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UNITED IN CREATIVITY

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Preface

In a world shaped by constant transformation and global interconnectedness, design emerges as a bridge between people, places, and ideas. Cumulus Monterrey 2024: Design Across Borders – United in Creativity invited the international design community to reflect on the profound potential of design to transcend cultural, geographic, and disciplinary boundaries, uniting us in the shared pursuit of innovation, inclusion, and positive change.

This edition of the Cumulus Proceedings gathers contributions that respond to urgent questions: How can design foster empathy and intercultural understanding? In what ways does it become a catalyst for social transformation in a complex, globalized world? Can design truly become a universal language—and what are the challenges in achieving that ideal?

The richness of perspectives represented in these proceedings speaks to the global nature of the Cumulus network. Authors, researchers, educators, and practitioners from across continents have come together to share insights, experiences, and provocations within four thematic tracks:

- Design for Change explores design's role in social innovation, sustainability, equity, and the circular economy—highlighting projects that place co-creation and inclusion at their core.
- Speculative Futures ventures into emerging territories shaped by technology, artificial intelligence, and immersive experiences, imagining the future of creative practice.
- Education in Art and Design focuses on pedagogical innovation, interdisciplinarity, and the challenges and opportunities of digital transformation in global learning environments.
- Translocality brings critical attention to issues of migration, decolonization, and the Global South, recognizing the importance of diverse voices and perspectives in shaping a more equitable world through design.

Together, these contributions reflect a collective commitment to harnessing creativity as a force that transcends barriers—linguistic, political, cultural—and brings people together around shared values and visions.

We are proud to present this volume as a testament to the power of design to imagine, inspire, and unite. May it serve not only as a record of this important moment in time but also as a spark for continued dialogue, collaboration, and transformation in the global design community.

Design Across Borders: United in Creativity

Lorenzo Imbesi
Full Professor, Sapienza University of Rome
President, Cumulus Association

The Cumulus Monterrey 2024 Conference marked a timely and vital moment in the global conversation about the role of design in shaping a better world. Hosted at the prestigious design institutions of Tecnológico de Monterrey and Universidad de Monterrey (UDEM), the international gathering has been further enhanced by the unique Monterrey's rich heritage and cultural identity, contributing to a thriving ecosystem of creative exchange for scholars, researchers, and practitioners across various design disciplines.

The central theme of the conference, "Design Across Borders: United in Creativity," provided an inspiring gateway for exploring how design holds the possibility to transcend geographical, cultural, and disciplinary boundaries. In particular, the conference was framed by four imperative trajectories: "Design for Change," investigating how design practices can drive social innovation and sustainable development; "Design Futures," exploring the interplay between technology and creativity, immersive experiences, virtual realities, and the implications of artificial intelligence; "Education in Art and Design," investigating pedagogical approaches in the field; and "Translocality," addressing complex issues of migration, decolonisation, and North-South dynamics. Themes highlight the broad scope of contemporary artistic and design pursuits.

At the heart of the conference was a shared recognition that design can be a dynamic force for empathetic understanding and intercultural dialogue. Through a rich program of keynote lectures, panel discussions, workshops, exhibitions, and informal exchanges, the international community demonstrated determination to work collaboratively across geographical and cultural divides, confirming the foundational premises of the conference: that creativity knows no boundaries, and through design, we can forge connections that transcend the limitations of space, time, and cultural difference. In an era of unprecedented global challenges, from climate change to technological acceleration, from cultural conflicts to social inequities, designing without boundaries means identifying areas of commonality, intersection, and convergence, highlighting them in ways that resonate with and reflect the spirit of our transborder region. As traditional confines between nations, disciplines, and cultural contexts become increasingly permeable, the design community must find itself uniquely equipped to harness this fluidity. Rather than resisting uncertainty, design must embrace it, transforming constraints into opportunities for innovative problem-solving and cross-cultural exchange.

The proceedings collected in this edition offer an extensive variety of perspectives on the ideas and projects discussed at the event. They include case studies, speculative work, educational reflections, and practical strategies, all pointing to the evolving role of design to shape societal interactions, encouraging intercultural dialogue, and building a more harmonious and interconnected world. However, these proceedings capture only a portion of the energy and insight shared during the conference, with the remaining impact continuing to reverberate through ongoing collaborations and dialogues within our global community.

As we move forward, the conversations from Cumulus Monterrey 2024 remind us that creativity thrives not in isolation, but in community. And in a time marked by division and uncertainty, design, when practiced with care and intention, can truly serve as a bridge. One that brings us together to learn, to act, and to imagine a positive change.

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PAPERS

“DECONSTRUCTING THE TRADITIONAL BOUNDARIES OF THE AUTOMOTIVE SYSTEM THROUGH THE RECYCLING OF COMPOSITE MATERIALS IN THE DESIGN AND PRODUCTION OF THE FUTURE CAR”.

Alessandra Savina[a]* , Leandro Leucci[b], Francesca Demichelis[c]* ,
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ABSTRACT | The automotive sector is one of the most environmentally impactful contexts, not only in terms of the car production chain, but also in the use phase, which is still associated with the consumption of fossil fuels. The type of materials used also contributes to its overall impact. However, what happens when eco-design is followed in the automotive scenario, deconstructing traditional boundaries of design and production phases, and embracing the circular economy approach? Experimentation in bio-based materials and the recycling of high-performance materials is developing a broad strand of research. Therefore, investigating consumer perceptions of sustainability in the automotive industry is crucial. Although the demand for products with a low environmental impact lifecycle is steadily increasing, in the automotive context the research for sustainable solutions has to deal with other priority requirements, such as mechanical performance, fuel consumption, etc. The requirement of environmental sustainability often remains secondary. This contribution aims to present the research conducted by the Department of Applied Sciences and Technologies of the Polytechnic University of Turin (Italy), which explores new possibilities of recycling carbon fiber and glass fiber-based composite materials, which, for the same performance, can be reintroduced circularly in the production of new components, to contribute to the reduction of emissions by 2030. The ultimate goal is to design a systemic scenario based on the recycling of composite materials in the automotive industry, in which the user will be able to ‘drive sustainability’, expanding the boundaries of what the car product has identified until now.

KEYWORDS | CAR SYSTEMS, ECODESIGN, RECYCLED COMPOSITE MATERIALS, AUTOMOTIVE SUSTAINABILITY, CIRCULAR ECONOMY

1. Introduction

1.1 The impact of the automotive sector and the value of material selection

Nowadays the automotive sector contributes significantly to the social well-being of several urban and peri-urban areas of the world, as it allows the rapid mobilization of one or more individuals and the reaching of more or less distant destinations with comfortable methods and less effort, compared to the past. This industrial product, of intricate design and production, has been able to modify the lifestyle of entire communities enormously and, at the same time, the structure of cities and neighborhoods, encouraging the development of districts and outskirts, in this way not more isolated from the workplaces, health services, places of leisure, etc. (Handy, 2005; Jacobs, 1961).

Therefore, the car has also changed the urban infrastructure, requiring the planning and construction of roads, highways, parking lots, etc. However, the complex production and supply chain of current cars is progressively leading to negative environmental and social impacts, such as air pollution and climate change, due to the constant extraction of resources, the consumption of fossil fuels, and the consequent emission of greenhouse gasses (Levente, 2021; Hawkins, 2012).
In the past, the research for sustainability in this production field has focused exclusively on the use phase of the motor vehicle rather than on its entire life cycle. This direction was motivated by the fact that the use phase represents a key point in terms of economic impact on the end user and energy consumption (Traverso et al., 2015).

These elements, added to the increase in crude oil prices and the introduction of stringent limits for vehicle emissions, have led to a growing interest in the design and production of more efficient and less impactful cars on an environmental level, influencing consumer purchasing choices. Automotive companies have thus expanded their research into the materials sector, with a specific focus on very light materials, capable of reducing the overall weight of the car and improving its efficiency during use. In this, Automotive Design has played a significant role, in particular for its ability to study and design aerodynamic shapes, as well as Materials Technology. Currently, however, to reduce the environmental impact of the automotive industry, the focus extends to the entire life cycle of the product, also contemplating the impact of the extraction of raw materials, the production of materials and components, the assembly and manufacturing of the car, of its disposal at the end of its life. In the automotive production chain, the selection and processing of materials is a fundamental phase that consistently contributes to the level of sustainability of the finished product, its use, and its end of life. Nevertheless, it is good to point out that a material is also characterized by its own life cycle and, therefore by its ecological burden (Lanzavecchia, 2000). For this reason, a growing interest has emerged in the use of less energyintensive materials, secondary source materials (generally composite, thermoplastic, and metallic materials), and biobased materials, to facilitate the recyclability of components at the end of their life and a reintroduction of recycled materials into the production chain.

In this scenario, the tools and approach of EcoDesign, and in particular of Systemic Design, are fundamental for considering the entire life cycle of the car upstream, up to evaluating the methods that can facilitate the recycling of its technical components, once decommissioned. Furthermore, these approaches can support the analysis of the complexity of current supply chains and their impacts, facilitating the development of future predictive scenarios, to trigger a change in production models starting from the design of more sustainable products, in their complexity. In this context, the research conducted by the Department of Applied Sciences and Technology of the Polytechnic of Turin (Italy) was born, which intends to explore new possibilities for recycling composite materials based on Carbon-Fiber and Glass-Fiber (S.R. Naqvi et al., 2018, Chen et al., 2019), which with the same performance can be circularly reintroduced into the design and production of new components of the car, to contribute to a 50% reduction in emissions by 2030.

1.2 The high-impact linear production processes of Carbon Fiber and Glass Fiber used in the Automotive Sector

The present project intends to contribute to the decarbonization process through the awareness of the composition and impacts of a set of innovative materials for automotive applications. Specifically, the project assesses the impact in terms of carbon footprint of the production of carbon fibers and glass fibers.

Carbon fiber is a fibrous material with a carbon content of more than 92 %wt [Huang, 2009]. The atomic structure of carbon fibers consists of carbon atoms organized in hexagonal structures. These fibers have interesting characteristics in terms of mechanical strength as well as electrical and thermal conductivity [Huang, 2009], making them an attractive material in various industrial fields, such as aerospace, sports (suits, shoes, frames), and automotive. Currently, about 90% of commercially available carbon fibers are produced from polyacrylonitrile (PAN), a polymer derived from oil exploitation. The traditional process consists of three main steps: spinning, stabilization, and carbonization (Figura 1). The first consists of treating the starting compound, called precursor, to obtain a raw filament product. The latter is then treated with oxygen in a furnace between 200 and 400 °C, and then passes into the stabilization phase, to stabilize the fiber. Subsequently, the filament undergoes gradual heating in a no oxygen atmosphere, up to a temperature of 1000 °C, to remove all non-carbon from the fiber surface [Huang, 2009].

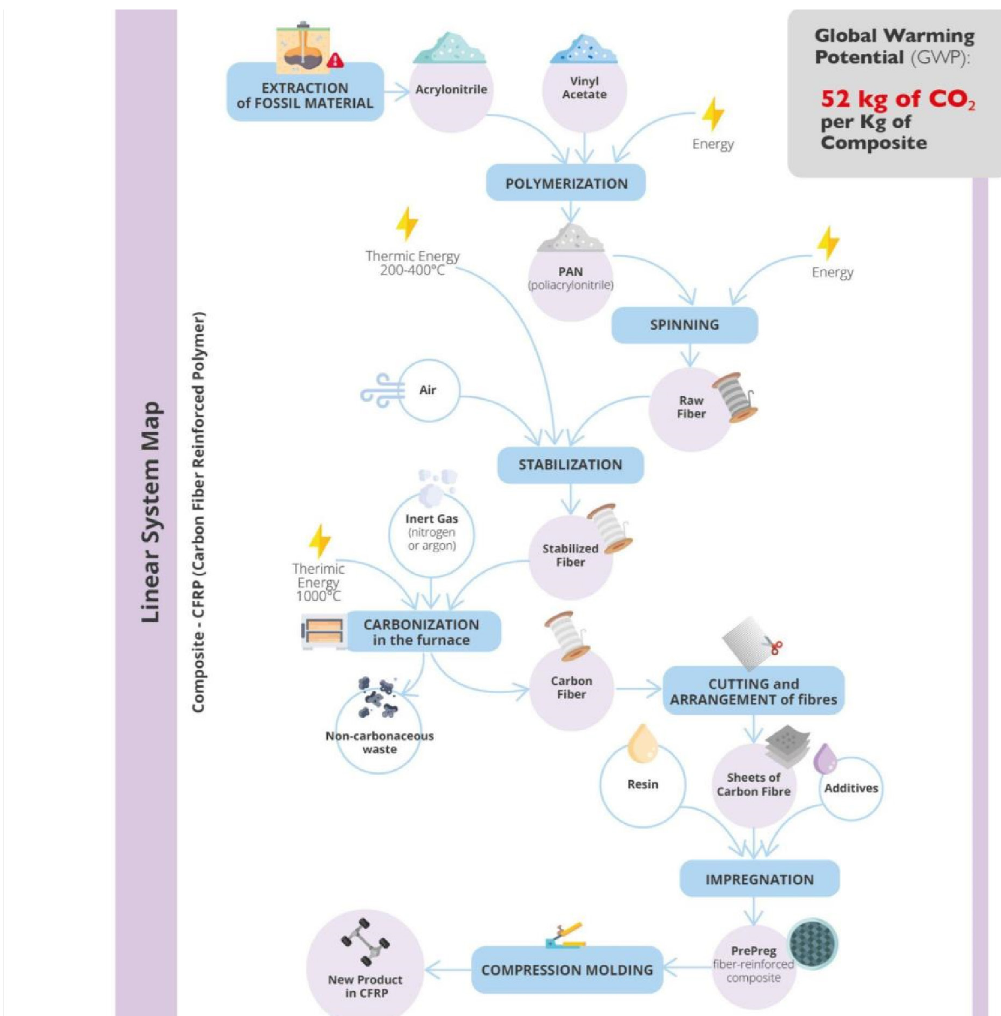

Figure 1. Design of the graphic map of the high-impact linear production system of Carbon Fiber, evaluating inputs and outputs through the Holistic Diagnosis phase described in the methodology.

The conventional carbon fiber production process is critical in terms of the cost of the precursor, which accounts for 53% of the total process [Le et al., 2022], and does not guarantee the sustainability of the process itself, since polyacrylonitrile is a fossil polymer. Consequently, it becomes necessary to focus on the choice of raw material that will be transformed into fiber, thus proceeding to a change of compound, preferring a bio-based precursor (lignin, cellulose), or implementing the use of recycled carbon fiber.

The main application of carbon fibers in the industry is their use in composites with a polymer matrix (epoxy resin, PP, PA6, etc.), defined as a 'fiber-reinforced polymer composite' (FRPC). Specifically, carbon fibers constitute 'carbon fiber reinforced plastic' (CFRP) with percentages between 30-60%wt. These composites are widely used in the aerospace, renewable energy (wind power), and automotive sectors, due to their high mechanical strength, high stiffness, and good corrosion resistance. In addition, they exhibit low density, making them a suitable candidate as a substitute for steel parts in chassis, in the context of weight reduction in cars, with a consequent saving in fuel consumption and thus environmental impact [Das, 2011].

The lifecycle of CFRP is 15 to 20 years [Chen et al., 2023], and considering an increase in the use of this material, attested by the passage from 28,2 to 48,7 billion dollars of global revenue from the sale of CFRP in 2020 [Karuppannan, Karki, 2020], makes the issue of the treatment of the composite at its end-of-life preponderant to avoid the intensification of the environmental impact of the production chain. As a consequence of this, the multidisciplinary research group of the Politecnico di Torino focused on the recycling treatment of the carbon reinforced composite, considering it interesting to search for a recycled treatment that would guarantee both sustainability and adequate mechanical properties to the fiber. In particular, pyrolysis (thermal degradation without oxygen) has been chosen as the best way of treatment, because the fiber recovered has mechanical properties similar to virgin fiber's ones and it does not request a high energy to operate at a commercial level.

Glass fiber is a fibrous material generally consisting of silica, used in several industrial applications, and can be classified into different categories according to its chemical composition and consequently its technical characteristics. A common application is within composites with plastics, to strengthen thermal resistance, gas penetration, and impact resistance. According to the EuCIA (European Composites Industry Association), 95% of the FRPC trade is for glass fiber composites (GFRP). These composites are used in many industrial sectors, such as building, electrical and electronics, transport, production of renewable energy (wind), etc. Their life cycle is around 20-25 years and the estimated waste production of GFRP in 2025 will be 80,000 tonnes from the transport sector only, including the automotive one. This is the third contribution to overall waste production, behind the building industry and electronic sector. In addition, the increase of waste glass fibers due to the development of a growth sector such as wind energy production should not be underestimated, as blades are made of

62%wt GFRP [Gonçalves et al., 2022].
In the automotive sector glass fiber composites are implemented in internal components such as center stack retainer, pull handle, console reinforcement etc. The cost of virgin glass fibers is around 1,20-1,90 €/kg, while carbon fibers cost 105 €/kg in the highest quality cases [Naqvi et al., 2018]. This significant price difference means that the valorisation and disposal costs of glass fiber waste are crucial in seeking to implement an improvement in waste management. As a consequence of the low cost of raw materials for virgin glass fibers, mechanical recycling is the most widely used process to recycle, reducing the size of composites through a grinding machine. The resulting mill is composed of resin, fiber, and possible filler, which are separated by gravity (Figura 2). It has several advantages such as industrial scale-up, low environmental impact, and cost-effectiveness, but It causes a significant degradation of fiber that will not be used in the same components as a virgin material. In this project we evaluate the impact of mechanical recycling compared to the traditional process of manufacturing glass fiber composite.

With a view to applying the Circular Economy to the production system of materials used in the automotive sector, in the following paragraphs the design methodology applied in the explored research project will be described and the experiments carried out with a view to recycling materials and producing new components of the car starting from greater sustainability of the system.

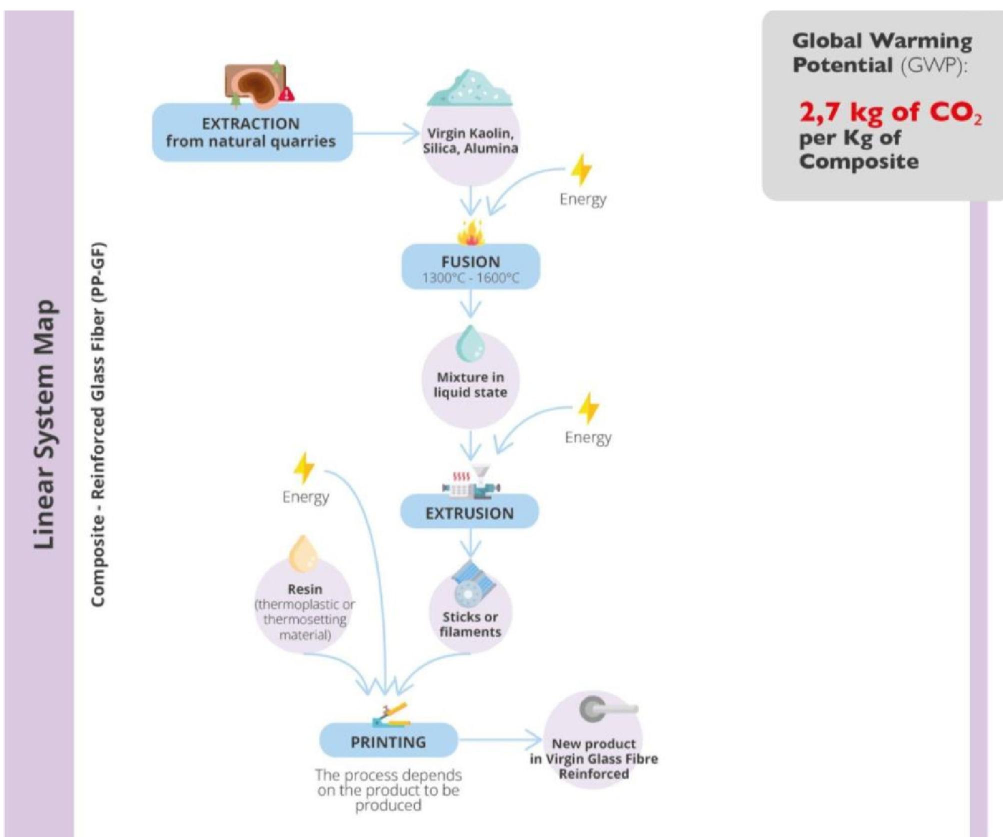

Figure 2. Design of the graphic map of the high-impact linear production system of Virgin Glass Fiber, evaluating inputs and outputs through the Holistic Diagnosis phase described in the methodology.

2. Methodology

2.1 The EcoDesign approach in the methodological path undertaken

For the general development of the project, the typical EcoDesign methodology was followed, with a specific focus on systemic design. EcoDesign is an ecological approach applied to the design of products, structures, architectures, technologies, industries, and processes, aimed at bridging the gap between sustainable ecological systems (therefore what is part of the great system of Nature) and artificial human scenarios (thus what has been designed, produced and created by man to develop his contemporary lifestyle). For this reason, the EcoDesign principles reflect the organizational ones that Nature has always used to support life. Adopting the EcoDesign approach requires first of all a change of cultural, design and production paradigm (Capra & Luisi, 2014). It overcomes the linear production model (Take-Use-Dispose)(Ellen MacArthur Foundation, 2012) whose objective is to exclusively exploit natural systems for the constant extraction of resources, in order to develop new design and production strategies that look to Nature as a model, measure, and guide and try to understand how to cooperate with it, rather than dominate it (Benyus, 1997).

For simplicity, it is possible to summarize two large macro-categories, intrinsically connected, into which EcoDesign is dissected:

· the recycling of elements, materials, and waste products mainly within the production chains, where further specific approaches are used that are compatible and complementary to those of eco-design, such as the Systemic Design and Circular Economy approach;

· the sustainable design of products, structures, processes, architecture, and even cities, giving space to Design by Components or the development of EcoCittà and Green Architecture which follow the Biomimicry approach, according to which many human problems have already been largely solved by other living organisms present in Nature.

At the basis of these approaches is the key principle of ecology (Commoner, 1971) according to which nature knows no waste, therefore every manufactured product, every transformed material and all industrial or domestic output produced must necessarily become a form of nourishment for others systems, compatible with the first pillar of Systemic Design, according to which the outputs of a system must be valorized as inputs of another system (Bistagnino, 2011). This form of nourishment depends on the type of metabolism (biological or technical) in which a working group operates. In the case of production chains such as the automotive

one, the outputs are considered real technical nutrients, i.e. all those non-biodegradable elements that belong to industrial cycles and which consequently cannot be metabolized by other living organisms, as instead happens in biological metabolisms (e.g. composting or fermentation processes) (McDonough, 2013). A technical nutrient is designed to be part of a technical cycle, therefore its recycling in the industrial field is profoundly different from other types of ordinary recycling (such as domestic recycling), as it is necessary to preserve the high intrinsic quality of the material, which must undergo reduced levels of contamination and degradation.
In this research the discipline of EcoDesign met that of Chemical and Environmental Engineering and that of Materials Technology, developing a technical methodology in which the evaluation of environmental impacts is fundamental.

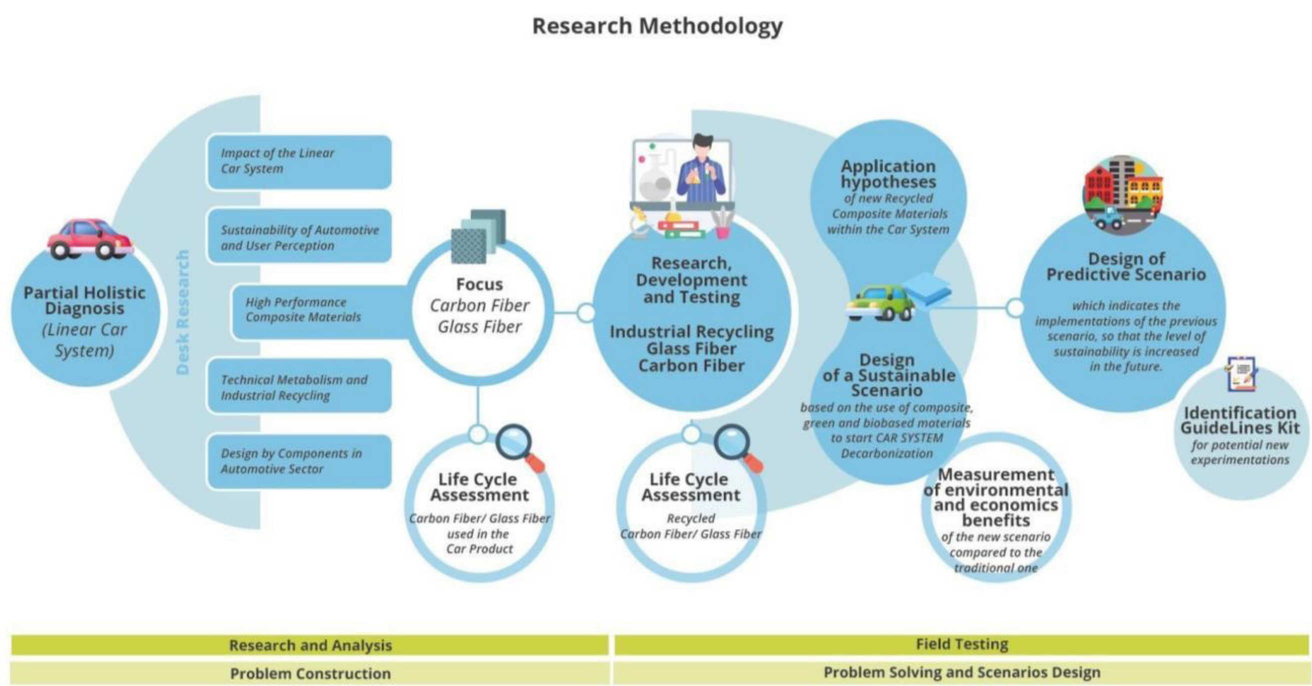

Figure 3. The methodology followed in the research undertaken for the application of circularity to the car system: the complementarity of EcoDesign and LCA approaches and tools

The starting point was the development of a partial Holistic Diagnosis of the car's high-impact linear system (Figura 3). Considering the complexity and breadth of this system and the choice of predefined materials (Carbon Fiber and Glass Fiber), only the car components made of these materials were considered, but it was also useful to evaluate those which, although produced in different materials, they could potentially be produced with study materials, in the future.

Through desk research, the generic environmental impacts of the motor vehicle and the perception of sustainability in the purchasing decisions of a car by the end user were investigated. Furthermore, the existing scientific literature on traditional production models of carbon fiber and glass fiber and their recycling possibilities was examined. Finally, considering the technical metabolism to which the automotive supply chain belongs, the potential of Design for Components (Felfernig et al., 2014) in the Automotive sector was explored. The latter is an approach adopted upstream in the design of a product, in order to facilitate its disassembly at the end of its life cycle, the recovery of materials and components, differentiation according to materials and, in cases of reconditioning, the replacement of specific damaged components. It is therefore fundamental in the case of complex multi-material products, especially if the objective is to extend their life cycle and/or that of the materials used in them.

The second fundamental step was carrying out the Life Cycle Assessment of Carbon Fiber and Glass Fiber currently used in the automotive sector, which supported the start of the phase of concrete experimentation and the development of recycling techniques for these composite materials. The objective will be to develop a new LCA on new materials obtained from the recycling process to evaluate the benefits of using the latter in the same sector, as well as in others.

Subsequently, specific hypotheses for the application of the new circular materials to the car system will be developed, designing a more sustainable scenario based on the recycling of composite materials to contribute to the process of decarbonization of the car product. In this way, it will be possible to compare the new scenario with that emerging from the Holistic Diagnosis of the high-impact linear system.

To conclude, the last step involves the design of a predictive scenario that can indicate the necessary implementations of the project, so that the level of sustainability achieved is expanded, also considering additional factors in addition to decarbonization (e.g. water footprint, social sustainability, etc.). In this sense, a kit of guidelines will be developed for new potential experiments not only in the sector of the materials investigated, but also in the use of further materials explored by the Polytechnic of Turin, such as bioplastics, lignin, hemp, and the use of low impact alternative batteries.

2.2 The role of Life Cycle Assessment in ongoing research

As already mentioned, within the methodology followed, the evaluation of the environmental impacts of the life cycle of the materials investigated was a key element. In detail, the Life Cycle Assessment (LCA) is an international standardized methodology (ISO 14040-44) adopted to evaluate the environmental impacts of products, processes, and services. The assessment encompasses all stages from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling. The study of Life Cycle Assessment (LCA) in the automotive sector plays a crucial role in evaluating and reducing the environmental impact of vehicles throughout their entire life cycle. LCA can quantify the vehicle's environmental impact from the raw material extraction phase, through production, use, and disposal, by identifying the life cycle stages with the highest environmental impact. This stage represents the bottleneck and requires to be reduced to decrease the whole environmental impact associated with the investigated product, process, and services. Currently, the key actions taken by the automotive sector include optimizing materials and resources to design vehicles with lower environmental impacts across various impact categories and contributing to the decarbonization of vehicles in their whole life cycle. Specifically, the optimization of materials and resources for vehicle design involves two fundamental points: 1. material recovery and recycling and 2. optimization of production processes. Material recycling involves studying the life cycle to improve the recycling of vehicle components, reducing waste, by enhancing material efficiency and preventing resource consumption (Del Pero et al, 2018). Optimization of production processes identifies energy-intensive production stages and develops strategies to reduce energy consumption and emissions, like for instance considering alternative and renewable energy or increasing efficiency. For automotive companies, the LCA represents a credible tool for clear and transparent communication of their commitment to environmental sustainability to stakeholders (customers, regulators, investors). Environmental studies based on LCA can support marketing strategies and corporate social responsibility initiatives. Information obtained from LCA supports strategic decisions regarding research and development, new product design, and supply chain management. Companies can make informed choices to improve the overall sustainability of their operations.

In the present study, the LCA aims to evaluate the impact of the processes of manufacturing traditional composite and composite made of recycled fiber, either for glass and carbon fiber.

This comparison is based on global warming potential (GWP) ($kg_{CO2}/kg_{Composite}$). For the production process of composite from virgin fiber, we will analyze production "from cradle to gate", meaning that we consider the production system from the raw materials to the composite ready for the application stage in the car. The production system of recycling process is evaluated "from grave to gate", so from the composite at the end of its life to another composite ready for the use phase (Gregson et al., 2015; Braungart et al., 2007; Hauschild et al., 2005),. The scope is increasing use of materials from circular economy processes in the overall design of automotive production chains. In this sense, we aim to contribute to the general sustainability of the car product, acting on the steps that precede the use phase and which do not have direct contact with the end users, although they can influence in them purchasing choices.

3. Results

3.1 The recycling of Carbon Fiber and Glass Fiber as a process to increase the level of decarbonization of the cars of the future

As mentioned in the previous paragraph, the first phase of analysis of the methodology undertaken involved carrying out the Life Cycle Assessment of the materials analyzed in order to evaluate the current environmental impact of carbon fiber and glass fiber in the traditional car product.

Specifically, concerning results of LCA for carbon fiber, the amount of carbon dioxide released into the atmosphere from the production of the composite from virgin carbon fiber is 52,4 kg CO_2 eq. The process of treating CFRP to obtain rCFRP releases 11,4 kg CO_2 eq into the atmosphere. In the carbon fiber production process, the carbon dioxide impact of the initial compound is considerable, as it accounts for around 53% of the total. This is due to the use of raw material of a petroleum nature, but above all also due to the energy-intensive nature of the process, as the high energy required to produce one kilogram of carbon fiber, a value that is also consolidated in the literature [Chen et al., 2023]. As far as the composite calculation is concerned, carbon fiber plays a greater role than epoxy resin. On the other hand, the carbon footprint of the thermal recycling treatment of CFRPs is mainly dependent on the energy required for pyrolysis process and on the impact related to the use of new epoxy resin to produce composites from recycled fiber. The latter is the raw material that can be considered as the main contributor to the environmental impact of the recycling treatment. Possible process improvements to reduce the CO_2 release are the possibility of exploiting the pyrolysis gas, initially by trying to recover possible condensable compounds that together with a liquid phase produced by pyrolysis (not considered in this first analysis) can constitute a compound comparable to a resin of a phenolic nature [Quan,2010].

To evaluate possible improvements of the process, experimental tests were conducted on the pyrolysis of a carbon fiber composite to evaluate the products obtained, analyze them, and hypothesize energy and chemical enhancement solutions. Experimental tests designed showed the excellent recovery of carbon fiber from the composite, with the production of a gas phase and an oil component (Figure 4). These two phases are composed of all those molecules resulting from the degradation of the resin present in the starting composite. The gas phase was analyzed, showing the increased presence of compounds such as hydrogen and methane, making it actually interesting from the point of view of energy utilization for the purpose of powering the recycling process itself. The oil phase has compounds called “phenols,” which have various applications in industry, from nylon production to cosmetics. Moreover, the presence of such molecules in the oil phase is also attested in literature [Quan, 2010].

To better trace the qualitative comparison between the traditional production systems of the investigated materials and the circular systems experimented with their recycling and reuse in the automotive sector, graphic relational maps (generally typical of Systemic Design) were developed. Indeed, through a graphic representation, understanding the inputs and outputs of both processes, as well as the different phases used in them, is more immediate.

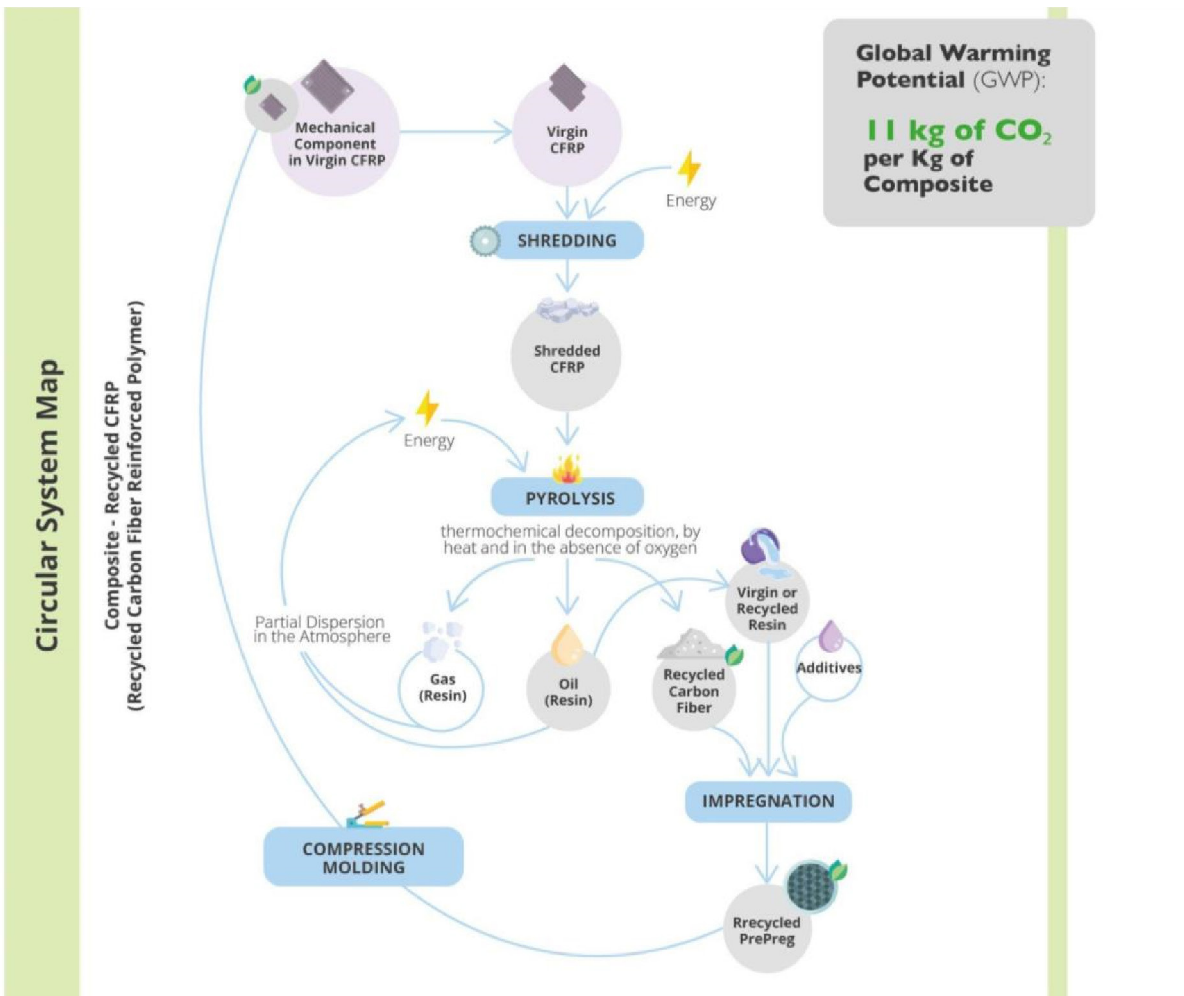

Figure 4. Design of the graphic map of the circular production system designed, experimented and tested for the Carbon Fiber Composite. Inputs and outputs reintroduced into the system were evaluated.

The same evaluation and design process for new recycling processes was also carried out for glass fiber. The amount of carbon dioxide released into the atmosphere from the production of glass fiber composite (GFRP) is 2,7 kg CO2 eq. Instead, the alternative process of grinding GFRP and re-moulding recycled glass fiber with virgin fiber and polypropylene releases 2,3 kg CO2 eq into the atmosphere (Figure 5). The main contribution to the carbon footprint of the composite with only virgin fiber and with the virgin/recycled blend is given by polypropylene (respectively 59 and 65% of the total GWP calculation). There is a difference between the two processes: the recycling process is less impactful than the traditional one, but this is not so wide. It could be a consequence of not reusing the polypropylene from the mechanical separation by grinding, stressing the concept of consumption. The mechanical recycling process of composites can be improved through the above-mentioned reuse of recovered polypropylene, but also by considering a higher percentage of recycled fiber within the composite. Consequently, a further project could be the evaluation of all the blend options proposed by Kang et al. (2021), including the use of long glass fibers, both virgin and recycled. To assess the consistency of the work carried out, it is interesting to compare the results obtained with what can be found in the literature. As far as the modeling of the traditional process is concerned, the GWP related to the traditional production of GFRP is around 3-5 kg CO2 eq, thus in line with what was calculated through this analysis [Rajendran et al.,2012] [Reichenbach et al.,2021]. In fact it is necessary to consider that the process of recycling and producing a composite has one more step compared to the traditional one, namely the mechanical treatment, which, by its nature, requires the use of energy.

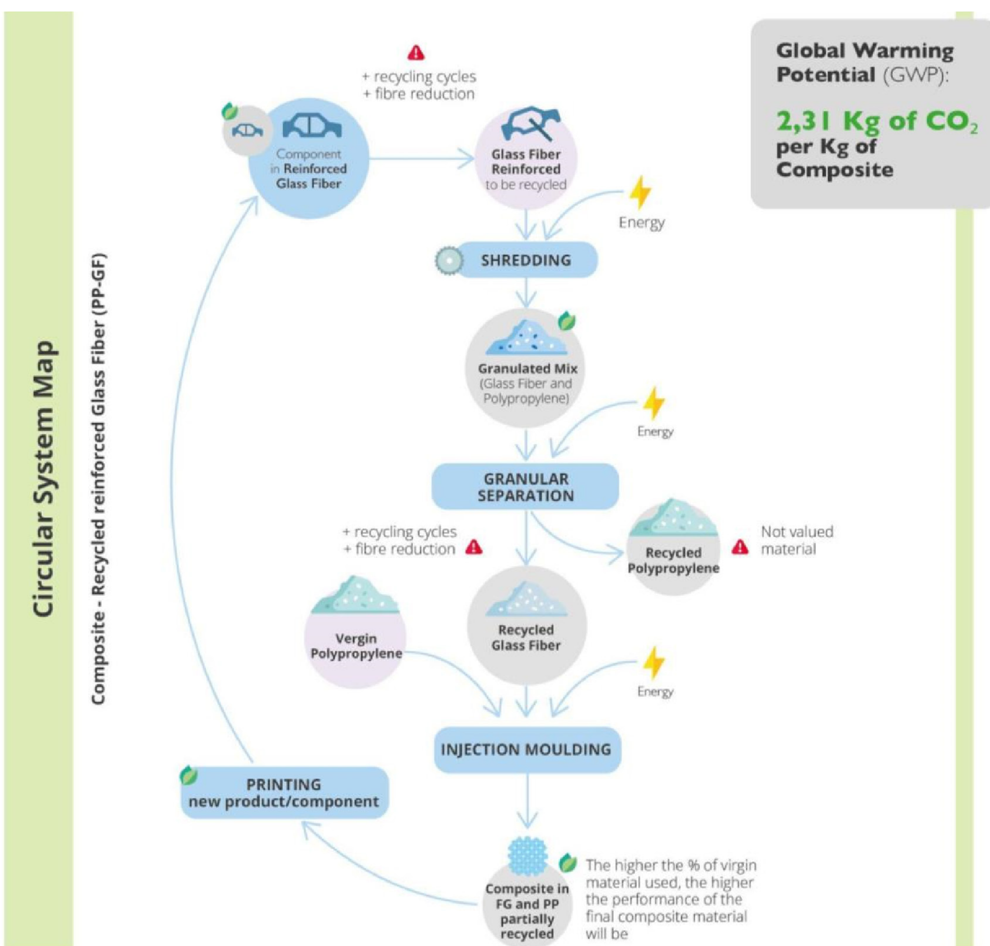

Figure 5. Design of the graphic map of the circular production system designed, experimented and tested for the Glass

Fiber Composite. Inputs and outputs reintroduced into the system were evaluated.

To conclude, it is possible to assert that the mechanical performances, properties of the composite made from recovered carbon fiber are about 90%, compared with the composite made from virgin carbon fiber [Chen et al., 2023]. To prove this, experimental mechanical stress tests will be conducted in the future in order to have direct data. Also regarding glass fiber reinforced composite, the formation process of the composite made from the recycled fiber was modeled in order to have mechanical properties not less than 90% of those of the virgin fiberreinforced composite. The blend (recycled fiber + virgin fiber) that allows the composite to meet this standard is at 60:40 (wt%). This choice has been made by taking in consideration a similar study conducted by Kang et al. (2021), where the authors tested blends of virgin mixes (glass fiber + polypropylene) with recycled ones. In this case we model a blend of virgin and recycled glass fiber with virgin PP. For these reasons, investing in the recycling of these composite materials is an important direction to achieve greater levels of sustainability of the vehicle.

Considering that they are adequate to offer good structural resistance and durability, comparable to virgin fiber in many cases, some application hypotheses have been presumed in the automotive system to reduce the overall weight of the macro-product, increasing efficiency in terms of speed, emissions, and fuel costs. It has been estimated that recycled carbon fiber composite can be used in some components of the external bodywork of the car, such as the bonnet, bumpers, and doors, and other internal components, such as the dashboard, the internal structures of the seats, defined as underbody sections and frame, handles, etc. Complementarity, the recycled fiberglass composite can be used to cover side mirrors and grilles, which, in addition to requiring a weight reduction, need excellent resistance to atmospheric agents. However, it can also be used in the production of the center console and trunk linings, acoustic/thermal insulation panels.

3.2 The uses of EcoDesign for a more sustainable Automotive System

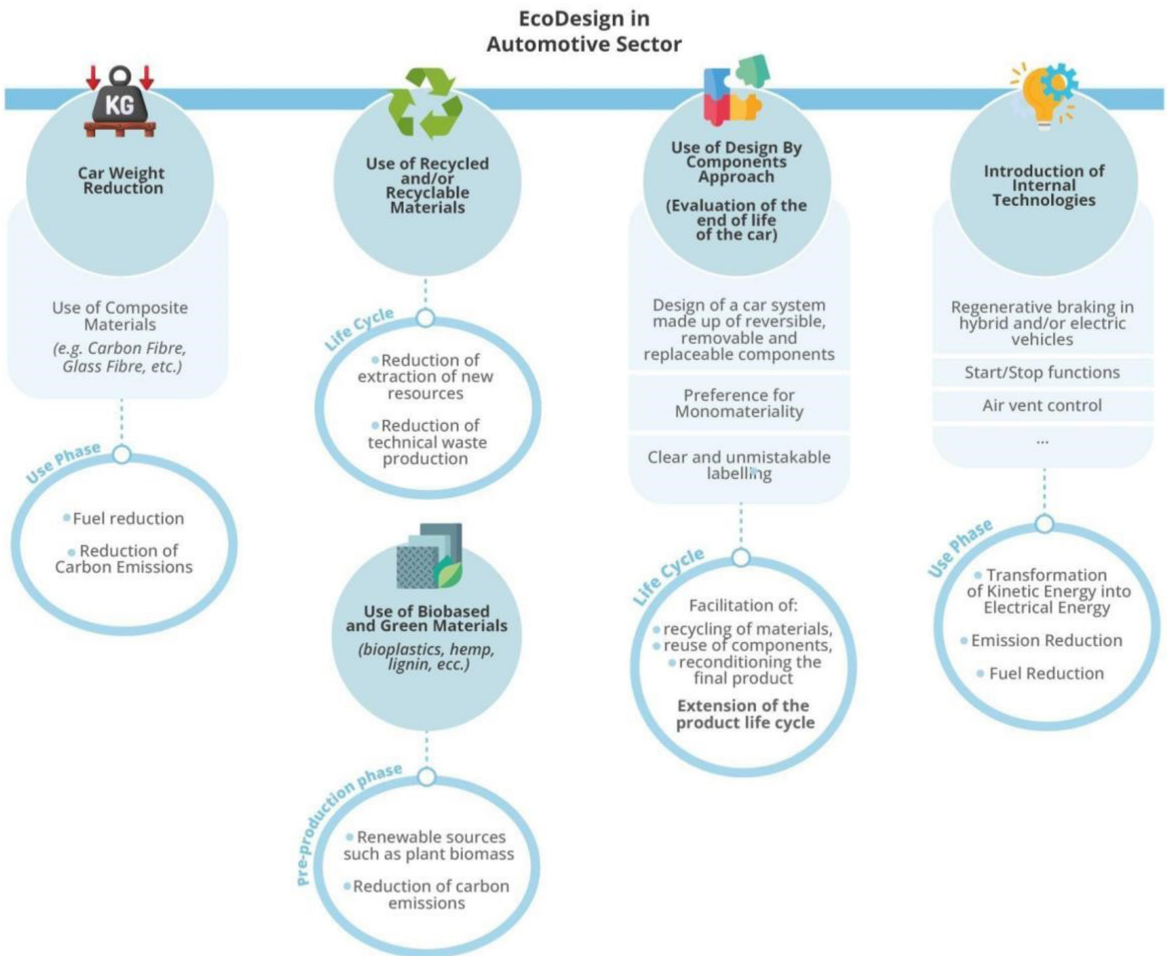

Figure 6. Applications of EcoDesign Approach in the Automotive Sector

Designing products with a minimum weight, by reducing the quantity of materials used and through the use of lightweight, high-performance, and durable materials at the same time, is a challenge that does not only belong to the automotive sector but in general to any market segment who wish to design and produce sustainable and easy-to-use everyday products. The scenario of increasingly lighter products (to the point of reaching dematerialisation) and with a reduced ecological burden is also increasingly requested by consumer communities. In the case of extremely complex products that require numerous components, some of which are characterized by high thicknesses and metallic materials, good eco-design is fundamental. This is the case of the car system, which increasingly requires a change in the design of its life cycle. In this project, fundamental guidelines have been drawn up which, through the adoption of the EcoDesign approach, can lead to the production of increasingly green cars, not only in terms of decarbonisation (Staniszewska et al., 2020), where the requirement of a correct choice of materials remains imperative.

These guidelines can be summarized in (Figure 6):

- Reduction of the overall weight of the car, through a formal and functional design of its components and the use of highly performing composite materials characterized by a low specific weight, such as carbon fiber and glass fiber. The reduction in weight, in fact, allows to reduce the need for fuel during use phase, consequently minimizing the emissions produced.

- The use of recycled and/or recyclable materials, coming from the automotive production chain (closed system) or other supply chains (open system), in order to decrease the extraction of new resources and the disposal of difficult-tomanage technical waste.

- A significant growth in the use of green materials and/or biobased materials, coming from renewable sources such as plant biomass, to reduce the extraction of resources from fossil sources. An example of these materials are hemp, lignin, and the entire family of bio-polymers, characterized by a less impactful life cycle.

- The adoption of Design by Components as a design approach, although considered upstream in the life cycle of a car, allows for efficient and sustainable actions at its end-of-life. The design of a system characterized by reversible, removable, and replaceable components, distinguished as much as possible by monomateriality and clear labeling, would greatly facilitate the recycling of materials used in the automotive system and their reintegration into the same or other production chains, thereby extending the life cycle of both the materials and the vehicle itself (also overcoming the barrier of planned obsolescence).

- Finally, the adoption of technologies inside the car capable of strategically reducing emissions and fuel use during use (a good example could be the design of regenerative braking, in the case of electric cars, useful for transforming energy kinetics into electrical energy to power the batteries).

These design directions demonstrate the fundamental role of the eco-designer in the preproduction phase of a product's life cycle. The eco-designer is capable of having a systemic view of the production chain, evaluating the inputs and outputs of each phase of the chain, and consciously designing an end-of-life for the product that avoids material and energy losses, thereby extending the life of materials and products. However, implementing such a design and production change in the automotive sector requires overcoming a series of organizational and economic obstacles. These are not only connected to the research and development of new technologies but also, and more importantly, to managerial resistance (Kayikci, 2021). For this reason, it is essential to plan training and awareness programs for stakeholders throughout the production chain to promote a corporate culture oriented towards sustainability. Additionally, fostering partnerships with other companies, research institutes, and governments is crucial to creating true ecological clusters where the exchange of resources, energy, and information is fundamental to deconstructing the traditional boundaries of the automotive system.

4. Conclusion

The experiments initiated within the project presented in this paper are not yet concluded. The project is considerably broader, and the Politecnico di Torino, through the transdisciplinary collaboration of various departments (Department of Applied Science and Technology, Department of Environmental, Land and Infrastructure Engineering, and Department of Energy), where several designers are working, is indeed initiating a series of research and development tests on additional materials and technologies of interest for a more sustainable and comprehensive automotive system scenario, with the aim of modeling a design and production change for the latter in the coming years.

The results presented focus exclusively on the recycling of high-performance composite materials, such as carbon fiber and fiberglass; however, their use in the automotive industry must be considered by evaluating all the dimensions and requirements of EcoDesign previously explored.

Similarly, it is possible to assert that the use of Life Cycle Assessment (LCA) is not exhaustive if the goal is to calculate the most comprehensive dimension of a product's sustainability (environmental, social, and economic). In fact, in the experimental tests presented, LCA was primarily used to evaluate the Global Warming Potential (GWP) of the composite materials investigated. However, currently, techniques such as the Life Cycle Thinking Approach (LCT) (Traverso et al., 2015) exist, which are capable of implementing a joint evaluation of the results derived from Life Cycle Assessment, Life Cycle Costing (LCC) (evaluation of all costs related to the product life cycle and translation of these into environmental costs), and Social Life Cycle Assessment (SLCA) (evaluation of the social performance of a product's life cycle, considering working conditions, impact on the local community, etc., and extending this evaluation to all actors in the production system).

Within the sustainability of the automotive system, the final consumer also plays a key role, influencing product and technology design through their preferences and purchasing choices. Although the car is an extremely functional consumer good, it is not uncommon for it to represent a status symbol, especially as brands, models, and materials used increasingly align with the luxury sector, thus distancing themselves from the concept of sustainability (Fitt, 2023). While in the agri-food sector and fast fashion, there is a progressive increase in the demand for products with a low environmental and social impact life cycle, in the automotive context, the search for sustainable solutions and processes must contend with other priority requirements, such as mechanical performance, maintenance needs, consumption, costs, safety, and so on. In this regard, environmental sustainability often remains a secondary requirement, especially during the demand phase by buyers (Hetterich et al., 2012; Saari et al., 2020). Nevertheless, growing environmental awareness is having a direct influence on diverse purchasing decisions. Linked to the introduction and strengthening of increasingly stringent government regulations regarding vehicle emissions and air pollution, as well as appealing tax incentives, it is leading consumers to be more willing to spend more on more sustainable products and vehicles, which can result in future fuel savings and a reduction in environmental impact even during use. Environmental impact is indeed an increasingly important factor in the purchasing process. In this context, which certainly presupposes a transitional era, designing for low-impact life cycles can lead to substantial changes in the production sector and in the daily lives of consumers, who are increasingly eager to "live" and "drive" sustainability.

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