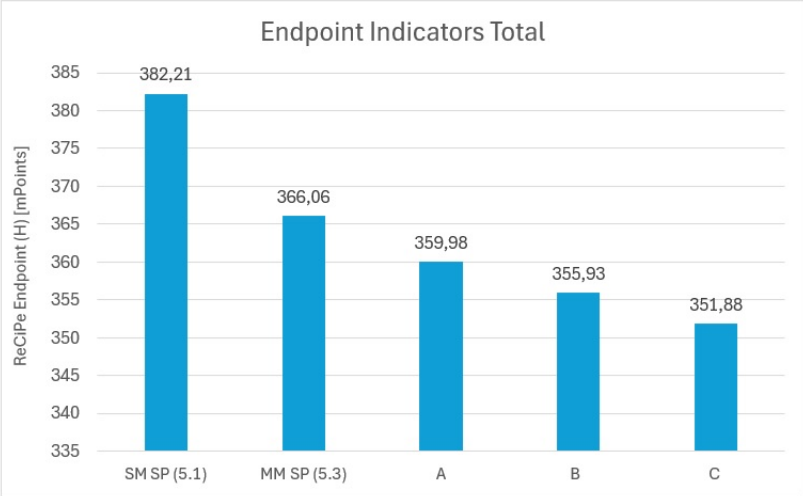


Figure 4.19: ReCiPe Endpoint results for the whole boundary system selected

The results show a critical maximum value of 382,21 mPoints for the scenario of case study 4.1, which has a 100% TPU composition, resulting therefore in the worst results obtained from a sustainability point of view. On the other hand, the scenario where the most sustainable results occurred was scenario C - Multi Material and Single Piece (MM SP).

To better understand this results, its necessary to analyse the graphics on figure 4.18. The ReCiPe Endpoint results from Product Stage are the result of the raw materials values with the manufacturing values. Since the printers and extruder machine energy consumption values are kept constant for all the scenarios, the manufacture stage presents the same values for the 5 scenarios and therefore, the variation observed in the Product Stage result come exclusively from the Raw Materials, confirming the lower environmental impact from PLA due to its bio-based composition, when compared to TPU.

Because of the lower environmental impact of PLA, the higher percentage it has on the tire composition, the lower will be the results for the ReCiPe Endpoint indicators on the Product Stage and that is the reason why the relation in figure a) is a linear negative slope.

On the other hand, when taking into consideration the ReCiPe Endpoint results from the EoL stage, if the first case where no PLA is present on the tire composition is disregarded, then a constant value can be observed for the four last scenarios (with a variation between the highest and lowest value inferior to 0,33%).

The results from the EoL come exclusively from the recycling process of 90% attributed to all four scenarios along with the reaming 10% going for open burning. To better understand why the EoL Stage results are not impact by variations in the TPU/PLA percentages it is necessary to comprehend how PLA recycling process and how TPU recycling process impact the total value for the Eol Stage.

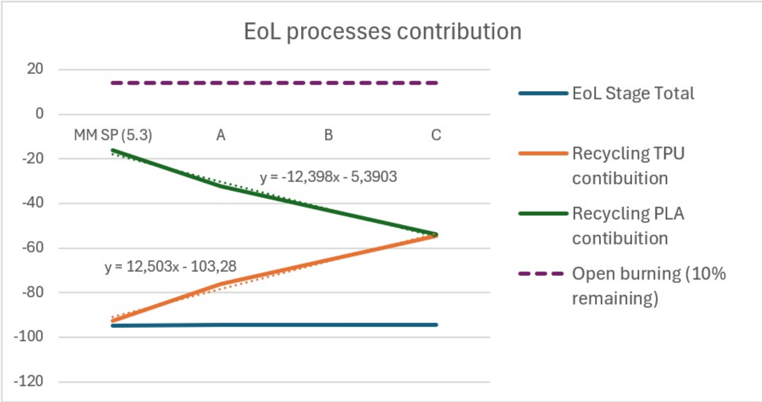


Figure 4.20: ReCiPe Endpoint Total for the EoL Stage

Figure 4.20 illustrates a expected inverse proportionality relation between the recycling TPU contribution and the recycling PLA contribution to the total value, with the last one increasing in function of the PLA percentage that also increases. However, the slopes have the same modular value, negative for TPU and positive for PLA, which is not expected having in consideration that the energy value to recycle TPU is almost 3 times higher than the value needed to recycle PLA.

An analysis done to both recycling processes for 1 kg of material, shown in table 4.20, indicates that recycling TPU has has the same final value as recycling PLA despite consuming the triple of the energy that recycling PLA takes, because of the value in the material recovered beeing 3 times higher for TPU when compared to PLA.

ReCiPe Endpoint	Total	Electricity	Material
Recycling PLA	-133,094	41,709	-174,803
Recycling TPU	-134,222	109,240	-243,462

Table 4.12: ReCiPe Endpoint Total values for recycling 1 kg of PLA and TPU

Concluding, the variation of the material percentages has no significant impact in the tire EoL and since the manufacture procedure is the same independently of the material percentages, the most sustainable material, defined by the Raw Material stage, will dictate the most sustainable tire. In this case since PLA is more eco-friendly, the tire with more PLA on it's composition will be the most sustainable, and therefore scenario C is the more sustainable.

EoL study

The End of Life chosen for the bicycle tire was one of stages impacting the results of the case studies performed and therefore its important to understand how the ReCiPe Endpoint results behave when subjected to different EoL scenarios.

As stated in case studies 4.1 and 4.2.1, the first two where the tire was made only of a single material TPU, the scenarios considered for the EoL were recycling 90% and the remaining 10% would go to incineration. On the last two case studies, 4.3 and 4.4, despite the tire being made of a bi-material, the same EoL rates were considered.

In this section, four more EoL scenarios were conducted for the single piece and multi material (MM SP) case study 4.3, where the percentage of recycled material decreases and the percentage of material going for incineration increases. On the last scenario, R0 I100, 100% of the material goes for open burning, representing the possibility of the materials being so well interconnected with each other that are not able to be separated and consequently not able to be recycled. These scenarios are presented in Table 4.13.

case study	Recycle (%)	Incineration (%)	mass (g)
MM SP (5.3)	90	10	900
R70 I30	70	30	900
R50 I50	50	50	900
R30 I70	30	70	900
R0 I100	0	100	900

Table 4.13: Recycling scenarios for the MM SP

A last scenario, with two case studies "H15 I85" and "H15 I8.5 R76.5", was considered for the reality where materials cannot be easily separated and instead of burning it, they are recycled. In order to recycle the tire, it is necessary to resort to a thermal or chemical recycling process.

Thermal hydrolysis can be used to separate mixed plastics and in this case hydrolysis can be applied to recycle PLA since it is a polyester and polyesters are susceptible to hydrolytic degradation [106] [107].

PLA can be selectively hydrolyzed in the presence of water (or in an aqueous solution) at elevated temperatures (typically 100-200℃) where during the process, the ester bonds break down into lactic acid or oligomers, effectively separating it from TPU [106].

In this scenario, on "Design for Recycling" step it is necessary to assure TPU resistance to hydrolysis or else the recycled PLA would get contaminated. For this, anti-hydrolysis agents can be added to TPU, like it was done in a study by A. Bardin et. al. [108].

After recycling PLA, two scenarios can occur to the TPU. On the first scenario the hydrolysis destroyed TPU properties and it can no longer be recycled, defining case study "H15 I85" where all the TPU goes for incineration. On the second scenario, TPU is suited for recycling and therefore it was considered that 90% of it is recycled and the 10% remaining go to incineration.

This scenario is presented in Table 4.14, and the percentages of each material were maintained from the previous scenarios.

case study	Recycle (%) PLA hydrolysis	Incineration (%) TPU	Recycle TPU (%)	mass (g)
H15 I85	15	85	-	900
H15 I8.5 R76.5	15	8,5	76,5	900

Table 4.14: Recycling through hydrolysis scenario

The results for the ReCiPe Endpoint indicators for the EoL process are illustrated in figure 4.21.

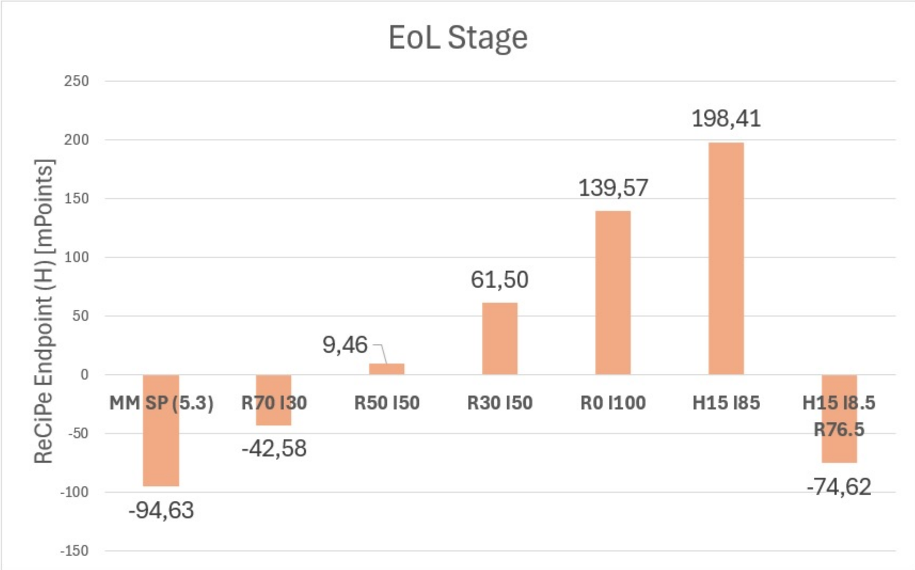


Figure 4.21: ReCiPe Endpoint results for the EoL stage

Since all the EoL scenarios were applied to the product stage (raw material and manufacture) of case study MM SP 4.3, the results from product stage are equal to all EoL scenarios in study and therefore, the results for the ReCiPe Endpoint indicators for the whole selected system can be seen in figure 4.22.

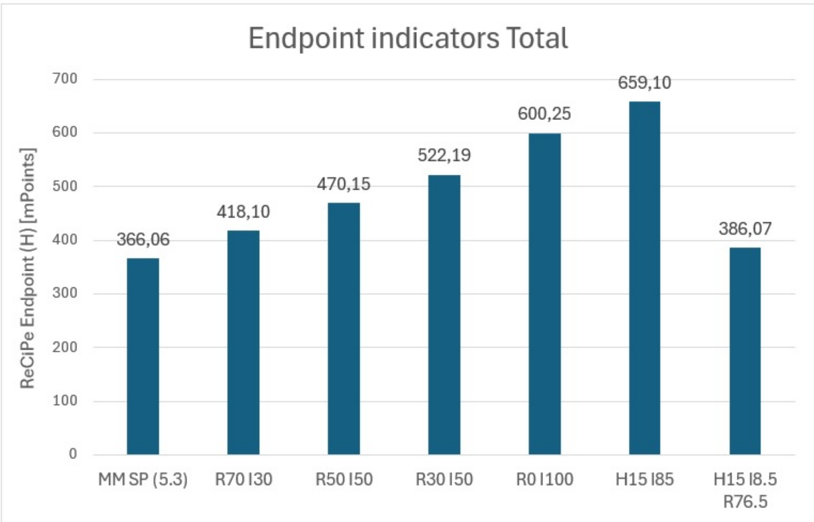


Figure 4.22: ReCiPe Endpoint results for the whole boundary system selected

Results on Figure 4.22 show that a reduction of 20% on the recycling rate has positive impact on average of 52 mPoints on the ReCipe Endpoint total value. Case study 4.3 obtains the lowest value with 366 mPoints.

The highest value of 659 mPoints belongs to scenario ”H15 I85”, where the PLA is recycled by hydrolyses and then TPU contaminated by the hydrolyses process cannot be recycled and processed with incineration.

Scenario "R0 I100" where all the material is processed with incineration has a value of 600 mPoints, 58 mPoints behind scenario "H15 I85" proving that the approach of recycling PLA by hydrolises and burning the remaining TPU, is not sustainably worth performing.

At last, comparing case study MM SP 4.3 with scenario F, shows that despite not being as sustainable with results 5,18% higher, scenario "H15 I8.5 R76.5" can always be a competitive approach for the End of Life of the tire, when separating materials easily is not an option.

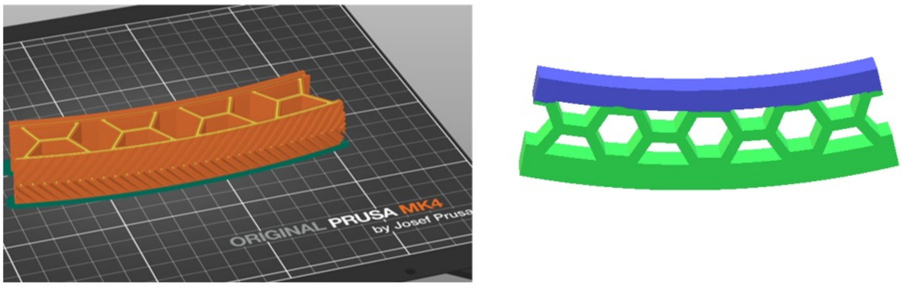
4.4 Case study: Multi Material and Multi Piece

4.4.1 Experimental Setup

At last, case study 4.4 explores the environmental impact of a tire produced by 15 modular parts like the one illustrated on figure 4.23 a).

LCIA results will help understand if this last case study that encompasses all the variables in study, bi-material and multi-piece, is the answer to build the most sustainable tire.

Similar to case study 4.3, the the bi-material modular part was not printed in laboratory.



a) b)

Figure 4.23: Multi Material and Multi Piece print with TPU (green) and PLA (blue)

To conclude the analysis, the results obtained from the LCIA were multiplied by 15 to simulate the values of the production of a full tire and then compared to the other case studies.

4.4.2 Life Cycle Assessment

Goal and scope definition

The goal is to analyse the environmental impact through the life cycle of a bi-material modular part of a bicycle NPT made out of TPU as the main material (with higher percentage on the tire composition) and PLA as a secondary material.

The assumptions valid for the tire part and for the bi-material stated for case study 4.2.1 and case study 4.3 are valid for this case and the functional unit for comparison is a tire, which is made out of 15 modular parts, as the one presented in picture 4.23 a).

In figure 4.5, the LCA scheme presents the cradle-to-grave system boundary selected for the environmental assessment. The life cycle stages considered for the NPT tire were raw material, manufacturing (extrusion and FFF), and recycling as the EoL scenario.

Inventory

Figure 4.24 illustrates in detail the inventory considered to perform the LCA, with data collected from the literature. As conducted in case study 4.1in case study 4.2.1 and in case study 4.3, the processes included in LCA, when not available in Ecoinvent library, were assessed by considering the respective energy. At last, the values used in the production processes, take into consideration the materials manufactured. In the End of Life phase, it was maintained the recycling rate of 90% and the remaining 10% going to incineration.

	Processes and materials		Ecoinvent	Value	Unit	Ref
Product Stage	Raw material	Thermoplastic Polyurethane	Polyether polyols, short chain {RER}| market for polyether polyols, short chain | APOS, U	0,0260	[Kg]	[103]
Product Stage	Raw material	Thermoplastic Polyurethane	Methylene diphenyl diisocyanate {RER}| market for methylene diphenyl diisocyanate | APOS, U	0,016547	[Kg]	[103]
Product Stage	Raw material	Thermoplastic Polyurethane	1,4-butanediol {GLO}| market for 1,4-butanediol | APOS, U	0,0088	[Kg]	[103]
Product Stage	Raw material	Polylactic Acid	Polylactic acid, granulate {GLO}| market for polylactic acid, granulate | APOS, U	0, 009063	[Kg]	[101]
Product Stage	Raw material	Thermoplastic Polyurethane granulate processing energy	Electricity, medium voltage {GLO} market group for | APOS, U	0,0129	[kWh]	[101]
Product Stage	Manufacturing	Extrusion	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	0,0467	[kWh]	[100]
Product Stage	Manufacturing	Fused Filament Fabrication	Electricity, low voltage {PT}| market for electricity, low voltage | APOS, U	1,216	[kWh]	a)
Product Stage	Manufacturing	Fused Filament Fabrication	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | APOS, U	0,42	[g]	[101]
EoL	Recycling		[TPU] - Electricity, medium voltage {GLO} market group for | APOS, U	0,733	[kWh]	[82]
EoL	Recycling		[PLA] - Electricity, medium voltage {GLO} market group for | APOS, U	0,28	[kWh]	[82]
EoL	Incineration		Waste plastic, mixture {GLO}| treatment of waste plastic, mixture, incineration| APOS, U	-	-	[101]

Figure 4.24: Stages and processes from the Ecoinvent v3.10 database for the NPT modular part MM MP and a) Obtained from Experimental procedure [101]

Impact assessment and interpretation

For the system boundary selected, Figure 4.25 (a) and Figure 4.25 (b) present the environmental impact of a Multi Piece and Multi Material NPT, for each of the endpoint categories (HH, EC, RS) and as a total (aggregated) for each step, respectively.

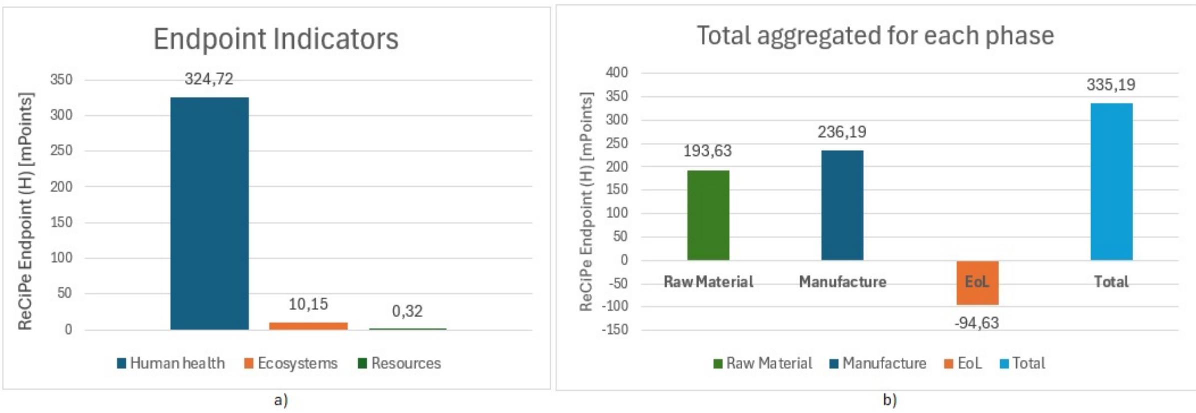


Figure 4.25: Multi Material and Multi Piece (MM MP) case study ReCiPe Endpoint analysis

The results reveal that the Endpoint indicator with the highest contribution to the overall score of 335,19 mPoints is in line with the other case studies with Human Health leading the contribution in 96.88%, followed by Ecosystems at 3.02%, and Resources at 0.09%.

Figure 4.25 b) illustrates the contribution of all processes considered within the system boundaries and their impact on the final total result. The Manufacturing stage has the largest contribution at 236 mPoints, followed by Raw Materials at 193 mPoints, bringing the subtotal to 429 mPoints. At last the EoL impacts negatively with 94 mPoints, reducing the total to 335 mPoints.

For the midpoint analysis, as shown in Figure 4.15, Terrestrial Ecotoxicity has an impact of 65,37 kg 1,4-DCB, Human Non-Carcinogenic Toxicity an impact of 8,89 kg 1,4-DCB and Global Warming has an impact of 7,87 kg CO_2 eq.

Impact Cathegory	Units	Total	Product Stage	EoL Stage
Global warming	kg CO2 eq	7,87	9,52	-1,65
Stratospheric ozone depletion	kg CFC11 eq	0,00	0,00	0,00
Ionizing radiation	kBq Co-60 eq	1,03	1,18	-0,15
Ozone formation, Human health	kg NOx eq	0,02	0,02	0,00
Fine particulate matter formation	kg PM2.5 eq	0,01	0,01	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,02	0,02	0,00
Terrestrial acidification	kg SO2 eq	0,03	0,03	-0,01
Freshwater eutrophication	kg P eq	0,00	0,00	0,00
Marine eutrophication	kg N eq	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	65,37	90,14	-24,77
Freshwater ecotoxicity	kg 1,4-DCB	0,82	1,00	-0,18
Marine ecotoxicity	kg 1,4-DCB	1,07	1,32	-0,25
Human carcinogenic toxicity	kg 1,4-DCB	1,10	1,60	-0,51
Human non-carcinogenic toxicity	kg 1,4-DCB	8,89	12,70	-3,81
Land use	m2a crop eq	0,47	0,81	-0,34
Mineral resource scarcity	kg Cu eq	0,03	0,04	-0,01
Fossil resource scarcity	kg oil eq	0,48	0,58	-0,10
Water consumption	m3	0,13	0,16	-0,02

Table 4.15: Multi Material and Multi Piece (MM MP) case study ReCiPe Midpoint analysis

Concluding, the product carbon footprint of the Multi Piece and Multi Material (MP MM) NPT , measured in kg CO_2 eq./tire registered an impact of 7,87.

4.5 Discussion

4.5.1 Endpoint Analysis

On the Table 4.16 the four case studies are summarized.

Case study	Mass	TPU (%)	PLA (%)
SP SM (4.1)	900	100	0
MP SM (4.2)	900	85	15
SP MM (4.3)	60	100	0
MP MM (4.4)	60	85	15

Table 4.16: Summary of the four case studies

Figure 4.26 presents the environmental impacts registered for each of the case studies performed and compares them side-by-side, as the sum of the three endpoint categories: Human Health, Ecosystems and Resources.

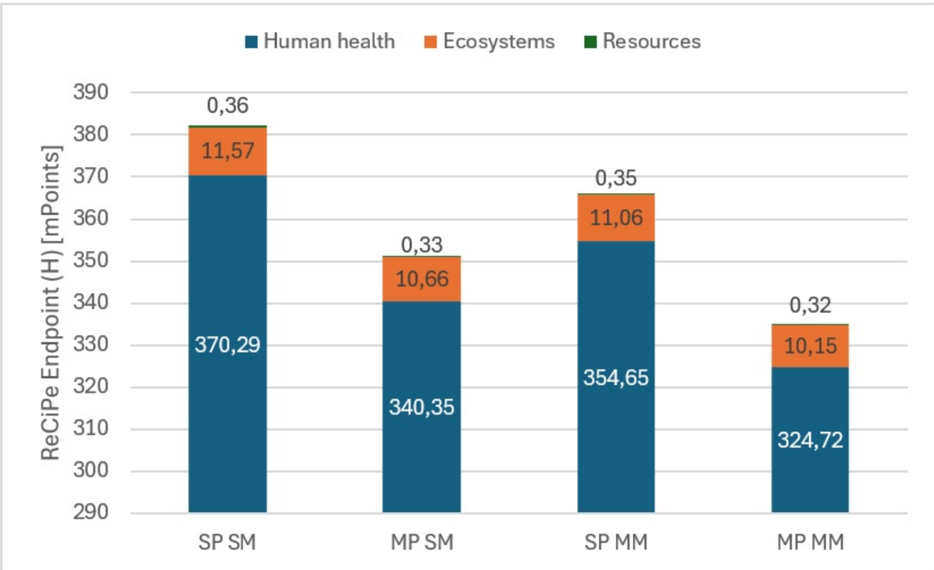


Figure 4.26: Case studies ReCiPe Endpoint comparison for indicators

SP MM case study 4.4 results are 12,30% better than the ones registered for SP SM case study 4.1, the one with the highest environmental impact of all four case studies. These results are a consequence of the optimization of the two main variables in study, culminating in lower values on different processes as it can be seen in figure 4.27.

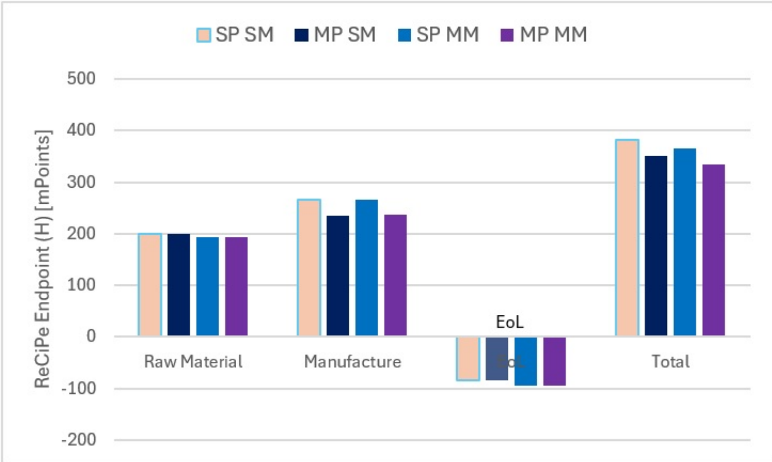


Figure 4.27: Case studies ReCiPe Endpoint comparison for processes

By analysing the Raw Material stage, it is possible to conclude that the presence of PLA on the tire composition resulted in a lower impact from this stage. With this in mind, case study 4.3 and 4.4 which are both Multi Material score the lowest value of 193 mPoints compared to the 199 mPoints scored for the Single Material, 3,11% higher.

The Raw Material stage strengthen the conclusion obtained in chapter Material Variation Study 4.3.2, that the presence of another material more eco-friendly than TPU, such as PLA for it's bio based composition, non-toxicity and biodegradability, reduces the environmental impact of the NPT, contributing with better results for the Raw Material stage.

Furthermore, on the Manufacturing stage two different scenarios are compared: the Single Piece NPT versus the Multi Piece NPT. Since the values registered for the extrusion process are maintained, the manufacturing stage is fully dependent on the FFF process, which values were measured in laboratory and verified that the energy consumption of the Industrial Printer for the production of a full tire is greater than the energy consumption of the Pruza MK4, used as model for a "standard" printer, for the production of the same tire. With this in mind, case studies MP SM 4.2.1 and MP MM 4.4 obtain the lowest values of 235,9 and 246 mPoints respectively, compared to the 266 and the 267 mPoints of case studies SP SM 4.1 and SP MM 4.3. The negligible variations between these values are justified by the scraps of production, namely the ones designated for the FFF process that despite having the same percentage in all all the cases, for the Single Material ones the material being recycled is TPU and for the Multi Material is TPU and PLA, which ends up being slightly better and causing a lesser impact on the manufacturing stage.

The Use stage was not taken into consideration for the motives explicit in the case study's goal and scope section, but an important aspect to take into consideration is that, when a tire is printed in Multi Pieces, it is possible for the user to swap a part of the tire that requires maintenance by printing another one. On the Single Piece tire, the same is not true and the user is required to print a full new tire, even if the problem is located on a specific part of the tire. This consideration plays an important role when comparing the use stage and maintenance of the Single Piece with the Multi Piece NPT's, benefiting the

Multi Piece option, even tho it was not considered in this dissertation.

At last, the End of Life stage chosen for the four case studies was 90% recycling and open burning for the remaining 10%. Results show that the Multi Material case studies have a higher negative impact with -94 mPoints comparing to the Single Material ones, with only -84 mPoints.

On the Material Variation study in chapter 4.3.2, it was concluded that regardless of the PLA/TPU percentage, the EoL results would maintain constant, contrary to what is verified on Figure 4.27. To understand why the Multi Material case studies have a higher negative impact, a analysis on ReCipe Endpoint Indicators for the EoL of SM and MM was conducted and results are presented in table 4.17.

	Total	Recycle total	Recycle TPU	Recycle PLA	TPU Open Burning	PLA/TPU Open Burning
SP SM	-84,395	-108,719	-108,719	-	24,323	-
MP SM	-84,395	-108,719	-108,719	-	24,323	-
SP MM	-94,625	-108,582	-92,4116	-16,170	-	13,956
MP MM	-94,625	-108,582	-92,4116	-16,170	-	13,956

Table 4.17: ReCipe Endpoint Indicators for the EoL of the 4 case studies, in mPoints

The ”Recycle total” values prove the veracity of the conclusion achieved in the Material Variation study 4.3.2 with the recycle values for the 4 case studies being around -108 mPoints.

However, the open burning process varies from Multi Material to Single Material. This happens because PLA is once again a more sustainable material and it’s contribution in open burning is lower than the one from TPU. For this reason, the case studies with the presence of PLA have a higher negative impact.

To conclude, case study MM MP combines the advantages of the Multi Material on the Raw material and EoL stage, with the advantages of the Multi Piece on the Manufacture Stage, achieving the best results with the lowest environmental impact.

4.5.2 Midpoint Analysis

Figure 4.28 presents the ReCiPe Midpoint results obtained on the four case studies, comparing them side by side.

	SP SM			MP SM			SP MM			MP MM			
Impact Cathegory	Pruduction Stage	EoL Stage	Total	Pruduction Stage	EoL Stage	Total	Pruduction Stage	EoL Stage	Total	Pruduction Stage	EoL Stage	Total	Units
Global warming	10,30	-1,55	8,75	9,61	-1,55	8,06	10,21	-1,65	8,56	9,52	-1,65	7,87	kg CO2 eq
Stratospheric ozone depletion	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	kg CFC11 eq
Ionizing radiation	1,33	-0,18	1,15	1,23	-0,18	1,06	1,28	-0,15	1,13	1,18	-0,15	1,03	kBq Co-60 eq
Ozone formation, Human health	0,02	0,00	0,02	0,02	0,00	0,02	0,02	0,00	0,02	0,02	0,00	0,02	kg NOx eq
Fine particulate matter formation	0,01	0,00	0,01	0,01	0,00	0,01	0,01	0,00	0,01	0,01	0,00	0,01	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	0,02	0,00	0,03	0,02	0,00	0,02	0,02	0,00	0,02	0,02	0,00	0,02	kg NOx eq
Terrestrial acidification	0,04	-0,01	0,03	0,03	-0,01	0,03	0,04	-0,01	0,03	0,03	-0,01	0,03	kg SO2 eq
Freshwater eutrophication	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	kg P eq
Marine eutrophication	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	kg N eq
Terrestrial ecotoxicity	100,11	-27,19	72,92	93,52	-27,19	66,33	96,73	-24,77	71,96	90,14	-24,77	65,37	kg 1,4-DCB
Freshwater ecotoxicity	1,11	-0,20	0,92	1,02	-0,20	0,82	1,10	-0,18	0,92	1,00	-0,18	0,82	kg 1,4-DCB
Marine ecotoxicity	1,47	-0,28	1,20	1,35	-0,28	1,07	1,45	-0,25	1,19	1,32	-0,25	1,07	kg 1,4-DCB
Human carcinogenic toxicity	1,79	-0,56	1,22	1,68	-0,56	1,12	1,71	-0,51	1,20	1,60	-0,51	1,10	kg 1,4-DCB
Human non-carcinogenic toxicity	14,09	-4,14	9,95	13,08	-4,14	8,94	13,71	-3,81	9,90	12,70	-3,81	8,89	kg 1,4-DCB
Land use	0,64	-0,14	0,50	0,60	-0,14	0,46	0,84	-0,34	0,51	0,81	-0,34	0,47	m2a crop eq
Mineral resource scarcity	0,05	-0,02	0,03	0,04	-0,02	0,03	0,05	-0,01	0,03	0,04	-0,01	0,03	kg Cu eq
Fossil resource scarcity	0,63	-0,09	0,54	0,59	-0,09	0,50	0,62	-0,10	0,52	0,58	-0,10	0,48	kg oil eq
Water consumption	0,17	-0,02	0,15	0,16	-0,02	0,14	0,17	-0,02	0,14	0,16	-0,02	0,13	m3

Figure 4.28: ReCiPe Midpoint Results for the Product and EoL Stage of the four case studies

In accordance with the results obtained for the Endpoint results, the case study MP MM 4.4 presents the lowest impact in the majority of the impact categories when compared with the other three case studies. The category "Land Use" is the only exception where case study MP MM does not present the lowest values with case MP SM registering the lowest impact value. This category registers higher values when PLA and TPU are combined and also higher values when the tire is printed in a single piece. Therefore MP SM case study combination results in the lowest value for this impact category.

4.5.3 Comparison with industry bicycle tires

For a better understanding of how the results obtained are in line with the reality of the industry, the values obtained for the carbon footprint of each case study, measured in Kg C02 eq./tire were compared with values from literature and bicycle tires data sheets available online and compiled on the graphic in Figure 4.29.

The carbon footprint analysed is restricted to the Raw Material stage and to the Production Stage.

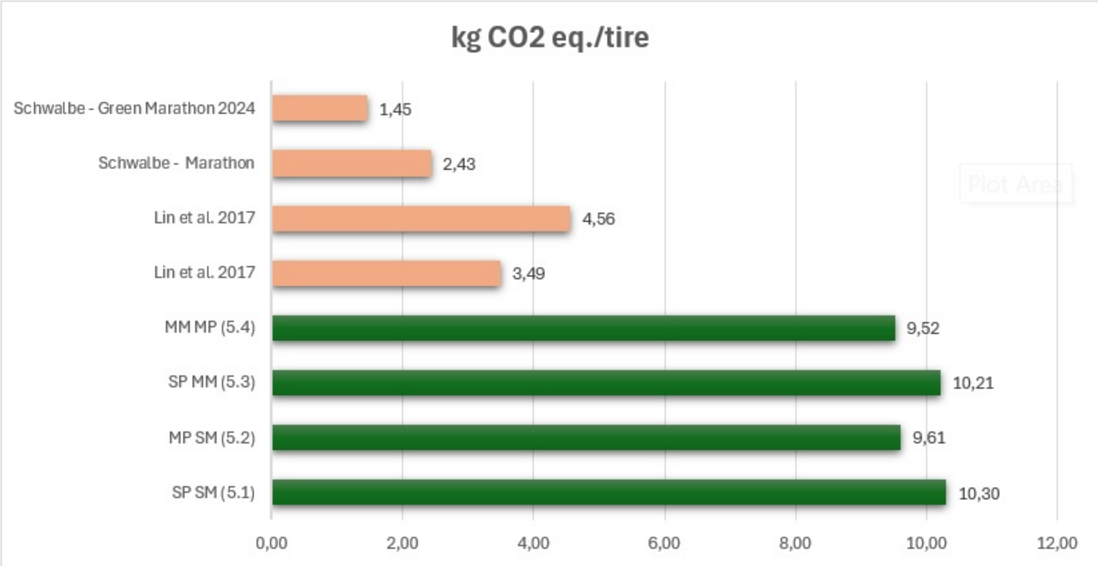


Figure 4.29: C02 footprint from case studies and literature values [109] [110]

Despite the simplicity of materials paired with low consumption energy spent on the manufacture processes, results show a carbon footprint twice as higher than values from other tires in the industry and even higher when compared with competing sustainable tires as the one from "Schwalbe" named Green Marathon 2024.

Of the four case studies presented, case study MP MM 4.4 registered the lowest carbon footprint value.

Chapter 5

Conclusions

5.1 Achievements

The research undertaken in this thesis is focused on the design, sustainability, and manufacturing of NPTs produced through FFF for bicycles.

The first accomplishment confirmed that reducing the mass of the NPT, lowers its environmental impact proportionally in human health, ecosystems, and resources indicators. The scenario where the lowest mass was considered, emerged as the most sustainable, underscoring the value of mass optimization through thoughtful design.

In addition to this, the material variation study revealed the critical role of material selection in minimizing environmental burden. Tires incorporating PLA, a bio-based material, exhibited better sustainability outcomes compared to those made solely of TPU. The Multi-Material Single-Piece (MM SP) design, which combined both PLA and TPU in equal percentages (50%-50%), achieved the best overall performance among other scenarios with different percentages, demonstrating that the use of eco-friendly materials is essential in reducing the tire's environmental footprint.

The research also highlighted manufacturing efficiencies associated with multi-piece designs. Modular designs (Multi-piece) not only reduce energy consumption and material waste during production but can also offer practical benefits for maintenance, allowing the replacement of individual parts rather than the entire tire, during tire's Use stage.

Furthermore, the End-of-Life analysis emphasized the advantages of recycling processes, particularly when involving PLA. Chemical recycling methods, such as hydrolysis, provided a sustainable pathway for material recovery in the scenario where easy material separation methodology is not viable, although results show that this methodology can only compete with the other EoL scenarios if the recycling process of TPU is still feasible after PLA hydrolyses. Full burning of the tire showed much higher environmental impacts only staying behind the scenario where PLA is recycled by hydrolysis and then TPU open burnt, reinforcing the importance of designing with recycling in mind and proving at the same time that is rather sustainable burning the full tire, then recycling PLA with hydrolysis and then burning TPU, since the energy consumption for hydrolysis is too elevated.

In conclusion, this thesis has demonstrated that by optimizing mass, incorporating sustainable materials, and embracing modular designs, significant improvements in the environmental sustainability of non-pneumatic tires can be achieved, contributing to the development of more sustainable transportation solutions.

5.2 Future Work

While this research has provided valuable insights into the sustainability of NPTs, there are several areas where further research is needed. One area of interest is the exploration of additional materials that can further enhance the sustainability of NPTs, particularly biodegradable options that can reduce the environmental impact in production and disposal.

Another area of interest lies in the study of a design for interlocking the Multi Piece modular parts, culminating in a effective assemble process which should also allow for an easy replacement of the modular parts whenever needed.

Additionally, further studies could investigate the performance of NPTs in real-world conditions to better understand their durability and functionality over extended periods, providing data and better insights over the Use Stage of the bicycle tire.

Another potential avenue for future research lies in the optimization of the structure chosen for the tire. The structure design has a important contribution on the Use Stage, by enhancing the life longevity of the tire.

At last, FFF has shown promise by providing improvements in energy efficiency and material usage, but further research on multi-material 3D printing with production of prototypes made out of two materials will strengthen the results fro Multi Material scenarios.

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