Doctoral Dissertation
Doctoral Program in Management, Production and Design (35th Cycle)

Life cycle assessment to support the design of a new road manufacturing process with recycled materials

By

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Politecnico di Torino 2022

Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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2022

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

I have not failed. I've just found 10,000 ways that won't work

Thomas Edison

Acknowledgment

I would like to acknowledge the contributions of the researchers from the DIATI Department of Turin Polytechnic University, Prof. Chiappinelli and Dr. Tefa, for their support in organizing the LCA work. I would also like to thank the companies that contributed to the data collection SAM SpA and Proplast.

Abstract

Plastics are a key asset used in many manufacturing sectors, but in addition to convenience factors such as affordability and easy processability, negative impacts due to their production are increasingly being considered. One solution to production from fossil fuels can be recycling, which allows these materials to be given new life. Such practices are becoming increasingly popular, in numerous fields of application; one example for different polymers concerns the use of recycled polymeric materials within asphalt mixes in order to increase specific mechanical or thermal properties. The world of asphalt and road construction also allows the recycling of both individual asphalt layers and stone aggregates. This type of operation usually requires a lot of energy consumption and is limited in terms of polymer reuse and the environmental impact of extracting bitumen from petroleum.

There are several methods for assessing the environmental impact of a product/process. One of the most internationally recognized and regulated by both standards and European protocols is Life Cycle Assessment (LCA). This methodology makes it possible to obtain estimates, on different environmental indicators, of a product, to obtain a wide-ranging assessment, not limited to a single category or subsystem.

The main focus of this Ph.D. research, conducted at the Materials and Micro Systems Laboratory of the Polytechnic University of Turin (Chilab), concerns a life-cycle assessment of a new process for road production. This process in order

to construct the road layer uses recycled materials, such as polymers and milled asphalt.

The research involved conducting two case studies. The first concerns a case of classic asphalt production from virgin materials (stone aggregates, bitumen, bitumen emulsion and filler). While the second case concerns production according to the newly developed technology involving the recycling of polymers and milled and reprocessed asphalt. The analysis was comparative in nature, and consequently the same functional unit, the same main information database, and the same methodology for calculating impacts were used. The conduct of the classic case is motivated by the need to obtain benchmark data with which to compare the indicators of the innovative case.

The thesis is organized by a theoretical research section on the various recycling technologies for polymers and asphalt and a second section in which the analyses conducted are described and the results obtained are compared. For each analysis, the research focused on creating a Life Cycle Inventory by production process, collecting data from both primary sources through experimental measurements and secondary sources from literature. Following the analyses, an inventory of results was produced for each of the two processes.

The end result was the obtaining of a profile of environmental indicators related to the process as a whole and the identification of the individual processes with the greatest impact, so that the innovative process could be developed according to a greater environmental consciousness.

Contents

List of Figures

List of Tables

Chapter 1

Polymer recycling process

1.1 Introduction to polymers

Plastics are one of the fundamental components in today's human life. Since their industrial development, they have emerged with a remarkable rate of growth as the best alternative for many applications. Their uses are numerous and different from each other, such as the production of consumer goods, in food or medicine packaging and in the production of clothes. This preponderance is valid from many points of view, such as the ease of processing in industrial processes, the wide availability of raw materials and low process costs. All these factors led to the widespread consumption of plastics in recent decades, to the point of making them a normal component of people's everyday lives.

However, despite their countless advantages, plastics also entail many environmental disadvantages linked to their use. It is only in recent years that criticism has begun to arise on these aspects thanks to a greater awareness of the subject. To fully understand the impact of polymers on the lives of humans and the Earth, it is necessary to understand what plastics are and the mechanisms that govern them.

Polymers are high molecular weight macromolecules made up of many elementary molecules, called monomers, joined together to form long chains of various shapes. Based on their origin, polymers can be classified into natural and synthetic. Synthetic polymers, i.e. those produced through chemical synthesis, are the most widespread and consequently also the most interesting for their environmental impact.

A polymer can be represented from a chemical point of view by knowing the starting monomer, the monomeric unit (what is left of the monomer inside the polymer) and the repeating unit, that is the structure that is repeated n times in the polymer.

There are various criteria by which to classify synthetic polymers; the most used relate to the properties of greatest interest, such as the type of reaction used in their synthesis, the type of growth of the macromolecules, the structure of the chains, and their most important mechanical, thermal, and electrical properties.

Polymers are synthesized in processes called polymerization in which macromolecules are produced. There are different types of processes depending on how the synthesis is developed, however all of them start from a low molecular weight substance called monomer that will form a high molecular weight product, that is the polymer. The processes of synthesis are very important, because starting from the same monomer it is possible to obtain different macromolecules of different molecular weight or different degree of polymerization. Based on the kinetics of the synthesis reactions, polymerization processes can be classified as step-growth or chain-growth.

Step-growth polymerization, that in most of the cases coincides with the polycondensation reaction, occurs through the reaction between two functional groups, with formation of a new functional group in the main chain that is not present in the monomer. Polycondensation involves the formation of a low molecular weight by-product. In this case the starting point are two different monomers, with appropriate reactive groups able to react eliminating secondary substances (water, etc.): the reaction produces the formation of covalent bonds between the two monomers that alternate regularly in the growing chain. This type of reaction is called step-growth polymerization because it involves two successive stages:

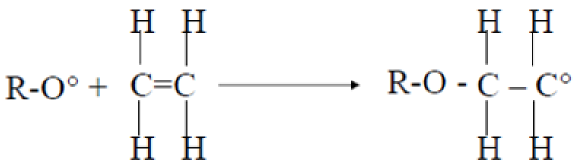
- in a first reaction stage, the condensation product between the two monomers is formed;
- in a second successive stage, the various condensation products react with each other with chain elongation.

Chain polymerization, that in most of the cases coincides with the polyaddition reaction, occurs with three stages: initiation, propagation and termination. Initiation consists in the activation of the monomer molecules by the opening of the double bond by reactive species (a group of atoms with an unpaired electron that can bind covalently with an unpaired electron of another molecule). The polyaddition can be: radical, cationic, anionic, depending on the nature of the growing reactive center. The most common is the radical polyaddition, in which radical initiators such as peroxides are present, which fragment in a homolytic way by heating releasing radicals and initiating polymerization.

Equation 1: Formation of free radicals from peroxides

$$R - O - O - R \xrightarrow{heat} 2R - \dot{O}$$

Equation 2: Opening of the double bond by the free radical



In propagation, monomer units are added to the chain. It is an energetically favored process because the sum of the energies of the polymers produced is less than the sum of the energies of the monomers.

Equation 3: Addition of monomeric units to the chain

$$R - O - CH_2 - \dot{C}H_2 + CH_2 = CH_2 \longrightarrow R - O - CH_2CH_2CH_2\dot{C}H_2$$

Termination occurs by addition of a free radical or by the combination of two chains. Sometimes traces of impurities close the chain.

Equation 4: Chain termination

$$2\,R - O - CH_2CH_2CH_2\dot{C}H_2 \longrightarrow R - O - (CH_2CH_2)_4 - O - R$$

The polyaddition is carried out on single unsaturated monomers with double bonds or cyclic, or on two different monomers, one saturated with groups able to give addition to double bonds present on the other unsaturated.

Chain-growth polymerization is typically fast and highly exothermic, and significant molecular weight is developed from the beginning of the process. Conversely, in step-growth polymerization the process is typically slow, low exothermic and the average molecular weight grows slowly. The main synthesis processes are:

- Radical polyaddition
- Cationic polyaddition
- Anionic polyaddition
- Coordinated anionic polyaddition
- Polyaddition with isocyanate attack
- Ring-opening polyaddition
- Polycondensation: with SN_2 reactions, with carbonyl attack, with aromatic electrophilic substitution.

Polymer properties are influenced by multiple factors inherent in the synthesis process and the mutual positioning of molecules within the polymer chain. The chain structure of a polymer can be linear, branched, or cross-linked (Figure 1). In general, polymers with a linear or branched structure correspond to thermoplastics, while crosslinked ones are thermosets. Polymers with a linear chain are formed by an ordered succession of monomeric units; the chain can be arranged in different conformations, remaining straight or folding on itself. This chain arrangement influences the way in which the chains can pack: tangled chains produce a disorderly situation and the polymer is called amorphous, straight chains produce an orderly packing with the chains arranged in parallel and the polymer is called crystalline. Normally most polymers are in intermediate situations between the two extremes and have disordered areas interspersed with other more ordered ones. Polymers with branched chains have many small chains protruding from the main chain. These ramifications decrease the crystallinity because the packing is hindered by the reciprocal position of the chains; the consequence is the obtainment of a less dense polymer with lower mechanical properties and heat resistance. Polymers with cross-linked chains have the chains joined together by bridges that create a three-dimensional network structure that gives the polymer greater rigidity and great resistance to heat that does not allow it to melt. Another criterion concerns the order of positioning of the single molecules inside the chain: in case of asymmetry of positioning attactic polymers are obtained, i.e., without steric regularity.

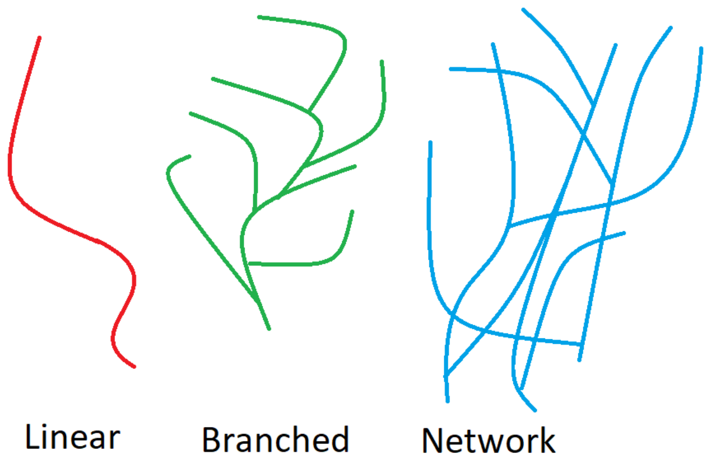


Figure 1: Polymer structures

The degree of polymerization of a macromolecule is given by the number of concatenated monomer molecules from which it is formed; in a polymeric material it is possible to establish an average degree of polymerization. The chains can be divided, according to the degree of polymerization, in oligomers and low, medium and high polymers as shown in the Table 1.

Table 1: Degree of polymerization

Type of macromolecule	**Average degree of polymerization**
Oligomer	2-10
Low polymer	10-100
Medium poymer	100-1000
High polymer	>1000

Many mechanical properties of polymers, such as viscosity, heat capacity, elastic modulus, and coefficient of thermal expansion, are affected by particular critical temperatures typical of the materials. In crystalline polymers, a melting temperature is reached as the temperature increases. Instead, amorphous polymers are characterized by the presence of the glass transition temperature (Tg); below it the polymer is characterized by a limited molecular mobility and is glassy, while above it is flexible in the rubbery state. By further increasing the temperature, the material becomes fluid. The glassy transition is not a thermodynamic transition, but a kinetic one, which does not correspond to a change in the position of the atoms in space, as the polymer retains the structural disorder of the amorphous state. The change in mobility of the polymer chains results in a dependence of stiffness on temperature. A polymeric material in the glassy state has a brittle and rigid behavior. Semi-crystalline materials exhibit two thermal transitions, having both a glass transition temperature and a melting temperature. Polymers, in general, are good thermal and electrical insulators.

One of the most widely used classifications for polymers involves the division into thermoplastics, thermosets, and elastomers.

Thermoplastic polymers are those that can be repeatedly melted by heating and reshaped using appropriate molds, as they can flow and solidify again after melting. Thermoplastics have covalent bonds between individual monomers, while polymer chains have weak van der Waals bonds that can be broken as temperature increases. Thermoplastics have low melting temperatures and can be processed by a variety of industrial processes, such as injection molding, extrusion, and blow molding. The most popular and widely used thermoplastic polymers are Polyethylene (PE), Polypropylene (PP), Polyvinyl-chloride (PVC), Polyethylene Terephthalate (PET), Polystyrene (PS), Expanded polystyrene (EPS), ABS, SAN, Polyamides (PA), Polycarbonate (PC), Poly methyl methacrylate (PMMA), Thermoplastic elastomers (TPE), Polyarylsulfone (PSU), Fluoropolymers, PEEK and POM.

Thermosetting polymers are those that can be melted and shaped in a mold only once, in fact after the first solidification further heating only leads to decomposition. This is due to the fact that during the first solidification chemical cross-linking reactions develop which harden the resin permanently and prevent it from being remelted. Thermoset resins are characterized by the presence of a three-dimensional network of covalent bonds, high molecular weight, and exhibit greater thermal stability, stiffness, and creep resistance [1]. The most popular and widely used thermosetting polymers are Polyurethane (PUR), Unsaturated polyesters, Epoxy resins, Melamine resins, Vinyl esters, Silicone, Phenol - formaldehyde resins, Urea - formaldehyde resins, Phenolic resins and the Acrylic resins.

Elastomers, such as natural rubber or styrene butadiene rubber, are made of polymers that when above Tg can be deformed by tension or compression, but then return to their original shape.

Polymers are therefore materials with many remarkable properties, including their durability, low weight and low production costs. Furthermore, in the case of more stringent specifications than those of classic polymers, special additives can always be used to improve the performance aspects required of the materials. As a result, they can be used in many different applications. However, almost everything that from the application side is an advantage, from the environmental point of view translates into a disadvantage; for example, the great durability and resistance of polymers can be a disadvantage in the case of plastic waste abandoned to the environment and not subjected to an appropriate recycling cycle, as the material will take a long time before decomposing.

1.2 Economics of recycled polymers

To quantify the importance of polymers, it is important to evaluate data on the economics of production and recycling. The most complete and up-to-date estimates in Europe are provided by Plastics Europe, an association of companies representing about 90 % of European polymer production. The association, in collaboration with EPRO (the European Association of Plastics Recycling and Recovery Organisations), publishes updated data on the world of polymers every year [2], [3]. The data cited below comes from the 2021 and 2020 reports. The importance of polymers in Europe translates with the presence of about fifty-two thousand manufacturing companies, with a turnover of about 330 billion euros in 2020, slightly declining due to the presence of the health pandemic.

Production levels for virgin plastics are around 368 million tons globally, of which about 55 million tons are produced in European countries. From the Figure 2 showing the production trend in recent years, it can be seen that while the level of production from raw materials is rising globally, there is a gradual decline in Europe. This is due to the introduction of stricter regulations on plastics, which impose greater attention to recycling. However, the European decrease is offset by the increase in other continents.

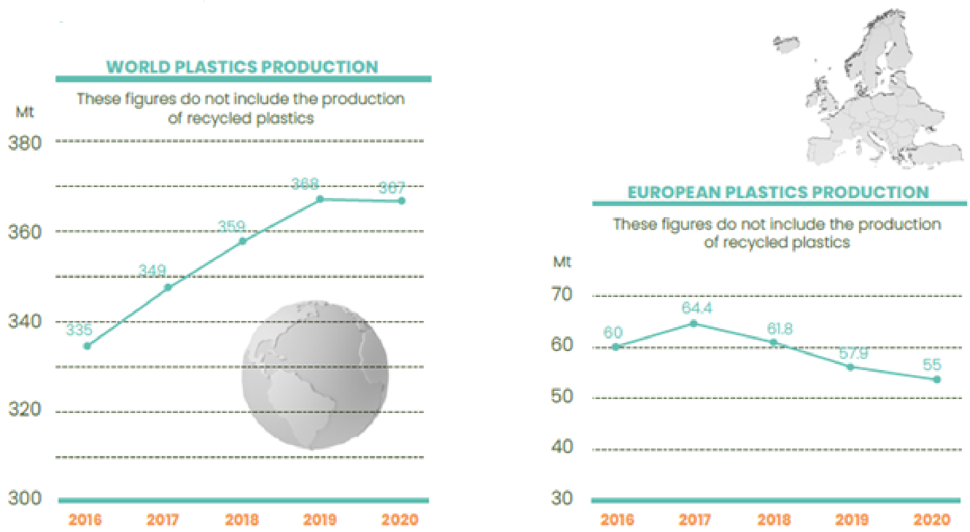


Figure 2:Global and European production level trend [2]

Global polymer production is broken down by the following percentages: China (32 %), NAFTA (19 %), Rest of Asia (17 %), Europe (15 %), Middle East and Africa (7 %), Latin America (4 %), Japan (3 %) and Commonwealth of Independent States (3 %). As far as Europe is concerned, the data regarding the individual states can be analyzed in detail using the Figure 3. Germany and Italy are the largest users of plastics, followed by France, Spain, the United Kingdom and Poland. Each of these nations has a need for more than 3 million tons per year.

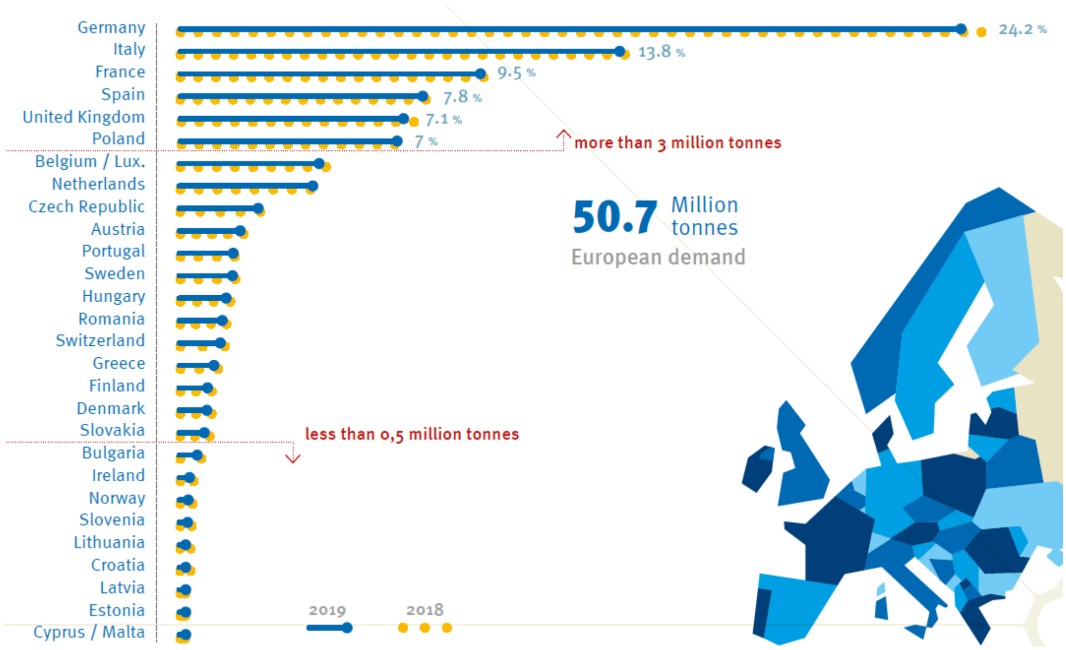


Figure 3: Plastics demand by country in Europe[3]

The breakdown by applications is shown in the Figure 4. It can be seen that the packaging sector is by far the largest user of polymers; in fact, historically it has been the one most affected by policy actions dedicated to recycling strategies. The wording "Others" indicates materials suitable for medical applications, mechanical and technical engineering parts.

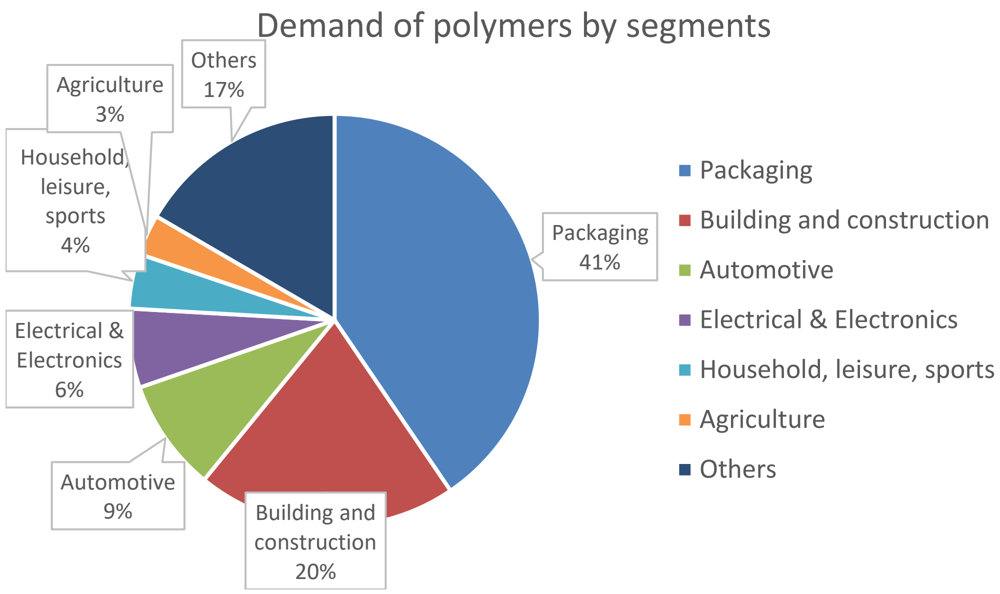


Figure 4: Demand of polymers by segments in 2020 in Europe

In addition to the various applications, it is important to know what specific materials are being used. The Figure 5 summarizes the production levels of the main polymers by comparing the years 2019 and 2020. As can be seen, Polypropylene (PP) is the most widely used, followed by Polyethylene (PE) and Polyvinyl chloride (PVC).

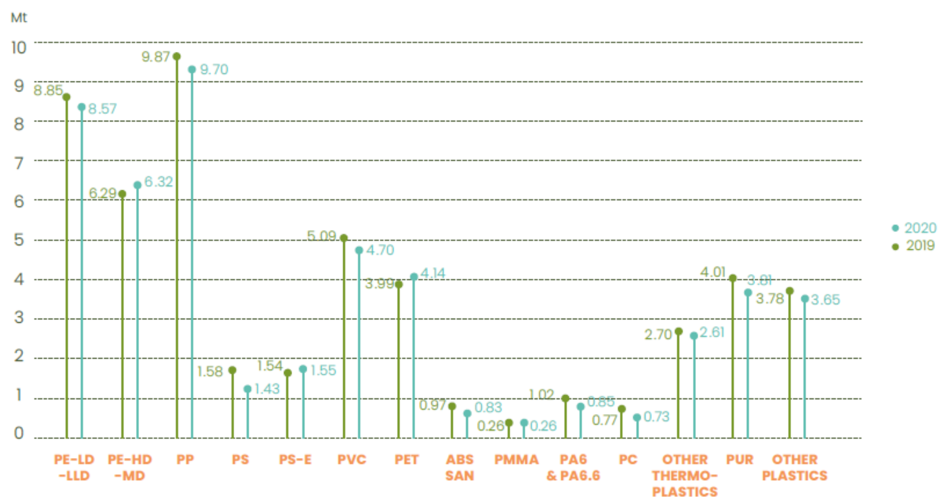


Figure 5: Production level of the main polymers in 2020 in Europe [2]

Finally, we can cross the data and understand which are the most used materials at the level of single applications, information that we find in the Figure 6. Also in this case, as expected, PE, PP and PET are mainly used in packaging, while PVC is used in the building sector and the automotive sector, the third most important one, uses many different materials.

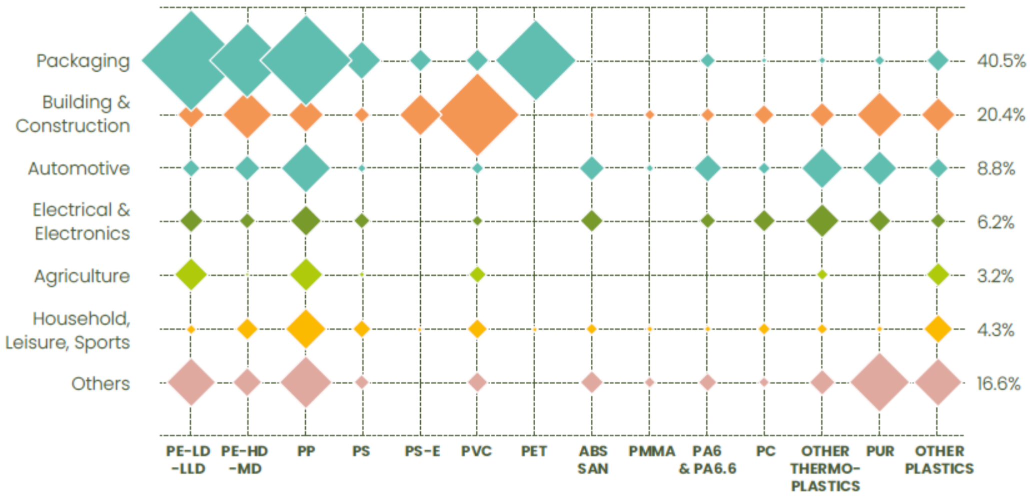


Figure 6: Polymer uses by application segment in 2020 in Europe [2]

1.3 Polymer recycling processes

The data presented so far allowed to understand the importance of both the quantities produced and the variety of applications of polymers. Currently, most polymers are produced from fossil fuels, causing damage to the environment that is present throughout the entire life cycle, from extraction to disposal of materials in the form of waste. The increased sensitivity towards the environment has produced significant progress in recent years. First of all, research over the years has developed alternative polymers, produced from renewable sources and with characteristics that have less impact on the environment. In addition, a solution already available concerns the use of a strategic view that focuses on the life cycle of materials, in which all or almost all of the material produced is re-emitted into the production cycle once the life cycle is over, in the form of recycled materials or energy. Depending on the different cycle possibilities, we talk about a closed-loop recycling system, as in the case of bottles, in which all the material is reused, or an open-loop recycling system. In this context, various political actions have been encouraged towards a greater awareness of the reuse of materials, through various forms of recycling. In March 2022, the UN Environment Assembly (UNEA-5) passed a resolution considered of historic importance to end plastic pollution [4], establishing an Intergovernmental Negotiating Committee (INC) that will begin its work in 2022 and over the next two years must draft a legally binding treaty to be signed by UN countries by 2024. The text will need to address the entire lifecycle of plastics, including production, design, and disposal, with the ambition of dramatically reducing the amount of plastic produced.

In this context, it becomes crucial to understand which are the most used methods for recycling polymers and especially which are the most effective for the various categories of polymers. There are mainly five families of methods to recycle polymers, which differ according to the materials to which they can be applied, the outputs produced and the environmental effects resulting. These classifications are also regulated by international standards such as ISO/TR 23891:2020 (Plastics — Recycling and recovery — Necessity of standards) and ISO 15270:2008 (Plastics — Guidelines for the recovery and recycling of plastics waste).

Primary recycling refers to the recycling of homogeneous, uncontaminated post-industrial materials that are either regenerated as is or added to virgin polymer in the same process. This process is referred to as closed loop recycling [5]. This type of recycling is considered the easiest to do. In fact, if one considers plastic processing such as injection molding or film production, it is easy to see that what are processing wastes can simply be ground up and put back into the same production cycle. However, it is necessary to take into account the progressive loss of properties of the material subjected to several processing cycles.

Secondary or mechanical recycling refers to recycling that occurs from a selected material that is reused to produce consumer goods again in a facility other than the primary production facility. Secondary recycling can be classified into post-industrial recycling and post-consumer recycling. Post-industrial secondary recycling involves collecting scrap from companies and processing it through extrusion [6]. Post-consumer secondary recycling is that which is carried out from materials recovered after use from finished products. Secondary recycling inevitably raises the issue of so-called "downcycling", whereby at each process cycle a product is obtained with inferior characteristics and performance, not always acceptable.

Tertiary or chemical recycling is the recovery through chemical or physical processes of monomers, oligomers or other compounds. Tertiary recycling involves the use of chemical or physical agents to obtain derivatives from polymeric materials that can be reintroduced into the same production cycle or used in others [7]. The main processes of this methodology are hydrolysis, pyrolysis, hydrocracking and gasification.

Another method, also known as quaternary recycling, consists of energy recovery due to the incineration of used polymers. This process is primarily used for materials that have already been recycled and whose properties have decayed due to too many processing cycles, or for materials that it is not structurally possible to recycle. Incineration is used for energy production, as many polymers have a high calorific value which makes the process of interest. For example, polyethylene has a calorific value of 45.83 MJ/kg, polystyrene 41.9 MJ/kg, values comparable to those of oil 42.3 MJ/kg, and kerosene 46.5 MJ/kg [8]. Despite the high values of calorific value of some polymers, this method has several disadvantages; as a matter of fact, an undesired effect of incineration is the creation and emission of fumes or possibly toxic substances, such as dioxins in the case of PVC. Because of these reasons, regulations require incineration to be a subsidiary tool to mechanical and chemical recycling, which have been identified as the primary options to be used.

One final method, in addition to the four mentioned above, is not really a recycling process but a method of waste disposal. It involves depositing waste in landfills. This option is decidedly unattractive from an environmental perspective, as it is not very sustainable due to the large operational and space occupation costs.

In most polymers, additives, both organic and inorganic, are used to increase the characteristics according to the application. This concept also applies to recycled polymers, as in most cases, recycling processes result in degradation of material properties. Production processes also negatively affect virgin materials, however, for recycled materials the incremental effect due to the presence of oxygenate groups created during previous life cycles must be considered. The main classes of additives are [9]:

- Antioxidants and stabilizers that serve to retard the degradation of material properties. Stabilizing agents are responsible for preventing degradation due to UV radiation and the effect of heat and oxygen. Photostabilization prevents photooxidation through three mechanisms called UV absorbers, quenchers (scavengers), and radical traps. Thermal stabilization by antioxidant agents prevents the combined effect of heat and oxygen that can cause oxidation.
- Impact modifiers that serve to improve mechanical properties such as impact strength.
- Compatibilizers increase the compatibility of properties between different polymers.
- Flame retardants are used to increase the ignition temperature of polymers and slow down the burning process.

Once the existing recycling mechanisms are understood, the life cycle logic can be described. The Figure 7 [10] represents in a synthetic way which are the flows present in the generic life cycle of a plastic material. From the production of the virgin material, which takes place through the consumption of fossil fuels and energy of various kinds, we move on to the production of the finished object and its consumption. Once the material has completed its purpose of use, the recovery phase begins. The first option as seen in the previous paragraphs is reuse through primary recycling in the same initial process flow. If the material is no longer usable, the alternatives are incineration for energy recovery, or the less preferable option of landfill disposal. If the material can be recycled, a careful separation phase will take place, in which different types of material will be separated. Having this material of homogeneous composition, the recycling can be mechanical and therefore provide new materials for the production of the object, or chemical and provide material for the production of polymers.

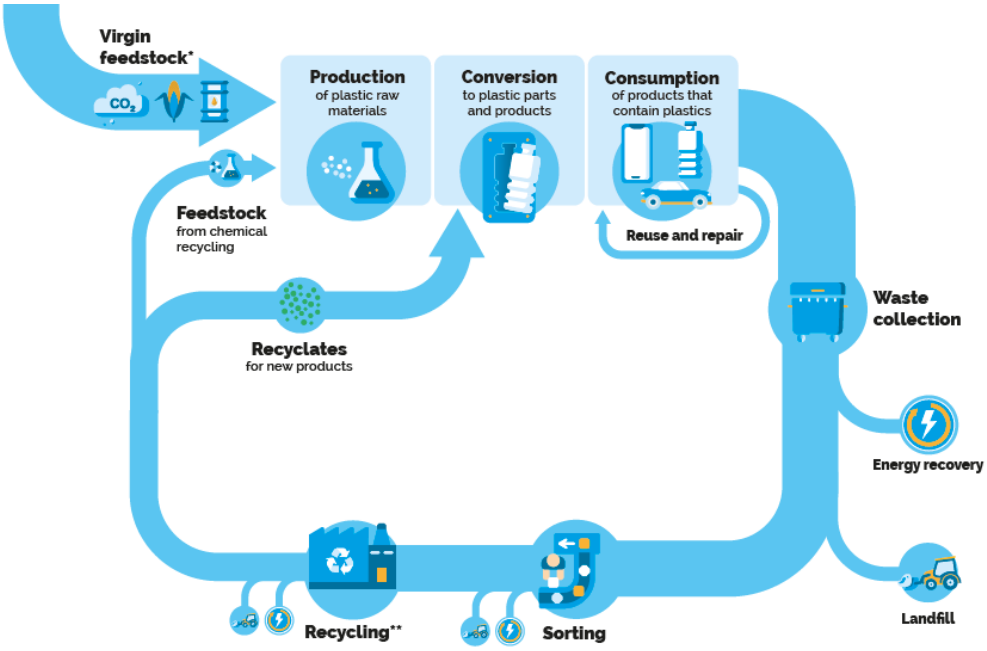


Figure 7: Waste management in a recycling life cycle perspective[10]

Increased environmental awareness and more stringent recycling legislation have had a significant effect in increasing and spreading recycling practices. In 2020, more than 29 million tons of plastic waste were collected in Europe, an increase of twenty percent compared to 2006. Of this, more than a third was shipped to recycling centers. The figure shows the trend in recycling, energy recovery and landfill disposal over the years 2006-2020. As can be seen, landfill disposal has undergone a sharp decrease, equal to 46.4 %, while recycling and energy recovery have increased by 117.7 % and 77.1 % respectively.

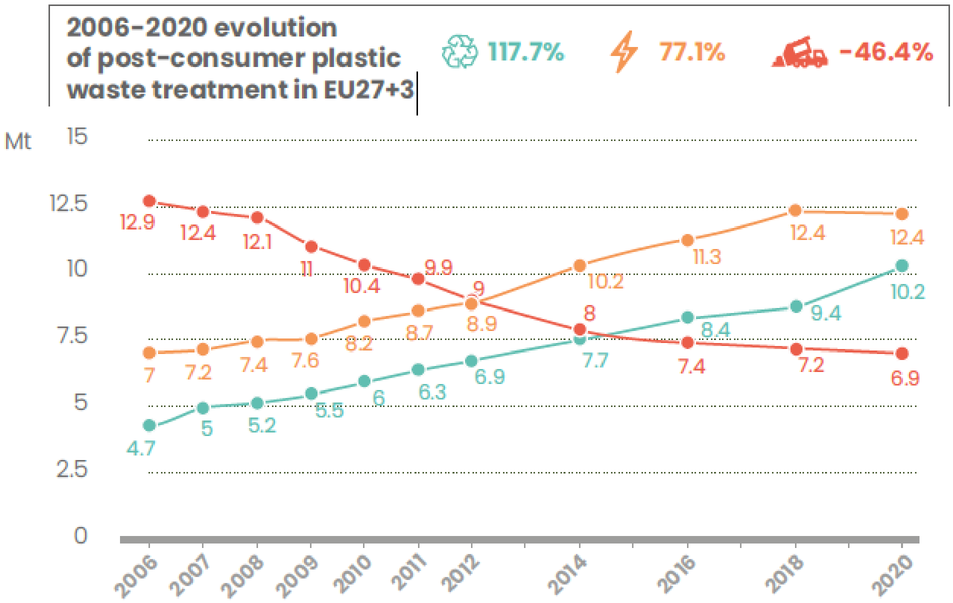


Figure 8: Trend of post-consumer plastic waste treatment in Europe [2]

To get a broader picture, data outside of Europe can also be analyzed. In the United States, for example, less than ten percent of the polymer waste produced in 2020 was recycled, while 15 percent was destined for energy recovery and 75 percent was destined for landfill (half of this volume was sent for disposal in China)[11]. Reading these numbers a significant difference with the European data is immediately perceptible, in fact in Europe the landfill is the last option and therefore the most discouraged. This different mentality is the result of more ambitious policies towards environmental sustainability, which have imposed stricter constraints for recycling. An example of these policies is Directive 2019/904 [12], which provides for a ban on single-use packaging in Europe starting in July 2021; the sale of the following single-use plastic items has been prohibited: plates and cutlery, straws, Q-tips, cocktail and beverage paddles such as coffee, balloon sticks, Styrofoam containers for food and beverages, and those made of expanded polystyrene, widely used in fast food. However, even in America there is more attention than in the past, this is also the result of the decision of China, which since March 2018 has decided to reduce imports of polymeric waste from abroad [13].

Recycled materials can be used in different applications. The graph in the Figure 9 represents the percentage uses divided by application segments of recycled materials in Europe in 2020. Also in this case, as in the case of virgin materials, the construction and packaging sectors play a major role in the use of polymers. On the other hand, the role of the automotive sector decreases, as it absorbs less recycled materials than virgin materials.

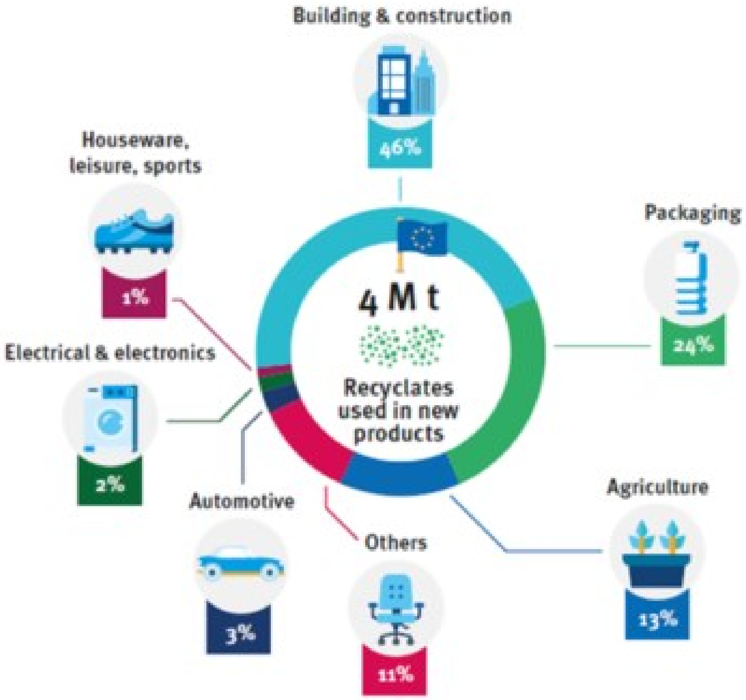


Figure 9: Application sectors for recycled polymers in Europe[10]

One of the fundamental aspects to be considered in recycling processes is the quality of reprocessed materials. In fact, especially in the case of mechanical recycling, the quality of mechanical and thermal properties degrades with the number of working cycles, to the point of talking about downcycling.

For the quality aspect, there are several criteria for establishing a meaningful quality concept. Three key aspects in this context were identified by the work of Vilaplana et al. [14]. These are, as shown in the Figure 10 [14], the degree of degradation, mixing, and the presence of low molecular weight compounds. Each of these aspects groups together various characteristics that can be checked to assess the quality of a recycled polymer. For example, degradation can estimate the drop in the performance of the material following recycling and life cycle, while the presence of compounds such as additives and contaminants can possibly be a warning factor for the presence of health hazards; finally, the presence of impurities can be due to a poorly performed sorting process, which affects the quality by affecting the miscibility of different polymers.

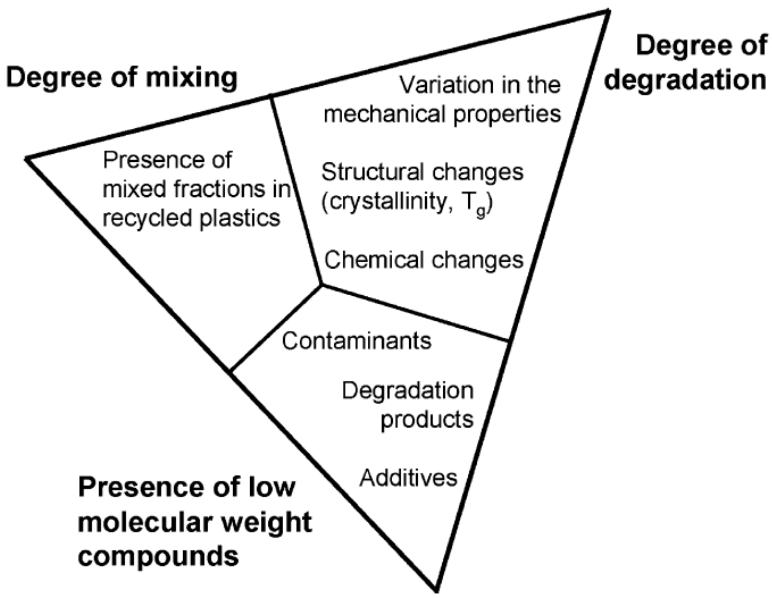


Figure 10: Criteria for evaluating the quality of a recycled polymer[14]

In addition to the performance aspect of the material, it is also necessary to consider the economic aspect. In fact, the cost of recycled materials must necessarily be compared with the price of virgin materials, with the latter representing a ceiling that must not be exceeded in order to be competitive on the market. Consequently, it becomes fundamental to also evaluate the price of oil, which acts as a primary source for the production of plastic [15].

1.4 Sorting

In order to obtain quality recycled materials, one of the necessary conditions, regardless of the mechanical or chemical recycling method, is to carry out an accurate separation analysis of the plastic materials. This type of analysis, carried out in the recycling centers, is a fundamental prerequisite since these centers receive different types of plastics grouped together, therefore it is necessary to correctly identify and separate the various types of materials in order to direct them towards the respective recycling processes. The process of separating plastics is motivated by the need to generate batches of materials that are as homogeneous as possible, since in order to be able to process polymers and obtain quality results it is necessary to satisfy the constraints of miscibility between materials.

At the process level, before separating the plastics, there is a preliminary step, in which the plastics arrive at the work centers and are washed and dried to remove the presence of any contaminating agents.

There are many different techniques for separating plastics [16]. Historically, one of the earliest practices involved the presence of a trained person who was able to recognize and sort the plastics running on a conveyor belt. This method relied solely on the experience of the employee and was subject to human error. One of the first innovations was introduced by European Directive 97/129 [17], which established identification codes for different materials to facilitate recognition and separation. The Figure 11 shows an example of the main codes, consisting of a triangular shape to indicate recycling, and a numerical code to which the associated material corresponds. Similar systems also exist in America and China.

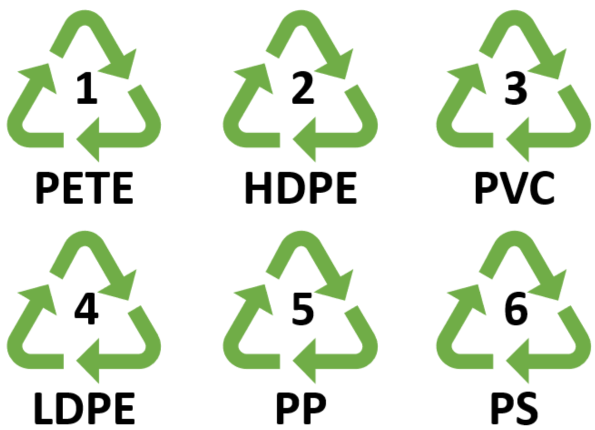


Figure 11: Graphic codes for plastic identification according to European law

In addition to these historical techniques, different automated processes have been developed over the years. Automated sorting techniques can be classified into two types: direct and indirect sorting. Direct sorting techniques use the intrinsic properties of the material to effect separation, such as in the plastics field the use of gravity density. Indirect sorting, on the other hand, uses sensors to detect the presence and location of recyclables in the waste so that automated machines can be used to sort and separate the identified recyclables.

The main direct methods are magnetic separation by density, triboelectrostatic method, hydrocyclone, jigging, froth flotation and air separators.

The triboelectrostatic method involves passing plastic grains through a pipeline in which electrification by friction of the materials takes place. Depending on the different polarities acquired by the materials as a result of the process, the materials, passing through an electric field are accurately separated. Consequently, knowing the behavior of the materials, it is possible to perform an automated separation.

Hydrocyclone is an instrument that uses density as a sorting principle for plastics. In this case the materials are treated in a conduit, where by the action of centrifugal force, they are separated according to their density. Another method that exploits the density of materials is vibrating screens or “jigging”. In this case the flow of materials passes through a chamber that moves along the vertical axis generating certain vibrations. In this way the materials with higher density will be deposited at the bottom, while the lighter ones will rise, allowing for separation. Density-based methods can have drawbacks because some materials have very similar density values, making separation difficult. This is especially the case for PET and PVC which have similar density values[18].

A separation method, which can solve such problems, is froth flotation, whose distinguishing principle concerns the hydrophobicity of the materials. In this case, the plastics are placed in a jet of water, in which through the introduction of air, froth is created. The plastics will tend to bind to the bubbles that are formed due to the hydrophobicity, consequently, being on the surface it will be easy then to separate them from any waste or contaminants. Foam flotation also allows PET and PVC to be distinguished by solving the problem related to similar density values; in this case, as demonstrated by Wang et al. [19], immersing the materials in an alkaline solution of sodium hydroxide allows one material to be hydrophilic while the other is hydrophobic, thus increasing discrimination sensitivity.

A graphic example of these methods is shown in the Figure 12.

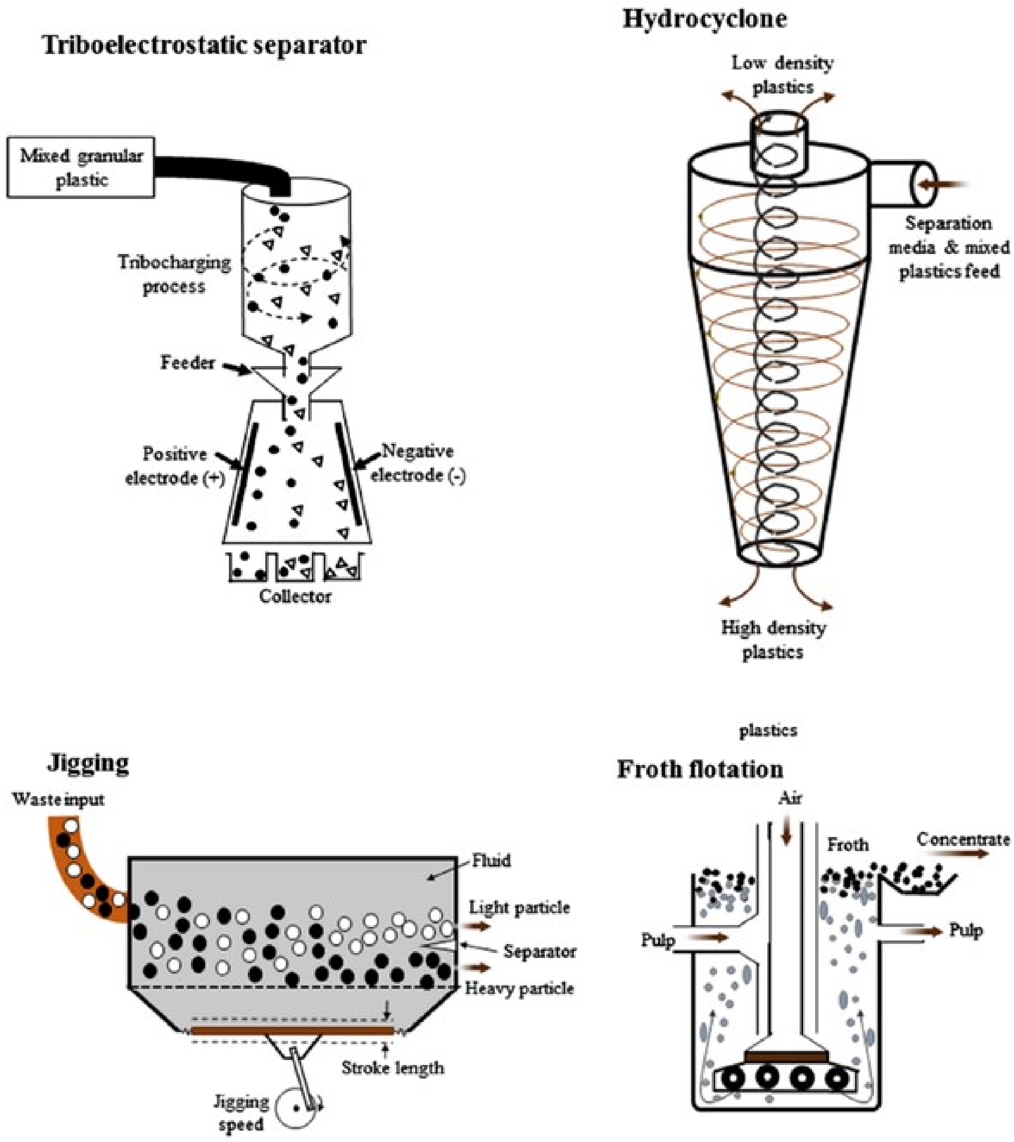


Figure 12: Direct methods for polymer separation [20]

The main indirect methods are LIBS, X-ray separation and spectrometry methods.

The Laser Induced Breakdown Spectroscopy (LIBS) system involves the material to be identified for separation slides on a conveyor belt until it reaches the analysis zone, where it is irradiated by a laser beam from a Nd:YAG source. The radiation emitted by the irradiated surface of the material is received by a spectrometer; this instrument compares the radiation with that of known materials, so that by comparing the characteristic peaks it can identify the material being analyzed and then direct it into the final containers.

The optical methods based on spectrometry include several reading techniques, such as Raman spectroscopy, Fourier transform infrared spectroscopy (FTIR), Near Infrared Spectroscopy (NIR) and Mid wave Infrared Spectroscopy (MIR)[21]–[23]. A typical schematic of an indirect separation system is shown in Figure 13.

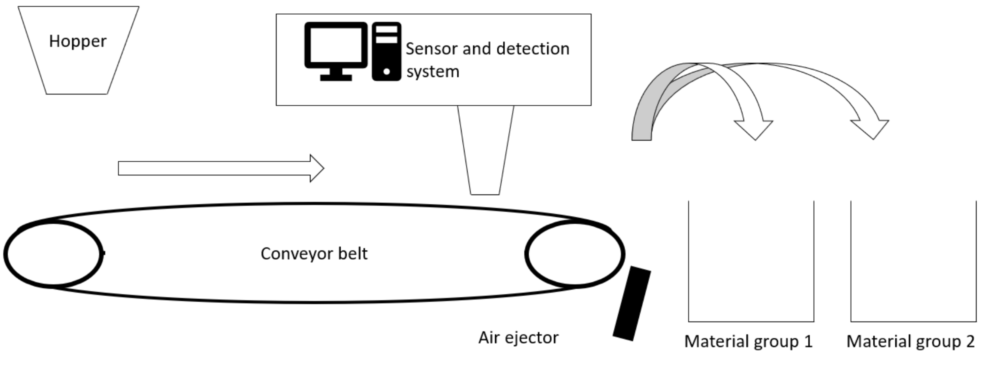


Figure 13: Typical scheme of an indirect separation system

This type of method is more widely used in industry because it is faster than direct methods and especially in some cases allows a higher degree of discrimination, as in the case of materials with similar densities. The most widely used technique is certainly the NIR, however one of its disadvantages is related to the low reflectivity of black plastics, this is a case that occurs very often because of the spread of carbon black used as pigment and UV stabilizer in polymers, and that strongly absorbs the signals of near infrared [24]. For the identification of dark polymers MIR can be used even if from an economic point of view it requires an expensive hardware system. Each of the presented techniques has some shortcomings, consequently each is used for specific separations. A new research approach to solving the problems presented involves a strategic revolution to the polymer world by introducing labeling of all polymers with fluorescent tracers[25], [26]. The minimal concentrations (sub ppm) introduced would allow for fluorescent emissions uniquely linked to the polymeric reference material so that materials can be distinguished without error. This structure, which could revolutionize the industry, needs complete adherence from the entire supply chain, from producers to recyclers.

In addition to the reasoning conducted on the techniques of separation of plastics, it is important to emphasize a further criticality dictated by the presence of additives in the groups of plastics arriving at the recycling centers. Each material contains specific additives, deriving from the initial application, so even if the polymers are grouped in homogeneous fractions, the additives present are different. All these characteristics of secondary recycling mean that it often leads to the material not being used for the same applications as the primary use, but for applications where these factors are not relevant.

1.5 Mechanical recycling

Once the preliminary plastics separation stage took place, the products are ready for mechanical or chemical recycling. As far as mechanical recycling is concerned, the input product consists of heterogeneous products of specific plastic material. The process steps involved are:

1. the shredding of plastics;
2. the formation of pellets;
3. working processes such as extrusion;
4. the production of a new finished product.

In mechanical recycling, the most widely used process for forming new polymers by heating and melting is extrusion. This process involves material in the form of pellets passing through an extruder, i.e. a device consisting of a heated cylinder containing a rotating screw. The movement of the pellet induced by the screw, leads to a heating of the material and at the same time to its compression, leading to melting. At the end of the cylinder there is an extrusion head, a device that serves to give the desired shape to the finished product. The process ends with the controlled action of a hauler that drags the material coming out of the head and a cutting device that separates the complete product from the extrusion head. The Figure 14 shows the scheme of a typical extruder.

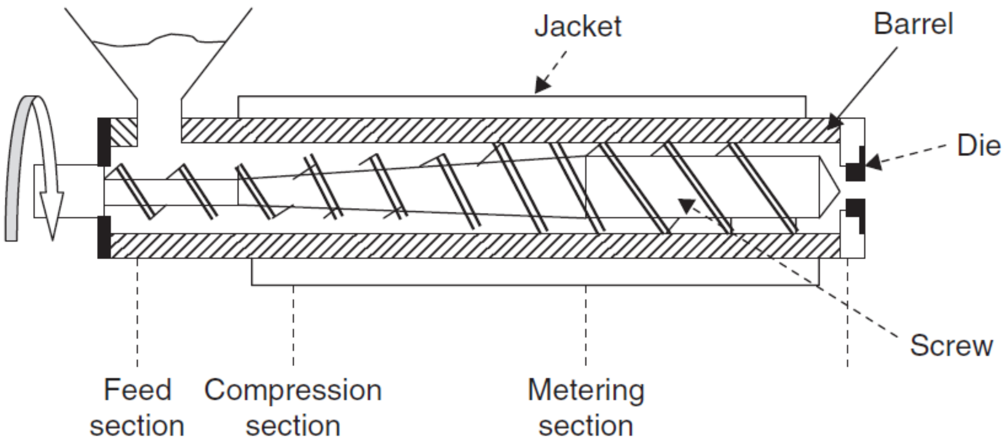


Figure 14: Example of extruder structure [27]

The work processes included in mechanical recycling lead to a degradation of material properties, so much so that a term used for this phenomenon is downcycling, which implies a decrease in properties. This downcycling is motivated by the forms of degradation that occur during the melting and subsequent forming processes of the materials.

Thermo-mechanical degradation involves the formation of free radicals within the polymer, which can lead, depending on the intrinsic characteristics of the material such as molecular weight, to two precise mechanisms shown in the Figure 15: the splitting of the chain into subchains (chain scission) and the formation of new chains by crosslinking, which respectively decrease and increase the molecular weight [28].

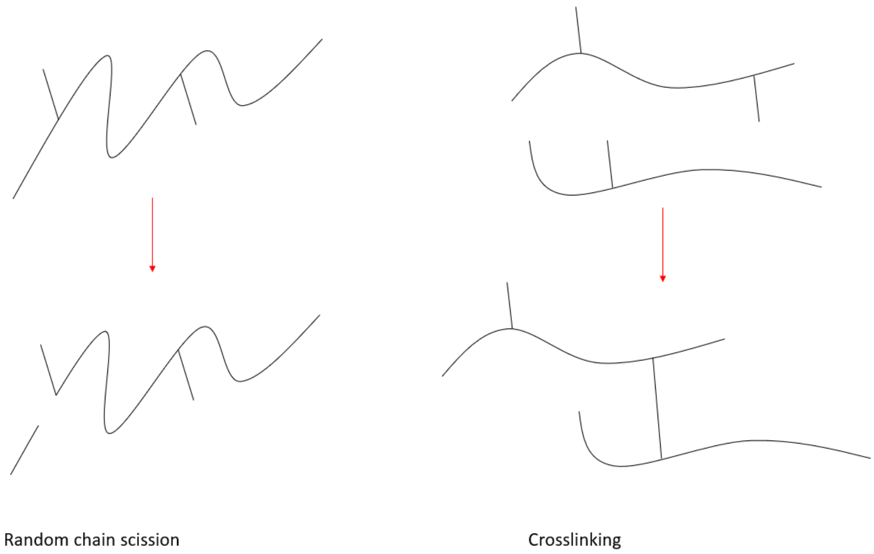


Figure 15: Chain scission and crosslinking

Degradation of mechanical properties results in most thermoplastic polymers in[29], [30]:

- Decrease in molecular weight
- Increase of Melt Flow Index
- Decrease of viscosity
- Decrease in tensile strength
- decrease in the elongation at break
- Decrease in Young's modulus

This decrease occurs progressively as the number of extrusion cycles increases and is increasingly significant if we also consider the thermal and mechanical stresses due to the life cycle of the products. Specific additives against the formation of free radicals can be used to counteract the decline in the mechanical and rheological properties of the recycled material. Another alternative is to use mixed pellets of both virgin and recycled material to balance the properties of the materials.

Up to now the ideal case of perfectly separated polymers has been presented, however in reality there are also cases in which it is not possible to perfectly separate each type of polymer. Consequently, at the time of mechanical recycling, there will not be a group of homogeneous material pellets, but heterogeneous pellets that, if processed, will produce polymeric blends. In this case the process must take into account several additional aspects such as the miscibility of these materials and the different melting points.

As far as melting points are concerned, in these cases the processes operate at the highest melting point of the polymer group to ensure that they all melt; obviously this brings consequences of degradation of some materials that will be at much higher temperatures than their own.

The other factor to consider is miscibility, and to ensure this some specific additives are used to compact the different polymers. These compacting additives decrease the surface tension, allowing adhesion between the various polymers. The most used are: block copolymers, copolymers with functional groups, graft copolymers, ionomers and mineral filler nanoparticles [6].

To assess the miscibility of two or more polymers, thermodynamic aspects are evaluated, with reference to the Gibbs free energy equation [31]. This relationship states that the free energy of the mixture must be less than the sum of the free energies of the individual components.

Equation 5: Free energy of Gibbs first condition

$$\Delta G_{mix} = \Delta G_{AB} - (G_A + G_B) \leq 0$$

Another condition that must be met to have the miscibility condition is Equation 6. Φ is the volume fraction of component B.

Equation 6: Free energy of Gibbs second condition

$$\frac{\partial^2 G_{mix}}{\partial \varphi} > 0$$

Mechanical recycling can only be used to process thermoplastic materials. In fact, due to the melt heating and re-forming of the materials, thermosetting materials are not processable as they would degrade.

Mechanical recycling is the most widely used industrial recycling for several reasons:

- it involves technically simpler work processes than chemical recycling;
- It has relatively low operating and plant costs;
- it can be applied to a large number of thermoplastic materials, which are widely used in different applications.

One of the most innovative applications of mechanical recycling is linked to the world of additive manufacturing. In fact, with the expiration of patents on Fused Deposition Modeling (FDM) technology, many machines were born, some even at very affordable prices, making it a most affordable and democratic technology. The polymer filaments used by these machines must meet very stringent specifications of use and as a result are very expensive. Mechanical recycling techniques are a possible solution to this problem, as they allow to form spools of filaments composed of recycled polymers. Obviously these materials will not have mechanical performances equal to the virgin ones, however from the economic point of view the saving will be considerable, as commercial filaments have a cost from 20 to 200 times higher than the cost of normal virgin polymers [32].

1.6 Chemical recycling

Chemical recycling is another family of methods that are used to recycle polymeric materials. Its use is complementary with the other methods, in fact it concerns materials that otherwise would not be recovered because technologically impossible or because it would not be convenient from an economic point of view. An example is thermosetting materials, which cannot be processed through mechanical recycling because they would degrade instead of melting, and therefore chemical recycling techniques are an excellent alternative. The perspective of chemical recycling is different from mechanical recycling; in fact, it is not a process in which the starting material is obtained again, but the output is composed of by-products such as monomers, oligomers or other compounds. This different recycling strategy allows to have an alternative in situations previously limited, consequently the opportunities related to chemical recycling are gathering a lot of interest both at technological and political level. In fact, as reported by Plastics Europe, the European Union wants to increase planned investments in chemical recycling from € 2.6 billion in 2025 to € 7.2 billion in 2030 [33].

The main chemical recycling methods [8] are shown in the Figure 16.

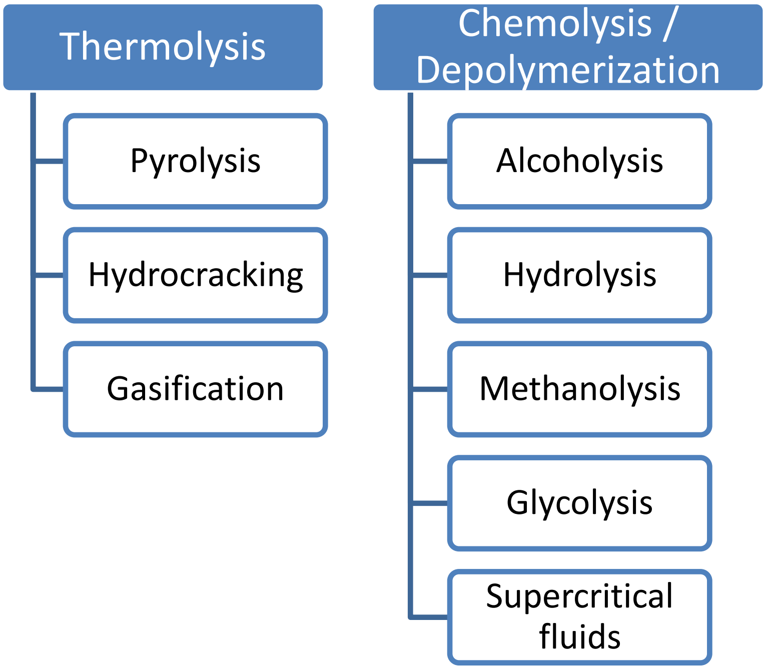


Figure 16: Chemical recycling processes

1.6.1 Thermolysis

Thermolysis processes are also known by the term feedstock recycling, as their output consists of petrochemical feedstock, i.e. basic chemicals such as hydrocarbons or synthetic gases. These products will need to be further processed before a polymer can be produced. For example, the first product by quantity of pyrolysis and hydrocracking is oil, followed then by gas while the gasification process produces mainly gas [34].

During the pyrolysis process long polymer chains are converted into small molecules through the effect of thermal degradation. The process operates in an inert oxygen-free atmosphere with a temperature range of 300-900 °C. The temperature parameter allows the control of the output product as lower temperatures result in the production of oil, while higher temperatures result in the production of gas. The yield of pyrolysis can be increased by using special catalysts that promote the thermal cracking reaction.

Hydrocracking, also known as hydrogenation, starting from polymers produces small molecules such as gasoline or kerosene. The process, which takes place in an autoclave, involves heating the material in the presence of H_2 and the use of high pressures (70 atm) with a temperature range of 375-400 °C. The output of the process is the formation of highly saturated products that can be used as fuels without further treatment.

The gasification process, based on the partial combustion of polymers to be recycled, produces syngas, a flammable gas composed of a mix of CO_2, CO, H_2, CH_4 and other light hydrocarbons at high temperature in the presence of oxygen; the output can be used to produce various types of agents for the production of polymers (methanol or ammonia), or as fuel or fertilizer. The process is conducted in the presence of sub-stechiometric quantities of air and at high temperatures 800-1600 °C, moreover there is a preliminary phase for the removal of humidity in order to increase the calorific value. The gasification process can also cause some environmental problems because one of the possible outputs is composed by harmful gases such as NO_X.

These three techniques can be compared according to their advantages and disadvantages. From a technological point of view pyrolysis does not produce dioxins unlike gasification, which does not operate in an inert atmosphere.

Hydrocracking is an expensive technique from an economic point of view because it requires the production of hydrogen. Compared to pyrolysis the cost is higher because the former uses hydrogen, while the latter uses the cheaper nitrogen. Pyrolysis, of the three techniques, is the most used on the market, however in order to work it needs a great quantity of energy in the form of heat and because of the production of coke it needs a regular maintenance. Gasification is a very versatile technique as it allows to process plastic waste even if not separated, therefore it is good for those products that are difficult to distinguish.

1.6.2 Depolymerization

Depolymerization processes are primarily aimed at polymers obtained by condensation. These processes essentially function as reverse reactions, as a matter of fact they produce monomers as output for use in subsequent polymerization reactions. The typical process involves breaking the network structure of bonds using solvents and heat.

Depolymerization conducted with alcohol is called alcoholysis; it takes place at pressures of 2-4 Mpa and temperatures of 180-280 °C. The depolymerization process conducted in an aqueous solution is called hydrolysis; it takes place at temperatures of 200-250 °C and pressures of 1-4.2 Mpa. There are different types of processes depending on whether the solution is acidic, alkaline, or neutral[35]. An example of this process is the depolymerization of PET into terephthalic acid (TPA) and EG monomers. Depolymerization conducted with methanol is called methanolysis. One example is PET methanolysis, where high temperatures (180°-280 °C) and pressures (20-40 atm) in the presence of zinc acetate as a catalyst produce DMT and EG, which can be used to re-polymerize PET. The depolymerization process conducted in the presence of glycols, such as ethylene glycols (EG) or diethylene glycol (DEG), is called glycolysis. The catalysts most commonly used in PET glycolysis are zinc acetate and titanium phosphate [36]. Depolymerization processes can also be conducted with sub- or supercritical fluids such as water or alcohol [28].

In the Figure 17, the methods described are applied to chemical recycling of PET. The process conditions and output products are described.

Assessment Characteristics	Alcoholysis	Aminolysis	Ammonolysis	Neutral Hydrolysis	Acid Hydrolysis	Alkaline Hydrolysis	Glycolysis
Degradation conditions	Pressure: 2–4 MPa Temperature: 180°C-280°C	Temperature: 20°C-100°C	Pressure ≤ 2 MPa Temperature: 70°C-180°C	Pressure: 1–4 MPa Temperature: 200°C-300°C	Temperature ≤ 100°C	Pressure: 1.4-2 MPa Temperature: 210°C-250°C	Temperature: 180°C-240°C
Separation, Purification	Needed	-	-	TPA purification is needed	-	-	-
Product(s)	DMT	Corresponding diamides of terephthalic acid	Terephthalamide (TPA-di-amide)	TPA	TPA	Alkaline metal salt of TPA which can be converted to TPA after neutralizing by a strong acid	BHET
	EG	EG	EG		EG	EG	Other oligomers
Safety issues	High requirement	Medium	Medium or high	Medium	High	High	Conventional
Corrosivity	-	-	-	-	Corrosive	Corrosive	-
Toxicity	Toxic methanol	Amines	Ammonium	-	Strong acids	Strong alkalis	-
Sensitivity to the waste type	High; well-defined waste	Medium	Medium	Medium	Medium	Low	Medium
Industrialization status	Industrially available	No evidence	No evidence	Commercially applied	Commercially applied	Commercially applied	Commercially applied

Figure 17 Methods for the chemical recycling of PET [37]

Chemical recycling processes are an excellent alternative to mechanical processes and specially to landfill disposal. To conduct comparisons between the various techniques the characteristics of the specific polymers to be recycled must be evaluated, however Chemical Recycling Europe [38] estimated that pyrolysis yields are about 70-80 % while those of depolymerization processes are close to 90 %.

Chapter 2

The use of polymers in road pavements

2.1 Road pavements

The road pavement is a structure whose purpose is to ensure over time the transitability of vehicular traffic in conditions of comfort and safety. It must distribute on the ground the static and dynamic actions of the means of transport and provide a regular rolling surface and little deformable. The most important characteristics for a road structure are high load-bearing capacity, good stability, low water permeability, good micro- and macro-texture characteristics and extended useful life. There are mainly three types of pavements, distinguished by their qualities, thicknesses, and purposes of use: flexible, semi-rigid and rigid. The stiffness of the layers, within the same pavement, must vary gradually, so that the structure as a whole, can react as a single body to stress. The road pavement is a multi-layered structure, in which each layer has different characteristics and performs a well-defined function. In general, going down from the surface to the depth, the following layers can be identified:

1. The wearing layer must ensure the regularity and stability of the road with reference to flatness and slope.
2. The binder layer has a function of connection between layers, allowing the homogeneous transmission of loads.

3. The base layer serves to transfer the overlying loads to the lower layers in order to prevent breakage.
4. The foundation layer transmits loads to the subgrade layer.
5. The subgrade layer is the one placed in the lower part, and has the task of absorbing loads redistributing them capillary, so as to avoid concentrated loads that could lead to breakage.

One of the key components of these of the road pavement is the bituminous conglomerate, that is a carefully proportioned mixture of stone aggregates, fillers, bituminous binder and possibly additives, generally produced at high temperature in specific plants. The bituminous conglomerate is mainly composed of a solid structure formed by aggregates (rocky materials of different granulometry such as fillers, sand and crushed stone) immersed in a binder matrix, bitumen, which guarantees consistency and cohesion to the mixture. The bituminous conglomerate must meet the following characteristics: high stability even under loads, durability and absence of cracks, low water permeability, and high adhesion to prevent slipping.

The conformation of the aggregates in a bituminous conglomerate is aimed at maximizing the density of the aggregates by mixing larger aggregates with some finer ones. This objective is achieved by using the granulometric curve which, through progressive sieving processes based on the size of the grains, allows to have a clear measurement of the sizes used. It consists of a diagram with the percentage of material that passes through the filters on the y axis and the diameter of the filter hole on the x axis.

In addition to the aggregates, the main component is made up of bitumen, a very viscous material at room temperature, which acts as a binder between mineral grains of different shapes and sizes, guaranteeing consistency and cohesion under load. Bitumen comes from the refining processes of crude oil. Bitumen is produced through the fractional distillation process of petroleum by which the fractionation of the crude is obtained by exploiting the differences between the boiling temperatures of its various components. Bitumen is a multiphase system of asphaltenes and maltenes (a group that includes saturated, aromatic and resin components).

Bitumen is subject to two degradation phenomena. The first one is related to its use during its useful life, as it is exposed to high temperatures during the production and installation phases. The second concerns aging caused by atmospheric conditions to which it is subject during the life cycle. These oxidation phenomena cause a progressive stiffening of the bitumen due to the loss of the more volatile components. As it is a valuable component, bitumen can be reused several times. In fact, it can be recovered by milling the floors in the demolition phases and reused through recycling processes. These processes require that the milled bitumen is heated to high temperatures and mixed with virgin stone aggregates to form new bituminous conglomerate. Obviously, since the milled bitumen has fewer properties than the virgin one, a percentage of virgin bitumen and additives are also used in the production mix to compensate for the loss of properties.

The recovery and reuse of milled material (aggregate and aged bitumen - also referred to as Reclaimed Asphalt Pavement - RAP) from existing pavement for the production of a new asphalt mix has several advantages:

1. reduction in the use of virgin raw materials, with reference to stone aggregates and especially the bituminous binder from non-renewable sources.
2. reduction of territories to be destined to landfills.
3. limitation of soil and atmospheric pollution, deriving from the transport and incineration of waste.
4. energy conservation.
5. economic advantages.
6. technical advantages.

2.2 The production and recycling processes

There are different types of production processes for asphalt, and the main classification concerns continuous cycle (with drum-mixer) or discontinuous cycle processes.

A plant with a discontinuous cycle process, the most common technique, provides in order that:

1. aggregates of specific sizes stored in special silos, are taken in the percentages of the production mix;

2. The aggregates undergo a drying process and are heated to the required temperature.
3. They reach the mixing tower where, through screening, a new reclassification of the aggregates takes place, which again separates the pre-dosed mixture into individual pieces. After the new separation, the aggregates are weighed by type.
4. The single components that will form the asphalt mixture (aggregates, bitumen, filler, additives) are mixed together in the mixing tower. The mixer consists of an armored container inside which a double shaft with counter-rotating paddles agitates the mixture of crushed stone, bitumen and filler, for a time varying from 35 to 50 seconds, depending on the potential of the machine. At the end of the mixing process, the asphalt mix is ready for paving.
5. The finished bituminous conglomerate is then unloaded into a silo or directly onto trucks for transport to the construction site.

In continuous plants, so called because there is no discontinuity of operation, the mixing of the material always takes place inside the dryer drum, which for this reason is much longer (being a dryer and a mixer); in other plants, however, the mixing takes place in a special unit called a mixing tower. A discontinuous production cycle allows greater flexibility of use, however the plant has higher costs because it requires the mixing tower.

In addition to bituminous conglomerate produced from virgin bitumen, bitumen recovered by milling old road pavements can also be included in the production phase. Recycling techniques can take place either hot or cold, both in fixed plants or directly on site.

In the cold process, the recycled material from the existing pavement is inserted cold downstream of the dryer; in contact with the virgin aggregates at high temperatures, it undergoes a heating phase before entering the mixer. This technique has several weaknesses:

1. Insufficient amount of heat available in virgin aggregates for the required heat transfer.
2. Insufficient heat transfer time for fluidization of recycled material and its complete incorporation into the mix.

3. Needs to avoid cracking of bitumen upon contact with highly superheated new aggregates.

The amount of usable recycled material is therefore limited by the possibility of overheating virgin aggregates and the moisture content of the recycled material.

In the hot process, the recycled material is preheated through the use of a second drum dryer (tandem drum) in which the recycled material is heated, dried and transported to the single mixer where it meets with the virgin materials normally heated in the first drum. In the hot process, at a higher cost due to the presence of an additional drying oven, higher percentages of recycled material can be achieved relative to total weight, as the heating promotes the mixing of materials and does not inhibit heat transfer.

The process of asphalt recycling involves significant economic benefits. In fact, a theoretical model [39] evaluates the price of asphalt on the basis of the sum of the costs of the individual components, and mainly as the RAP varies. With reference to the Figure 18, which shows the cost according to the percentage of RAP, the maximum theoretical case of conglomerate consisting only of RAP allows to obtain a percentage saving between 50 and 70 % of the price of conglomerate without RAP. As the level of RAP increases, the cost of raw materials decreases, but the cost associated with the use of additives to counteract the degradation of mechanical and rheological properties increases.

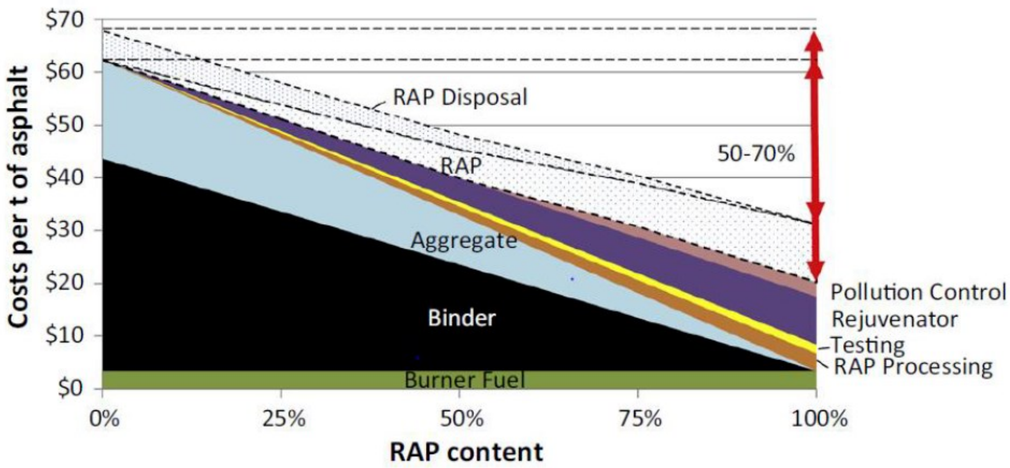


Figure 18: Cost of ton of asphalt according to RAP content [39]

Based on the EAPA data [40], asphalt production in the decade 2010-2020 for the major European producers (Spain, France, Germany and Italy) is shown in the Figure 19. As shown in the graph, Germany has significantly higher values than the other countries. It is interesting to evaluate the production data with those of the use of recycled conglomerate in road pavements. In fact, according to SITEB data[41], Italy has gone from a percentage of 20 % in 2014 to 25 % in 2018. Despite the increase, Italy is configured clearly behind the European average, which stands at 60 %. Consequently, comparing these data, Italy produces a large amount of asphalt, most of which is from virgin products.

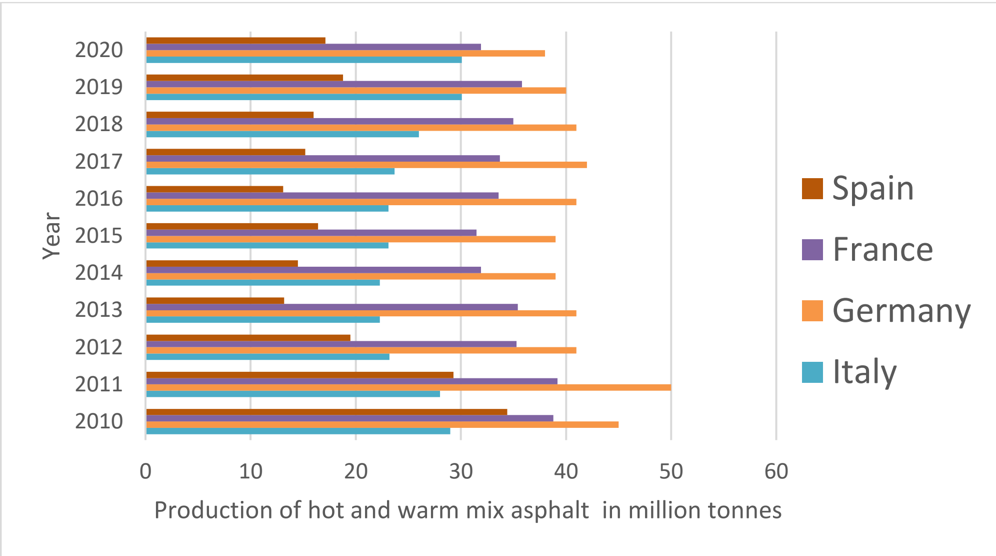


Figure 19: Production of asphalt for the main European producers

2.3 Polymer modified bitumen

The asphalt production process can be modified from what has been described above by the addition of recycled materials. These additions involve not only the use of asphalt milled from previous pavements, but also various waste materials or materials from recycling processes. Polymers are one of the main components for asphalt modification, as they can enhance certain properties of the material. Primarily improvements can be achieved with virgin polymers, however, the use of recycled materials allows for almost equal benefits, not to mention the excellent environmental and life-cycle benefits, as many materials can have new uses downstream of downcycling resulting from recycling.

Recycled polymers can be integrated into the asphalt production process by playing various roles:

1. partial substitute for stone aggregates
2. binder extender

There are mainly two methods for integrating recycled polymers:

1. Dry process: in this process the recycled materials are added to the heated aggregate before adding the binder. Then there is long mixing to ensure the homogeneity of the mixture. In this way, the polymers play a reinforcing role.
2. Wet process: this process involves mixing the material with bitumen and then adding the aggregates. This allows the polymers to change properties before meeting the aggregates.

These two methods produce totally different outputs, and different advantages and limitations are linked to them. The dry process, which is less widely used industrially, is relatively simple but is not regulated by standards and is limited by low water stability. In contrast, the wet process, although more costly economically because it requires special mixing equipment, is the more widely used because it allows greater control over the properties of the finished material[42].

There are different types of polymers with physical and chemical characteristics suitable for asphalt production processes. With regard to thermoplastics, the most widely used are polyethylene, polypropylene and EVA, while with regard to thermosets, crumb tire rubber (CTR) is widely used [43]–[45].

These changes result in improvements mainly in thermomechanical strength, elastic behavior, and adhesion. However, to achieve an increase in performance, the parameters to be acted upon are numerous, such as the size of the grains or fibers of recycled material, surface characteristics, mixing conditions, physical/chemical properties of the bitumen used as well as its origin.

Obviously, there are no mixing recipes suitable for each type of road pavement. In fact, the characteristics of the individual mixture must be studied according to the type of characteristics of the final road. So for example roads in high temperatures will be different from those in cold areas, just as there will be variation induced by travel frequencies and the loads to be borne. Consequently, there is no preconfigured recipe for every type of road, but various types. So also the recycled materials to be included are different depending on the type of result to be achieved. For example, some increase asphalt performance in high temperatures and not in low temperatures. Research on the use of recycled polymers for performance enhancement is based on identifying the optimal mix percentages and the best mixing processes to ensure the required performance and miscibility of all components.

There are several examples of research done in this field. In most cases, an attempt is made to quantify the ideal percentage of recycled material within the bitumen and aggregate mix. This percentage is derived from a trade off between miscibility of the components, maximization of performance and economic cost of the mixture. Several specimens at different concentrations are usually produced and characterization tests, such as the Marshall stability test, are performed.

Although there are undoubted advantages of using recycled polymers, there are also some limitations, such as poor aging resistance of the material and lower storage stability. However, many researches are trying to solve these drawbacks; the main solution hypotheses involve sulfur vulcanization, addition of antioxidant agents, use of hydrophobic clay minerals, functionalization by reactive polymers and saturation [46].

Chapter 3

Life cycle assessment of an innovative case study

3.1 Ecosmartroad 2.0 project

After evaluating the processes and data related to the economics of recycled plastics in the previous chapters, and after presenting the different uses in the road field, the experimental part of the thesis begins from this chapter. The research conducted involved a life-cycle analysis of a case study in which recycled plastic and milled asphalt are used to construct road pavement with greater environmental sustainability. The case study is related to the Ecosmartroad 2.0 project, funded by the Piedmont Region. The Ecosmartroad 2.0 project aims to build an innovative road system for bicycle applications with prefabricated modules composed of recycled plastic and milled asphalt with sensors for underground utilities, information point and charging point for e-bikes.

The Ecosmartroad 2.0 project introduces a new paradigm in roads:

1. Building roads in a prefabricated way, making all modules exactly the same, eliminating installation errors, as is the case today.
2. Modular structures, already equipped with the necessary space for the passage of cables and pipes and for rainwater runoff, can be prefabricated

directly at the factory and transported to the site of installation, reducing the time of work.
3. Realize inspectable modules that can be replaced individually.
4. Realize a system on which predictive maintenance can be applied.
5. Applying sensor technology transforms the road pavement into an intelligent system that acquires data and manages it.
6. Performing rapid maintenance without the invasive effects of the current traditional asphalt system.

In addition to process innovation, the project has several innovative points in the perspective of circularity of materials. The main one concerns the reuse of materials such as plastic and milled asphalt, which are widely used around the world, granting a second use instead of landfilling.

In fact, in terms of milled material alone, the Italian road network stretches over 800,000 km including highways, suburban roads, urban roads with an economic value of around € 1 trillion. The amount of reclaimed milled material is therefore very considerable. In addition, asphalt milling, resulting from milling operations performed on existing pavements, is classified as nonhazardous waste (EWC Code 170302).

The Ecosmartroad 2.0 project aims to create an innovative urban infrastructure system, i.e., a bicycle path made up of prefabricated modules composed of recycled and/or reclaimed materials such as plastic, milled asphalt pavement (RAP) to be placed in an urban area in the Municipality of Alba.

The modular structure consists of two separate elements: an end plate and a saddle. The plate element represents the closing element of the module and forms together with the upper mat the walkable surface. The saddle or support (consisting of prefabricated modules), from a functional point of view must contain the sub-services (cables and pipes) and act as a rainwater collector. From a structural point of view, it has a function of both supporting the upper plate and transferring the overall loads to the foundation layer through the saddle base plate.

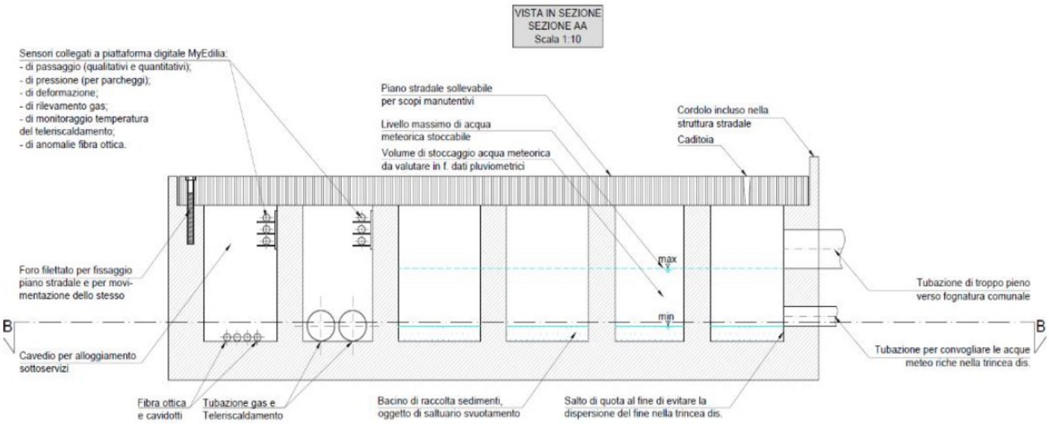


Figure 20: modular structure of the road

In addition, the structure includes the application of an advanced sensor system apt for predictive maintenance of the structure. The sensors return data on the amount and type of vehicular traffic, data on the deformation state of the pavement, and data for early location of any gas and/or water leaks. The modular system being designed includes bike lanes in their own right-of-way and therefore not alongside the road. The road goes from being a simple road network to a sustainable and intelligent system.

3.2 Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) is a quantitative methodology that is used to analyze a product or process from a life cycle perspective, with reference to numerous environmental aspects. From the ISO 14040 standard, LCA is defined as "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” [47].

The precursors of LCA date back to the 1960s when the first methods were developed. One of the forerunners was the Resource and Environmental Profile Analysis (REPA)[48]. One of the important bodies for the development of LCA was SETAC (Society of Environmental Toxicology and Chemistry), which began to standardize the various techniques. Over the years there has been a gradual development of techniques and a multiplication of methodologies. Confusion turned with the standardization that occurred through the establishment of ISO standards. Four standards were created in the late 1990s: ISO 14040 on principles, ISO 14041 on objective and context definition, ISO 14042 the life cycle impact assessment, and ISO 14043 on interpretation. These standards, which have been revised and updated over the years, indicate the methodology to be followed in conducting the analysis; however, there was room for ambiguity and contradictions arising from individual alternatives. As a result, further standardization work was carried out by the EU Commission's Joint Research Centre's Institute for Environment and Sustainability, which developed the uniform standards-based guidance known as the International Reference Life Cycle Data System (ILCD).

LCA is an analysis that has become increasingly popular in recent years. It can be used for different purposes depending on who is conducting it. For example to:

1. monitor the environmental behavior and impact of a product
2. as a marketing tool to communicate a product's environmental characteristics to the market;
3. as a strategic decision support in both business and policy fields.

LCA follows the best estimate principle, based on the average behavior of a system. It does not take into account so-called black swans i.e., very rare and unpredictable events.

In accordance with ISO standards, life cycle assessment consists of four steps:

1. Goal and Scope definition;
2. Life Cycle Inventory (LCI) analysis;
3. Life cycle impact assessment LCIA (Life Cycle Impact Assessment);
4. Interpretation of the results

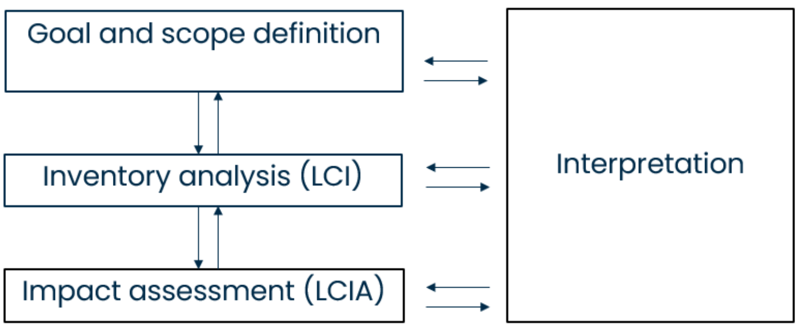


Figure 21: steps of LCA according to ISO 14040

In the field of LCA there are three typical models often used, in systems that involve recycling of products used in the life cycle:

- "Cradle-to-gate." LCA that examines the raw material extraction phase (cradle) to the construction phase (gate), excluding from the analysis, the use and disposal phases;
- "Cradle-to-grave": LCA that takes into consideration the phase of raw material extraction (cradle) to disposal/disposal (grave);
- "Cradle-to-cradle": closed-loop analysis in that it considers waste, i.e., flooring by-products generated from the construction and decommissioning phases, recycled or reused in the production of a "new" material.

3.2.1 Goal and scope definition

According to the ISO standard, the first stage of analysis involves defining the objective and context. At this stage, several aspects are defined that serve as a conceptual basis on which to begin thinking, delimiting the scope of the analysis and clarifying what is to be achieved in terms of the result. First, it is necessary to define the objective of the analysis. In defining the objective it’s necessary to:

1. Identify what are the intended applications for the results that will be produced, such as comparing different scenarios in what-if applications, or highlighting environmental characteristics of a certain product.
2. Explicit limitations due to methodological choices.
3. Explain the decision context and reasons why the study is being conducted.
4. Identify who the recipients of the study are, whether private organizations, clients, governments, etc.
5. Identify whether the study will be comparative in nature or not and whether it will be released to the public.
6. Name who the principal of the study is, so as to alert readers to possible conflicts of interest.

Once the objective is identified, the context can be defined:

1. Identify the deliverables that will be produced.

2. Define the functional unit, i.e., the unit of reference of the finished product that will be taken as the benchmark for quantifying flows.
3. Establish the boundaries of the system under consideration, so as to identify the processes that are inside and therefore will have to be analyzed, from those outside that conversely will be excluded.
4. Select the parameters that will be evaluated in the analysis and the reference flows of the various processes.
5. Select geographic and temporal boundaries, so as to use data that are relevant to the identified context.
6. Select the impact methods that will be used.
7. Planning for critical review to evaluate any errors.

3.2.2 Inventory analysis

The next step in an LCA is the life cycle inventory (LCI). The inventory analysis consists of collecting and compiling data on elementary flows from all the processes studied in the system. The result is the quantification of a set of elementary flows that cross system boundaries. There are six main steps for an LCI:

1. First, it is necessary to identify the processes for the LCI model, through identification of the elementary flows and process-by-process reconstruction of the system. Basically the user moves along the chain by following the flows.
2. Once the processes have been identified, the relevant data must be collected. For each type of data, characteristics such as the type of data, the source, and its accessibility must be known, so that it's possible to assess whether the data used has a higher or lower degree of specificity for the study application. There are various methods to find data: directly at the source of the production system, estimate it from other data, by asking experts, or on the Internet and LCI databases. There are numerous databases for LCA analysis, each with its own specific characteristics, the main ones are: Ecoinvent, ELCD, Agri-footprint, LCA Food, Swedish National LCA database, GaBi, NEEDS, NREL and ProBas.
3. Once the data have been collected, the process units must be built. All the data must have the right format for the process units and must be in the stream form. All flows must be scaled to 1 reference flow unit.

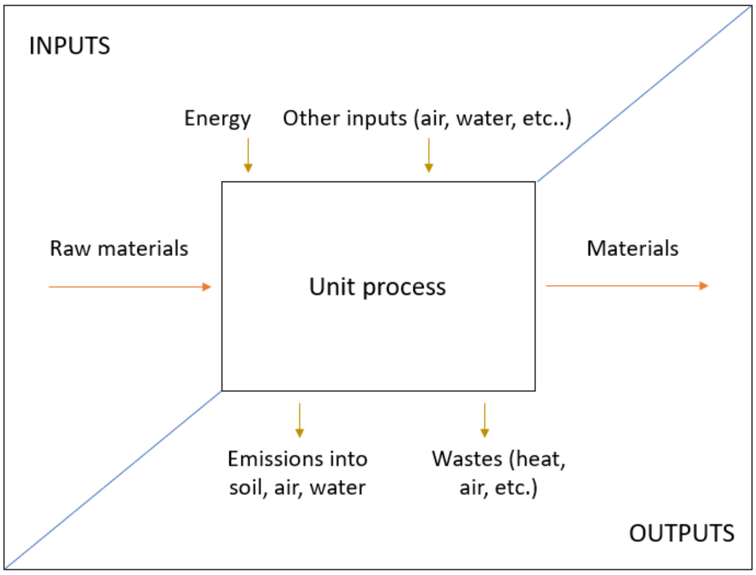


Figure 22: scheme of a typical unit process

4. When all the process units have been constructed or collected from an LCI database, the LCI model can be constructed. The output at the end of this stage is the compilation of the various elementary flows that comprise the LCI model.
5. The next step involves uncertainty management preparatory to sensitivity analysis. To understand the uncertainties of the complete model, one must understand the uncertainties of the individual parameters (their distributions and errors). For example, sensitivity analysis is done by varying one parameter and leaving the others stationary, to see how they change based on the single variation. Obviously it is more interesting to vary the parameters that affect the most to see their effects, not those that contribute little or nothing to the final results.

   Following data collection, it is interesting, in order to improve the quality of the analysis, to evaluate the data collected. A widely used method for this purpose is the Pedigree matrix developed by Weidema and Wesnaes [49] illustrated in Figure 23. With this method, various aspects that characterize the collected data, such as acquisition method, independence of data sources, representativeness, temporal, geographical and technological correlation are taken into consideration. For each of these aspects, the matrix needs a score on a scale from 1 (best quality) to 5 (worst quality).

Indicator score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or nonverified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from largerarea in which the area understudy is included	Data from area with similarproduction conditions	Data from area withslightly similar productionconditions	Data from unknown ordistinctly different area(North America instead ofMiddle East, OECD-Europeinstead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Figure 23: Pedigree matrix for data quality evaluation according to [49]

6. Finally, the reporting phase involves the creation of two documents, one summarizing the LCI model at the system level and the other, which for each process unit illustrates the references used (name, unit of measurement, data source and quantity).

3.2.3 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) stage is used to quantify the environmental impacts of each elementary stream. It examines the system from the perspective of environmental impacts using categories and indicators that agree with the inventory phase. The impacts of an LCIA are potential impacts, not predictions of true impacts. For this phase, ISO 14040 prescribes some mandatory and some optional steps.

1. First, impact categories, category indicators, and characterization models must be selected. The selection of impact categories, which must be justified in the report, must ensure that the categories are non-redundant so as not to duplicate impacts, complete and traceable, and consistent with the objective of the study. Indicators must be consistent with the objective of the study, must be justified and internationally recognized.
2. Classification: in this step, elementary flows are assigned to the impact classes to which they contribute (e.g., CO_2 emission may be assigned to climate change impact). Some flows may contribute to more than one category, depending on the method chosen.
3. Characterization: all elementary flows assigned to an impact category are multiplied by their respective characterization factors and added together, creating a score for the impact category. There are two different impact categories, on which the indicators reflect two different levels of detail: midpoint indicators and endpoint indicators. The former are positioned at the beginning of the chain of environmental effects and are more varied and rich in information, while the latter are at the end of the chain, being a grouping at a lower level of detail than the former. Examples of endpoint indicators are human health, natural environment and natural resources. Examples of midpoint indicators are climate change, Stratospheric Ozone Depletion, acidification, eutrophication, photochemical ozone formation, ecotoxicity, human toxicity, emissions, land use, water use, abiotic resource use. Using endpoint indicators provides less detailed and rich but concise information, while midpoints can be used for characteristics.

Obviously, the grouping of information must be done with logic and consistency, as some impacts may have different consequences over the time horizon, some occurring much earlier or later than others. The same reasoning that is made about time can also be made about the space in which they occur.

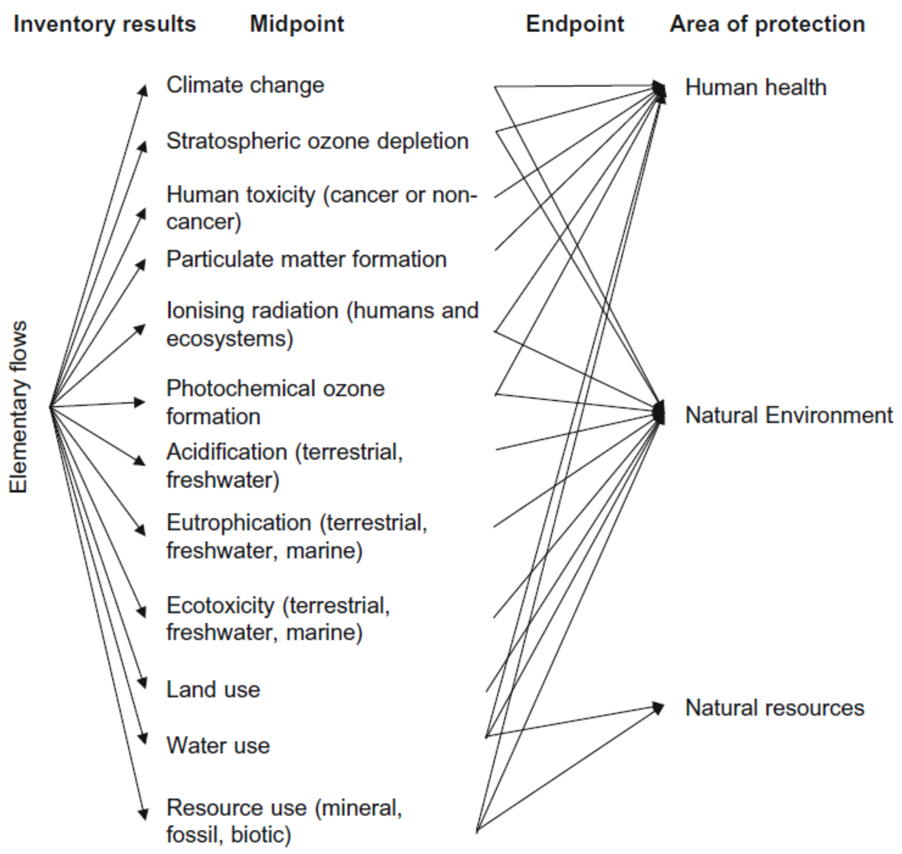


Figure 24: Connection between midpoint and endpoint indicator[50].

The ILCD provided guidelines [51] regarding the environmental impact assessment stage regarding which indicators are most recommended for the relevant impact categories. The evaluation assessed several indicators at the midpoint level and provided a judgment on a three-level scale; the highest level is indicated by I which represents a recommended and optimal method, followed by level II which indicates a suggested indicator but still to be improved, and finally the lowest level is III, recommended but to be used with caution.

Table 2: Recommended midpoint indicator and ILCD classification [51]

Impact category	**Midpoint indicator**	**Classification**
Climate change	Global Warming Potential	I
Ozone depletion	Ozone Depletion Potential (ODP)	I
Human toxicity	Comparative Toxic Unit for Humans (CTUh)	II / III
Particulate matter	Intake fraction for fine particles (kg PM2.5 eq/kg)	I
Ionising radiation	Human exposure efficiency relative to U235	II
Photochemical ozone formation	Tropospheric ozone concentration increase	II
Acidification	Accumulated Exceedance (AE)	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	II
Eutrophication, aquatic	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	II
Land use	Soil organic matter	III

From this point the optional steps according to the ISO standard begin, as a large margin of subjectivity needs to be introduced to conduct them.

4. Normalization: since impact categories are expressed with different units of measurement from each other, comparisons cannot be made and they are normalized by relating them to a reference system. When reading the results of a normalized LCA one has to be very cautious because the normalization depends on the chosen reference system, so it may change the original results.
5. Assignment of weights: the assignment of weights to the various impact categories takes place after normalization. It is necessarily a subjective process, lacking scientific evidence.
6. Clustering: clusters are made of the various impact categories.

3.2.4 Interpretation

The last stage of the analysis is to interpret and provide as output the conclusions and recommendations of the analysis. Interpretation is the stage of LCA in which the results obtained in the inventory analysis and impact assessment are combined with each other consistent with the objectives and scope of the study in order to derive insights and recommendations. Critical issues revealed in the impact assessment may lead to product and process changes that, iteratively, will be evaluated for impact reduction. In practice, this phase involves:

1. The analysis in terms of robustness and consistency against the objective pre-posed at the initial stage.
2. A sensitivity and uncertainty analysis is conducted on the results to see the robustness and level of variation as the input data vary. One makes the most significant data vary within the limits of their uncertainties and according to the identified distributions, so as to understand the effects on the results of variations.
3. A critical review phase conducted by external and independent consultants is also needed.
4. Conclusions are made and recommendations for future studies are provided.

LCA analysis involves an iterative approach, in that the resolution that is obtained at the conclusion can lead to a better understanding of certain aspects, emphasizing more important factors. One of the typical cases concerns the choice on the use of primary or secondary data on processes that are found to be significant at the end of the conclusions. Consequently as iterations increase there is an increase in the quality of the analysis, as initial assumptions flow better into the results.

3.3 Case studies

In order to conduct a life cycle assessment related to this case, which is related to an innovative way of building roads, it is necessary to clarify a few points. First, due to the nature of the methodology, it is not very useful to analyze only the innovative case, as the interpretation phase would be based on the environmental results produced without having a benchmark. In this case, the results that would be obtained would only be comparable in the abstract with other similar theoretical results from the literature. Consequently, in order to conduct a meaningful comparison and understand the advantages or disadvantages of the new construction methodology, it was decided to conduct a dual analysis. In fact, two life-cycle assessments were conducted, one related to a classical type of production and the other related to the innovative method. Obviously, the functional unit of both case studies was chosen so that comparisons could be conducted on the various indicators of both cases and to understand what the advantages and criticalities of both methods are.

Chapter 4

LCA on the classic asphalt production process

4.1 Summary

The first LCA analysis conducted concerns the life cycle study of classical asphalt production for a bicycle path. This first analysis is necessary to produce benchmark results with which to compare the results that will be obtained from the innovative production methodology. Consequently, in order to be able to obtain comparable data the output will have to be the same, obviously the methods, the materials used and their quantities will change to achieve the objective. In this first case, the production process uses only virgin materials, such as aggregates and bitumen, without introducing waste materials into the system, so that the effect of recycling can be compared on the next case. The analysis was conducted as prescribed by ISO 14040 and ILCD guidance.

4.2 Goal and scope definition

The study is conducted in order to obtain results that serve as a benchmark related to the production of asphalt used for a road of the bicycle path type. It is necessary to conduct this study so that the benchmark results can be compared with those of the innovative production methodology; in this way, the comparative analysis of the results will make it possible to understand whether there are positive or negative environmental impacts in the two processes. The study will therefore be comparative. In detail, the context concerns the production of a bicycle path in the town of Alba in Piedmont in 2022.

The main target audiences for the analysis are all stakeholders related to the development of the new road production methodology. A non-exhaustive list mainly covers asphalt producers, aggregate producers, plastic recycling operators, and all those involved in the development of the new technology. In addition to private companies, academic institutions such as the Polytechnic University of Turin are also included in the development. Other secondary stakeholders who might be interested in the results of the analysis include road and highway management bodies, for example the Italian ANAS, or the entire scientific community as the results enrich the literature with an innovative LCA case.

The study will initially be kept confidential until the technology is fully developed, as it is still being researched and is not yet a commercialized product. Later it is assumed that the study will be disseminated, both from an open access perspective and for marketing purposes. The study is being conducted by Gianluca Melis, author of the following doctoral dissertation text. Being an academic work, the principal of the analysis can be considered the Polytechnic University of Turin, through the researchers involved in the regionally co-funded research project Ecosmartroad 2.0.

There are no limitations related to the method used as it conforms to standards, while there may be limitations due to the assumptions made in the analysis. These assumptions relate, in some cases, to the use of secondary data because it was found that it was impossible to obtain primary data for some aspects related to production processes. This will be dealt with in more detail in the section on the analysis of the quality of the data used. Data research was conducted in the field, using primary data whenever possible; the data used can be considered representative of the model under analysis, as they all refer to the

Piedmonts' reality, the geographical location of the process. At the temporal level, the most representative data, as primary, relate to the asphalt production process and to the commissioning, while those related to aggregates derive from literature analyses conducted in previous years, always in the Piedmont context.

The functional unit chosen for analysis concerns the material used to produce a bicycle lane 20 m long, with a depth of 27 cm and 1.25 m wide. The functional unit chosen is special compared to those present in the state of the art, as usually in similar cases quantities such as 1 ton of asphalt mix are used. However, this choice was found to be necessary and indispensable because the new construction technology involves tiles of specific shapes that are to be placed on the road, not a continuous expanse of material as is the norm. Consequently, in order for the comparison to make sense, it was necessary to use the same yardstick, which is the size of the track to be built.

The deliverables that will be produced from this analysis are respectively a Life Cycle Inventory dataset related to the process and an interpretation of the Life Cycle Impact Assessment results ("LCIA results").

The boundaries of the system under analysis are relative to those of a cradle-to-gate analysis, in that the analysis considers virgin material production until the finished product is put in place, without considering the useful life cycle, nor end-of-life disposal. An attributional model was used for evaluation in the inventory analysis.

The Environmental Footprints database developed by the European Union as a result of the European Commission's Single Market for Green Products initiative and linked to the Community Product Environmental Footprints (PEF) methodology was used for the analysis. The database is free and can be downloaded from the OpenLCA website.

In order to choose an optimal methodology for calculating the impacts of the process under analysis, several methodologies were evaluated. The methods are respectively: Environmental footprints, Recipe Midpoint E and ILCD Midpoint +. The tables below show the impact categories for each method, also detailing the units of measurement used. These methods offer assessments on different impact categories, however, one criterion in compiling the tables was to respect an order of similarity among the various methods, reporting the impact categories found in all methods in the same order. Accordingly, the categories for climate change are reported first, followed by particulate matter, etc. Looking at the tables it can be noted that some impact categories found in the three methods are calculated with different units, as the method by which the estimate is obtained and the main the characterization factors used are different. There are desirable indicators in the state of the art (Table 2), however, each method can be used by giving reasons why. The impact model that will be used is the Environmental Footprint and is a midpoint level indicator. Although this method does not meet the ILCD guidance for all impact categories, it was chosen because its use is the best in accordance with the database used. Given the iterative form of the analysis, other impact methodologies were tested but did not produce consistent results.

Table 3: Impact categories with units of Environmental Footprint method

Name	Description	Unit
Climate change	Baseline model of the IPCC 2013 + some factors adapted from EF guidance	kg
Particulate Matter	The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level	Item(s)
Ionising radiation, human health	Valid on global and European scale.	kBq
Human toxicity, cancer	USEtox consensus model (multimedia model). No spatial differentiation beyond continent and world compartments. Specific groups of chemicals requires further works (cf. details in other sections).	Item(s)
Human toxicity, non-cancer	USEtox consensus model (multimedia model). No spatial differentiation beyond continent and world compartments. Specific groups of chemicals requires further works (cf. details in other sections).	Item(s)
Ozone depletion	Based on 1999 WMO assessment (World Meteorological Organization 1999)	kg
Land use	CFs set was re-Calculated by JRC starting from LANCAÂ® v 2.2 as baseline model. Out of 5 original indicator only 4 have been included in the aggregation (physico-chemical filtration was excluded due to the high correlation with the mechanical filtration)	Item(s)
Eutrophication marine	European validity. Averaged characterization factors from country dependent characterization factors.	kg
Eutrophication, freshwater	European validity. Averaged characterization factors from country dependent characterization factors.	kg
Acidification	European country-dependent.	mol

Photochemical ozone formation - human health	Only for Europe. Includes spatial differentiation.	kg
Ecotoxicity, freshwater	USEtox™ consensus model (multimedia model) - expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 day/kg). No spatial differentiation beyond continent and world compartments. Specific groups of chemicals requires further works (cf. details in other sections).	Item(s)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3
Eutrophication, terrestrial	European country-dependent.	mol
Resource use, fossils	ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016)	MJ
Resource use, minerals and metals	ADP for mineral and metal resources, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016)	kg
Climate change-Biogenic	Baseline model of the IPCC 2013 + some factors adapted from EF guidance	kg
Climate change-Fossil	Baseline model of the IPCC 2013 + some factors adapted from EF guidance	kg
Climate change-Land use and land use change	Baseline model of the IPCC 2013 + some factors adapted from EF guidance	kg

Table 4: Impact categories with units of Recipe Midpoint E method

Name	Unit
Global warming	kg CO_2 eq
Fine particulate matter formation	kg PM2.5 eq
Ionizing radiation	kBq Co-60 eq
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB

Stratospheric ozone depletion	kg CFC11 eq
Land use	m^2a crop eq
Marine eutrophication	kg N eq
Freshwater eutrophication	kg P eq
Terrestrial acidification	kg SO_2 eq
Ozone formation, Human health	kg NOx eq
Freshwater ecotoxicity	kg 1,4-DCB
Water consumption	m^3
Fossil resource scarcity	kg oil eq
Marine ecotoxicity	kg 1,4-DCB
Mineral resource scarcity	kg Cu eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Terrestrial ecotoxicity	kg 1,4-DCB

Table 5: Impact categories with units of ILCD Midpoint+ method

Name	**Unit**
Climate change	kg CO_2 eq
Particulate matter	kg PM2.5 eq
Ionizing radiation HH	kBq U235 eq
Human toxicity, cancer effects	CTUh
Human toxicity, non-cancer effects	CTUh
Ozone depletion	kg CFC-11 eq
Land use	kg C deficit
Marine eutrophication	kg N eq
Freshwater eutrophication	kg P eq

Acidification	molc H+ eq
Photochemical ozone formation	kg NMVOC eq
Freshwater ecotoxicity	CTUe
Water resource depletion	m^3 water eq
Terrestrial eutrophication	molc N eq
Mineral, fossil & ren resource depletion	kg Sb eq
Ionizing radiation E (interim)	CTUe

4.3 Inventory analysis

The LCA model that was developed is present in Figure 25. As can be seen, it is a Cradle to gate type model, in that the initial stages are derived from the production of the virgin input materials to the production process, and the final stages are concerned with the road commissioning, without considering the use life or disposal stages. This choice was made in order to abstract from the particular use-life cases, as it would have been necessary to increase the subjectivity of the analysis by assuming a time plan of maintenance verifications. As for disposal, the phases are well known in the literature, and the effects would not be directly comparable with those of the innovative case.

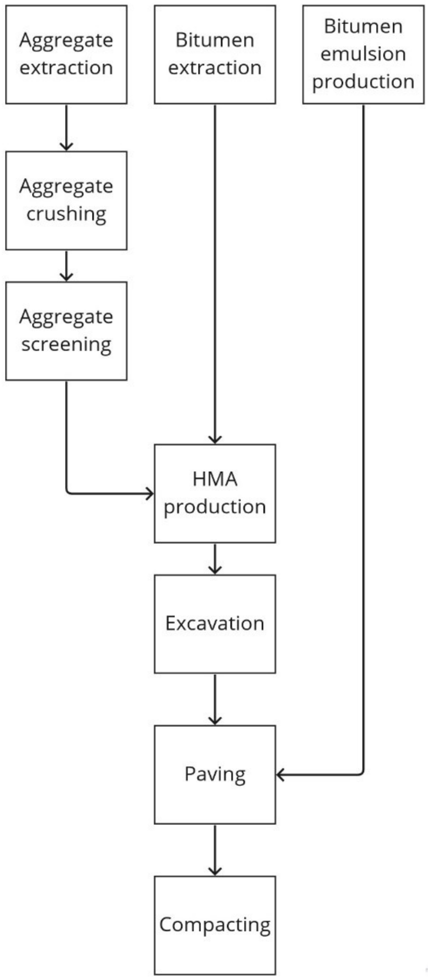


Figure 25: Flowchart of the system under analysis

The model is structured from two main input materials, aggregates and bitumen. The former are extracted from quarries and subsequently processed to obtain materials meeting the required constraints. Specifically, crushing is carried out to obtain smaller pieces than those extracted and a subsequent screening so that distinct piles of materials can be formed according to the size of their diameters. This first part is not present in the partnership of entities developing the new technology, so estimated data or data from literature were used.

For the extraction of aggregates, they were used in the article by Blengini et al. [52], which represents a study inherent to a production located in Piedmont in 2010. The data used are in the following tables and refer to the effects of both aggregate production and quarry creation through soil transformation due to quarrying.

Table 6: Inventory data for primary aggregate quarrying (data per 1 t) [52]

Resources & Land use		
Gravel, in ground	1.04	t
Water	1.38	m^3
Occupation, mineral extraction site	0.0125*13	m^2a
Transformation, from forest	0.0125	m^2
Transformation, to mineral extraction site	0.0125	m^2
Materials/fuels		
Diesel	4.904	MJ
Electricity	10.803	MJ
Light fuel oil	2.44	MJ
Hammers/jaws	0.0112	kg
Steel screen	0.02	kg
Lubricating oil	0.00181	kg
Steel	0.013	kg
Synthetic rubber	0.0073	kg
Tap water	10.1	kg
Infrastructure and recultivation		
Quarry infrastructure	1/(500000*30)	Unit
Recultivation	0.0125	m^2

Table 7: Inventory data for primary aggregate quarrying (Quarry infrastructure) [52]

Land use		
Occupation, industrial area, built up	150000	m^2a
Occupation, industrial area, vegetation	2100000	m^2a
Occupation, traffic area, road network	750000	m^2a
Transformation, from forest	60000	m^2
Transformation, to industrial area, built up	3000	m^2
Transformation, to industrial area, vegetation	42000	m^2
Transformation, to traffic area, road network	15000	m^2
Materials/fuels		
Concrete	2000	m^3

Steel	450	t
Belt conveyor	2200	m

Table 8: Inventory data for primary aggregate quarrying (Recultivation of 1 m^2) [52]

Land use		
Transformation, from mineral extraction site	1	m^2
Transformation, to water bodies, artificial	0.65	m^2
Transformation, to forest	0.25	m^2
Transformation, to traffic area, road network	0.1	m^2
Materials/fuels		
Diesel	6	MJ

For crushing and screening, a system of consumption and emissions was estimated based on the machinery used in these processes. By estimating energy consumption and production rates, it was possible to quantify these inputs to the model. The selected machinery is shown below, and for each function, based on the required load, the average consumption of the various machines was used as an estimate. The system involves a wheel loader depositing incoming materials and loading them via a conveyor belt to the crusher. After that the materials will move on another conveyor belt that will take them to the screening stage according to size. Then through a loader various pile of sorted materials will be made.

Table 9: Crushing machines details

Crusher	**Producer**	**Weight (Kg)**	**Feeding opening (mm)**	**Discharge opening (mm)**	**Output production (ton/h)**	**Power (Kw)**
MFP-060-040	Maitek Srl	6450	600x400	100-40	20	30
PJC 5038	BSI Impianti	7000	620x430	100-40	25	30
BR600	Mempsa	6350	600x425	/	30	45
MC 100i	Wirtgen	12000	950x550	130x20	220	160

EVO						
Powerscreen Metrotrack	Impianti Industriali Srl	28000	900x600	/	200	126
R60	REV	/	610x480	20x20	10	30
Serie P	Comec	12000	900x650	60x60	80	55
Caesar 1	Guidetti Srl	3200	450x280	20x50	20	21

Table 10: Feeding system details

Feeding system	**Producer**	**Throughput rate (ton/h)**	**Power (Kw)**
S5 model	BSI Impianti	100	5
MBW-15-19101	Wirtgen	150	5,5
Telestack	Impianti industriali Srl	400	36,9

Table 11: Vibrating screen machines details

Vibrating screen	**Producer**	**Output production (ton/h)**	**Power (Kw)**
MVI-120-300-4P	Maitek Srl	30	7,5
Serie VRO	BSI impianti	100	25
Titan 600	Impianti industriali Srl	280	45
V35	Loro Parisini	300	56
MSS-352-Evo-132p	Wirtgen	200	95
Stoneflex	CGT	190	26
VN350/A	REV	170	94

Table 12: Wheel loader details

Wheel loader	Producer	Bucket volume (m^3)	Power (Kw)
AS 210	Mecalac	2,8	129
437	JCB	2,7	136
HL955A	Hyundai	2,8	149
926M	Caterpillar	2,5	125

For the handling machines, it was possible to reconstruct emission data because these devices comply with European Stage V emission regulations. These data provide consumption-based emissions of major pollutants such as CO, HC, NOx, and PM [53].

Bitumen is a product of fractional distillation of petroleum. Data from the Eurobitumen[54] report version 3.1 of 2020 were used to estimate its production. These data represent an authoritative and recognized source and are suitable for use for a European context. Amounts due to production at the production site were also considered. A non-exhaustive list regarding the main contributions can be found in the Table 13.

Table 13: Data for the production of 1 ton of bitumen

Production of 1 ton of bitumen (process with infrastructure)	Unit	Crude oil extraction	Transport	Refinery	Storage	Total
Raw material						
Crude oil	kg	1 000				1 000
Consumption of energy resources						
Natural gas	kg	26	1,0	0,054	0,082	27
Crude oil	kg	11,2	9,5	1,2	0,54	22
Consumption of non-energy resources						
Water	L	811	90	206	7,2	1 115
Emissions to air						
CO_2	g	130 157	33 258	19 278	6 650	189 343
SO_2	g	486	384	48	22	940

NO_x	g	549	646	20	8,3	1 224
CO	g	385	96	11,0	2,3	494
CH_4	g	486	42	4,3	2,7	535
NMVOC	g	411	39	3,0	0,98	455
Particulates	g	159	102	6,3	3,2	271
Emissions to water						
Chemical Oxygen Demand	g	19 257	2 241	40	5,7	21 544
Biological Oxygen Demand	g	19 098	2 232	16	5,4	21 352
Suspended solids	g	260	34,2	7,22	0,55	302
Hydrocarbon (crude oil)	g	33,5	30	4,3	1,7	69,5
Emissions to soil						
Hydrocarbon (crude oil)	g	31,7	38	4,0	1,8	75

Once the input materials are available, the production of Hot Mix Asphalt (HMA) type of asphalt is proceeded. Various types of data were used for this stage.

Land transformation and occupancy data were calculated from the area used and daily production. Asphalt mix is produced at the Sam Costruzioni SpA plant near Cherasco. The area occupied by the plant is about 61854.5 m^2. Estimating a 30-year life for the plant and an average daily production of 180 t gives a production in 30 years of 180 t *200 gg/year *30 years=1080000 t. Using these calculations, soil transformation data can be calculated.

Table 14: Inventory data for HMA (data per 1 t)

Resources		
Occupation, HMA production site	0,0573*30	m^2a
Transformation, from forest	0,0573	m^2
Transformation, to HMA production site	0,0573	m^2

Table 15: Inventory for the production site

Land use		
Occupation, industrial area, built up	1855635	m^2a
Transformation, from forest	61854,5	m^2
Transformation, to industrial area, built up	61854,5	m^2

The reasoning, related to consumption and emissions, illustrated for HMA production applies to both wear layer and binder layer, which are obviously produced separately and consequently are two separate production cycles, as they use different proportions.

Based on the specifications required for a bicycle path with medium vehicular traffic and the loads estimated by structural engineers for the road structure, three layers were assumed starting from the bottom:

- 15 cm of foundation made from aggregates;
- 8 cm of binder made from 5 % bitumen by weight on aggregates and a void percentage of 6 %;
- 4 cm of wearing layer with 6 % bitumen by weight on aggregates and a void percentage of 5 %.

The material quantities for the following layers are shown in the Table 16.

Table 16: Quantity of materials for the wear and binder layers

Layer	Aggregate weight (kg)	Bitumen weight (kg)
Wearing	943,39	56,60
Binder	952,38	47,62

The following consumption (Table 17), estimated by Gschösser et al. [55], is used for HMA production for each layer. These data are derived from a case study related to Switzerland in 2012.

Table 17: Energy and operating materials for the production of 1 t of HMA [55]

Energy and operating materials		
Electricity, medium voltage	8,6	kWh/t
Heat, natural gas	152,7	MJ/t
Diesel, burned in wheel loader	11,1	MJ/t
Lubricating oil	3,01E-06	kg
Tap water	0,009	kg

Two sources are used for emission data; the first is a literature source, the article by Giani et al.[56] on a production case site in Milan in 2015. These data were supplemented with primary data (TOC, NO_X, CO and SO_X), measured at the production plant under analysis in November 2021.

Table 18: Emissions to air for the production of 1t of HMA based on data from [56] and integrated with primary data.

Emissions to air (kg/t)	
CO_2	9,58
N_2	278,87
O_2	52,42
NO_X	0,0414
TOC	0,036
SO_X	0,145
CO	0,055

Transport of input materials to the HMA layer production site was estimated as follows: for aggregates there are numerous suppliers in the area, where there is a high density of quarries, consequently an average distance of 30 km was used, while for bitumen an average transport of 130 km was assumed, which is equivalent to a qualitative average of instances of transport by sea with others of on-site purchase in Piedmont. These distances were multiplied by the quantities required to produce 1 ton of binder course and 1 ton of wearing course.

Once HMA was produced, it needs to be taken along with the aggregates and machinery to the track site, a distance of 24.8 km.

In order to lay asphalt, it is necessary to use bitumen emulsion. For this stream, the dataset developed by Eurobitumen [57] in the second edition of its report, produced in 2012, was used. As in the case of bitumen, this report represents the most authoritative source in Europe for providing inventory data in this production context. Also in this case, the data include the contribution due to the construction of the production site. A non-exhaustive list regarding the main contributions can be found in the Table 19. For bituminous emulsion calculation, the following is needed.

- 0.93 kg/m^2 for the layer between foundation and binder;
- 1 kg/m^2 between binder and wearing course.

The tack coat is the application of bituminous emulsion, performed before or during hot asphalt paving, which aims to improve and ensure the adhesion and perfect anchorage of the new layer to the underlying one. This is with the dual purpose of avoiding "slippage" between layers and achieving structural cooperation between them, making them work as a single body that distributes stresses and deformations to the entire structure and not only to the surface layer. A density of 2390 kg/m^3 was considered for both layers of HMA.

Table 19: Dataset of the production of 1t of bitumen emulsion [57]

Production of 1 ton of bitumen emulsion with infrastructure	**Unit**	**Bitumen**	**Emulsifier**	**HCl**	**Hot water**	**Emulsion milling**	**Total**
Raw materials							
Crude oil	kg	1 000	1,1				1 001,1
Consumption of energy resources							
Natural gas	kg	22,5	0,22	0,34	0,08	1,21	24,3
Crude oil	kg	50,5	1,4	0,4	1,8	0,4	54,4
Coal	kg	10,92	0,3	0,67	0,07	3,25	15,21
Uranium	kg	0,00026	0,00002	0,00004	0	0,00023	0,0006
Consumption of non energy resources							
Water	l	1 239	15	62	608	149	2 073
Emissions to air							
CO_2	g	226 167	4 602	3 985	5 459	15 455	255 669
SO_2	g	899	7,1	16	19	53	993
NOx	g	1 1 4 2	20	10	7,7	27	1 207

CO	g	1 040	4,9	4,1	2,9	5	1 057
CH_4	g	719	6	7,7	3,7	28	764
Hydrocarbon	g	52,4	14	0,3	0,5	1	68
NMVOC	g	404	0,9	1,4	2,3	2,1	410
Particulates	g	300,6	3	4,2	1,9	15,2	324,9
Emissions to water							
Chemical Oxygen Demand	g	675	93	6,3	24	6,7	806
Biological Oxygen Demand	g	5 1 1	1,4	4,4	24	6,3	547
Suspended solids	g	224	2,1	7,9	1,9	22	258
Hydrocarbon	g	150	0,4	1,1	7,7	1,9	162
Phosphorous compounds	g	77,41	4,4	10,76	0,82	48,92	142,3
Nitrogen compounds	g	23,70	5,03	4,35	0,29	14,85	48,22
Sulphur compounds	g	1 801,0	127,1	319,7	21,5	1 212,8	3 482
Emissions to soil							
Hydrocarbon (oils)	g	155	0,2	1,2	8,1	2	167

The road construction data involves, in order: excavation by excavator, ground leveling and compaction. Once the soil is ready, the laying of the various layers can begin, the first is the foundation layer consisting of aggregates and then the binder and wear layers. Each layer undergoes a compaction process, and bituminous emulsion is used between layers in order to better bind the layers together. For these stages, the consumption of the machinery used was estimated based on the required workload; the data, illustrated in Table 20, are derived from the study conducted in Sicily in 2016 by Celauro et al.[58]. The table shows the weight of machinery where it is not wheeled and has to be loaded onto a trailer for the transport phase.

Table 20: Data of machines for the road construction based on [58]

	Model	**Weight (kg)**	**Productivity (mc/h)**	**Fuel Consumption (l/h)**
Cleaning and grubbing	Cat wheel dozer 824H	/	740	71,4
Excavation	CAT 330D	8350	400	68
Lime spreading	Wirtgen SW 16MC	/	150	2
Evenly mixing lime with soil	Wirtgen WR240i	/	800	80
Compaction of unbound layers	Bomag BW 226 dh-4		500	37,6
Precision finishing of laid materials	CAT 12 M2	/	2500	40
Compaction of asphalt layers	Bomag BW 203 ad-4	1590	200	32,7
Laying of asphalt layers	BOMAG BF600	19800	600	43,1
Prime and tack coat spreading	Wirtgen SW 16MC	/	150	2

As for the transportation phase related to installation, the movement of what is needed to operate at the site, such as operating personnel, materials, and machinery, was considered. Table 21 presents data on the weights and kilometers to be traveled.

Table 21: Data related to transport to construction site

Type of load	***Weight (t)***	***Distance (Km)***	***T*km***
People	0,32	24,8	7,936
Operating machinery (roller, excavator, etc.)	21,39	24,8	530,472
Truck for aggregates	5,325	24,8	132,06
Truck for wearing layer	2,2705	24,8	56,3084
Truck for binder	4,4932	24,8	111,4314
Truck for bitumen emulsion for wearing layer	0,025	24,8	0,62
Truck for bitumen emulsion for binder layer	0,02325	24,8	0,577
Tot			839,40

Once the data inventory phase is completed, the quality of the data can be judged. For this reason, a pedigree matrix (Table 22) was compiled for each process analyzed in order to evaluate the data according to the required criteria. There are data that preempt from authoritative and recognized sources in the field of LCA, such as those related to bitumen and bitumen emulsion production. However, the quality of these data is minimally affected by the time aspect, a factor that mainly concerns bitumen emulsion, being data from 2012. In terms of aggregate extraction, a source from the same production and geographic context as the model under analysis was used, however, it is data from about ten years ago. For HMA production, the result is the average due to the use of primary data for pollutant emissions and secondary data for energy consumption. Obviously, production quantities were calculated with primary data. Literature data were used for the road construction part with reference to machinery use. Despite being data from a few years ago, the machinery analyzed are still on the market, so it makes sense to use such data to estimate energy consumption. In summary, the data used have good quality, and the scores by which they were evaluated for the various criteria show good representativeness of the technological, temporal and geographical context.

Table 22: Pedigree matrix for quality data analysis

Data	**Reliability**	**Completeness**	**Temporal correlation**	**Geographical correlation**	**Further technological correlation**
Aggregate extraction	1	1	4	2	1
Aggregate crushing	3	1	1	1	1
Aggregate screening	3	1	1	1	1
Bitumen extraction	1	1	1	2	1
Bitumen emulsion production	1	1	3	2	1
HMA production	2	1	2	1	1

Road construction	2	1	1	1	1

4.4 Life Cycle Impact Assessment (LCIA) and interpretation

Once the process inventory phase was completed and the quality assessment of the data used was conducted, it is possible to proceed to the evaluation phase and subsequent interpretation of the results.

The impact calculation phase is handled independently by the OpenLCA software; at this stage the impacts of each reference flow in the model are attributed to the various impact categories. As announced in Chapter 3, the analysis performed here stops at the characterization phase, not including the optional steps provided by ISO 14040, namely normalization, weight assignment and clustering. This is due because the analysis does not want to introduce further margins of subjectivity into the model, in order to keep it as objective as possible.

Consequently, it is possible to move on to the interpretation of the results of the analysis. For each impact category, the values most relevant to impact formation can be compared. The real comparison will be the comparative one between the impacts of the innovative case and the traditional case, however, the analysis of the impacts of the individual cases is also useful to understand, given the data used and the assumptions made, which processes impact the most in the various categories. Below are the impacts of the model in the main impact categories.

Regarding climate change, it can be seen that the largest share of impact, expressed in kilograms of CO_2 is mainly due to the electricity used. This energy source is mainly used in the crushing and screening of aggregates and in the production of the two asphalt layers. Another significant item is transportation, which is used heavily in moving materials and machinery for site work.

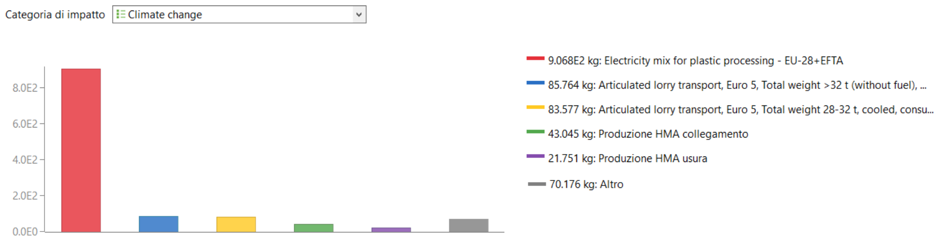


Figure 26: Climate change impact

In terms of acidification, the most impactful flow is electricity, followed by the road construction process to which transportation of machinery and materials are connected.

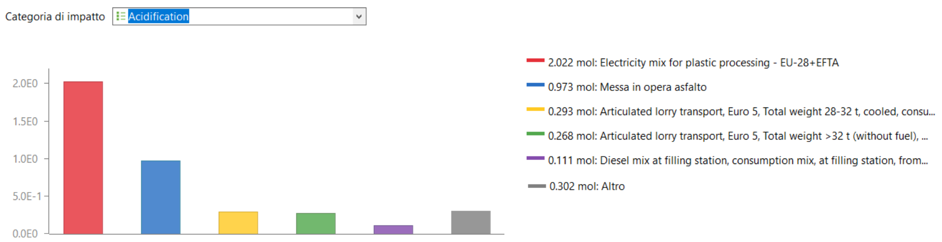


Figure 27: Acidification impact

With regard to freshwater eutrophication, the most significant items are due to the electricity used, diesel fuel used for transport stages, and also the use of tap water, which is present in HMA production and aggregate extraction.

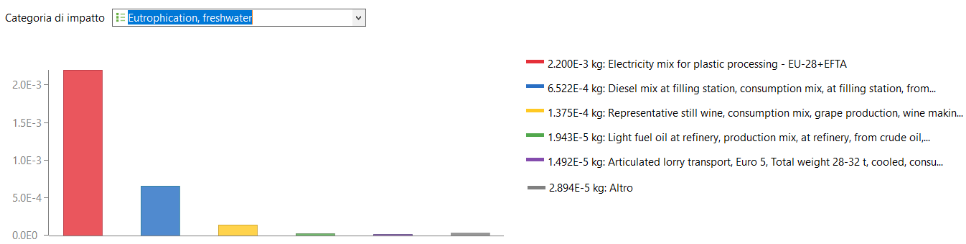


Figure 28: Eutrophication freshwater impact

For the Marine Eutrophication category, the most impactful process is road construction, followed by the production of the HMA wear layer.

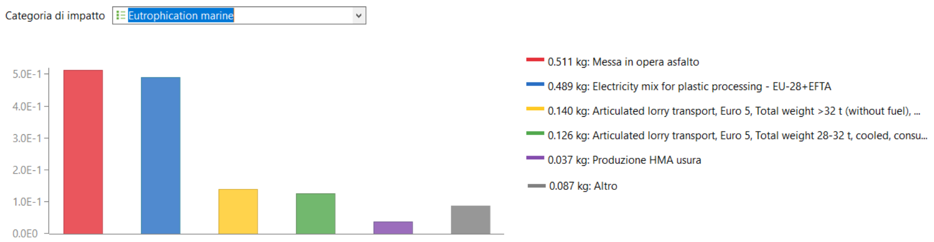


Figure 29: Eutrophication marine impact

For the Human Toxicity cancer category, the most relevant processes relate to the various energy items used, such as diesel, electricity and diesel burned in machinery. The same considerations can be applied to the Human Toxicity non-cancer and Ionising radiation categories.

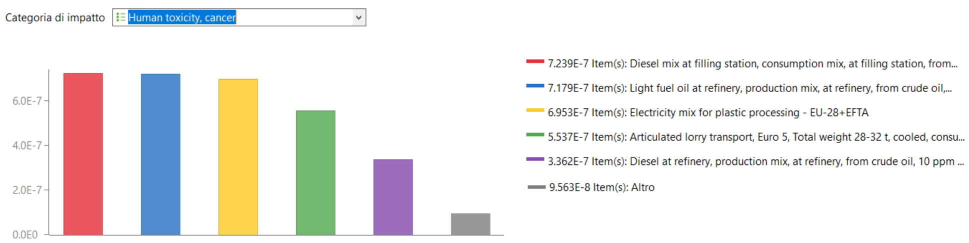


Figure 30: Human toxicity cancer impact

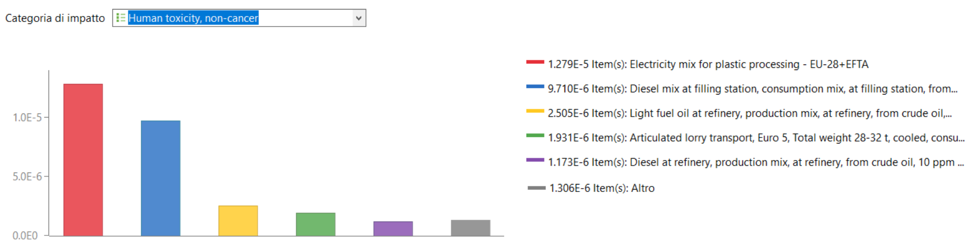


Figure 31: Human toxicity non cancer impact

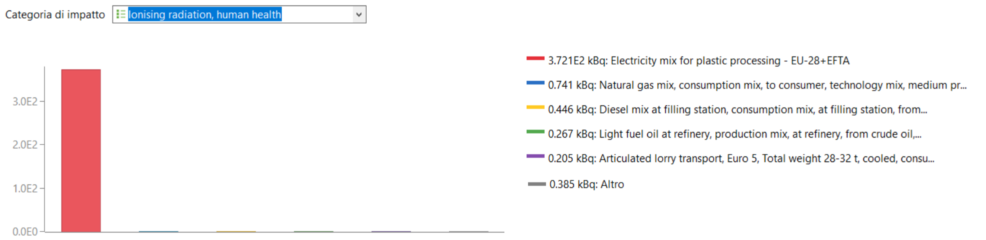


Figure 32: Ionising radiation impact

Relevant to land use are electricity and construction facilities where asphalt and aggregate production take place.

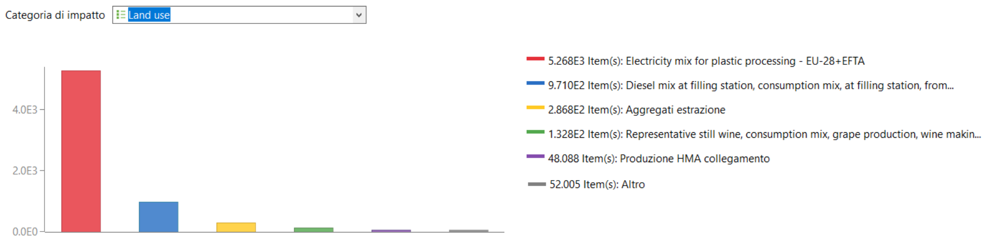


Figure 33: Land use impact

For the Ozone depletion category, the relevant impact is contributed by the electricity consumed in the various processes.

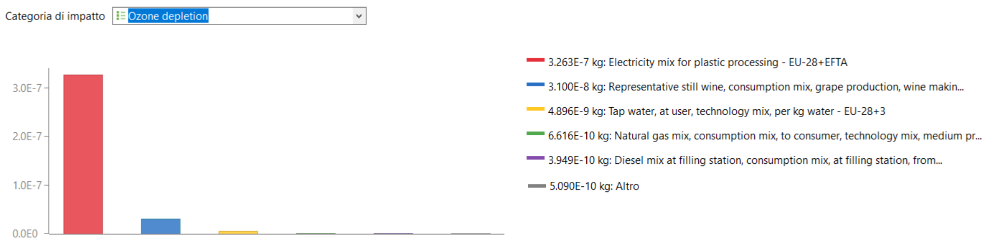


Figure 34: Ozone depletion impact

For the Particulate matter category, the most significant impact is electricity use, while the other items are less significant as they are several orders of magnitude apart.

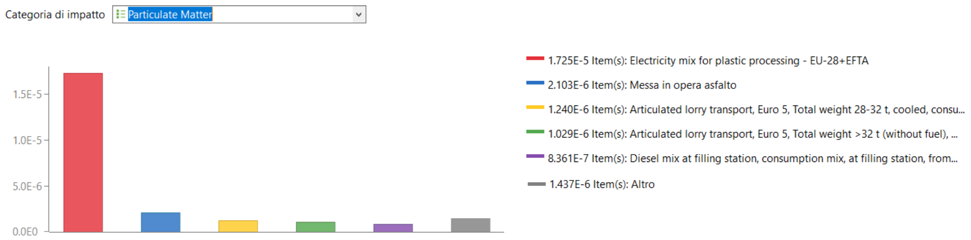


Figure 35: Particulate matter impact

Also in the case of Photochemical ozone formation the electricity is the most relevant item, followed by the process of road construction.

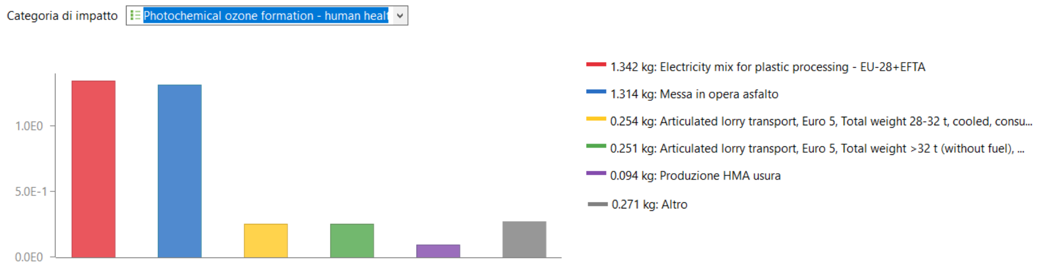


Figure 36: Photochemical ozone formation, human health impact

Water use is prevalent in aggregate extraction, while other streams impact relatively little in comparison. Water is also present for power generation.

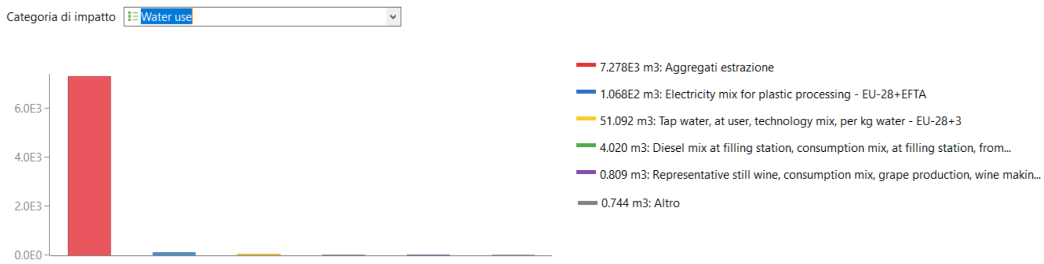


Figure 37: Water use impact

For the freshwater Ecotoxicity category, the greatest impact is from the production of bitumen emulsion, which is used for road production.

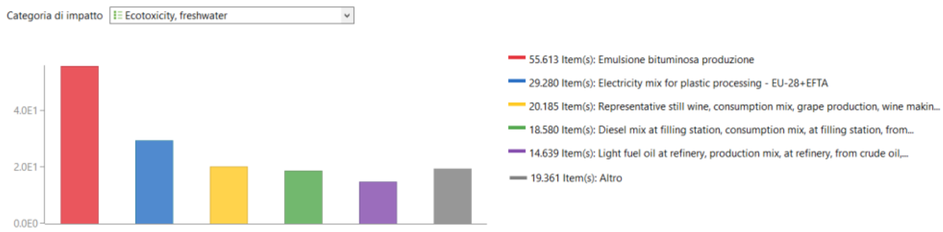


Figure 38: Ecotoxicity freshwater

After analyzing the individual categories individually, an overall judgment can be made. As can be seen from these analyses, the process of road construction according to the classical method is highly energy intensive, as energy use is one of the main consumptions. Thus energy, which is required to process the various materials, results in the largest item of impact in the various environmental categories. In fact, in most cases, energy consumption was the largest item, whether in the case of electricity or diesel use.

Another consideration that can be made concerns the transportation item. In more than one category these items emerged as relevant, since a large number of heavy materials, such as aggregates and asphalt in general, are moved in the various stages of the process. There is also to be considered that a relevant item is due to the transportation of machinery to the site to proceed with the work; this is very heavy machinery that has to be loaded onto a truck in order to be transported. Of course, this consideration with respect to transportation may be more of a general line, as it depends on the distances between the construction site and the production site. It should be emphasized that the distance considered, of about 25 km, is relatively short and that for longer distances this impact is bound to increase due to differences in energy consumption.

Once the innovative process is analyzed, it will be possible to compare the results on the many categories of environmental impact.

Chapter 5

LCA on the innovative smart asphalt production process

5.1 Summary

The second LCA analysis conducted concerns the life-cycle level study of the new asphalt production methodology for a bicycle path. This second analysis produces results that will be compared with those of the classic production case in order to establish a comparison on the various categories of environmental impact. Obviously, in order to be able to obtain comparable data the functional unit of the two analyses will have to be the same, instead the methods, the materials used and their quantities to achieve the objective will change. In this case, the production process uses waste or previously used materials, such as aggregates and bitumen, without introducing virgin materials into the system, so that the effect of recycling can be compared. The analysis was conducted as prescribed by ISO 14040 and ILCD guidance.

5.2 Goal and scope definition

The study is conducted in order to assess the profile of environmental impacts of the new road production technology. It is necessary to conduct this study so that the results can be compared with the benchmark ones of the classical production methodology; thus, the comparative analysis of the results will make it possible to understand whether there are positive or negative environmental impacts in the two processes. The study will therefore be comparative in nature.

In detail, the context concerns the production of a bicycle path in the municipality of Alba in Piedmont in 2022.

The main targets of the analysis are all stakeholders related to the development of the new road production methodology. A non-exhaustive list mainly covers asphalt mix producers, aggregate producers, plastic recycling operators, and all those involved in the development of the new technology. In addition to private companies, academic institutions such as the Polytechnic University of Turin are also included in the development. Other secondary stakeholders who might be interested in the results of the analysis include road and highway management bodies, for example, Italy's ANAS, or the entire scientific community as the results enrich the literature with an innovative LCA case.

The study will initially be kept confidential until the technology is fully developed, as it is still being researched and is not yet a commercialized product. Later it is assumed that the study will be publicized, both from a popularization point of view and for marketing purposes. The study is being conducted by Gianluca Melis, author of the following doctoral dissertation text. Being an academic work, the principal of the analysis can be considered the Polytechnic University of Turin, through the researchers involved in the regionally co-funded research project Ecosmartroad 2.0.

There are no limitations related to the method used as it conforms to standards, while there may be limitations due to the assumptions made in the analysis. These assumptions relate, in some cases, to the use of secondary data because it was found that it was impossible to obtain primary data for some aspects related to production processes. This will be dealt with in more detail in the section on the analysis of the quality of the data used. Data research was conducted in the field, using primary data whenever possible; the data used can be considered representative of the model under analysis, since they all refer to the Piedmontese reality, the geographical location of the process.

The functional unit chosen for analysis concerns the material used to produce a bicycle lane 20 m long, 29 cm deep, and 1.25 m wide. The chosen functional unit is special compared to those present in the state of the art, as usually in similar cases quantities such as 1 ton of asphalt mix are used. However, this choice was found to be necessary and indispensable because the new construction technology involves tiles of specific shapes that are to be placed on the road, not a continuous expanse of material as is normally the case. Consequently, for the comparison to make sense, it was necessary to use the same yardstick, which is the size of the track to be built. The only difference from the classic production case concerns the depth of the track; in fact, a greater thickness will be used because the asphalt tile needs, according to the structural calculations of the designers, a thicker foundation layer.

The deliverables that will be produced from this analysis are a Life Cycle Inventory dataset related to the process and an interpretation of the Life Cycle Impact Assessment results ("LCIA results"), respectively.

The boundaries of the system under analysis are relative to those of a gate-to-gate analysis, as the process flow starts from the recycling phase of input materials such as polymers and plastics. It was decided not to start from the raw material production phase, so as not to simulate the useful life phase of "asphalt mix" and "polymer" products. This phase would have involved a very large share of subjectivity, especially for polymers. In fact, for asphalt there are standard practices on which assumptions can be made, while the life of polymers before recycling would have been too difficult to estimate objectively, precisely because polymers can come from very different applications. Even at the end of the process flow, it was decided not to consider the useful life of the new road type, since being an innovative product, the analysis wants to estimate mainly the impact of production.

Also in this analysis, like the one for the classic manufacturing case, OpenLCA software and the Environmental Footprints database will be used. The same considerations made in the previous chapter about impact methods apply, so the Environmental Footprint impact method with midpoint indicators will be used here as well.

5.3 Inventory analysis

The LCA model that was developed is present in Figure 39. The model is of the gate-to-gate type, in that the process flow begins with the recycling steps of the input materials, leaving out their previous useful life. This choice is motivated by not wanting to introduce further subjectivity into the analysis. Finally, the process ends with the deposition of asphalt tiles for the construction of the bike path. Again, the useful life was not considered, as being an innovative product there is more interest in assessing the impacts of production.

The model can be summarized in the following steps:

- Reclaimed asphalt pavement (RAP) is recovered through the asphalt milling operation, and then it is processed through crushing and screening to arrive at the correct size pieces.
- In parallel, polymers are processed in recycling processes; at this stage PE and PP polymers are sorted, cleaned, crushed, and finally extruded to obtain pellets.
- Once the materials recycling process is finished, the preparation of mixtures for the tile molds is carried out. The base and the cap of the tile will be made of different blends of materials; consequently, the two blends are prepared and finally the devices are printed. Finally once the tiles are ready, the construction of the road is proceeded through the preparatory processes such as excavation and finally the deposition of the tiles.

Delving into the processes summarized in the flowchart in detail, it can be seen that the first step is the recovery of RAP. This process takes place with a milling operation on a road to be rehabilitated by placing a new layer of asphalt. This operation is carried out with the Wirtgen 150CF machine, which can excavate with a depth of 0.33 m and a width of 1.5m, with a milling speed of 1680 m/h and a consumption of 72 l/h. Based on this data, energy consumption is calculated, while emissions are calculated knowing that the machinery complies with the EU Stage 3a European standard that sets precise limits.

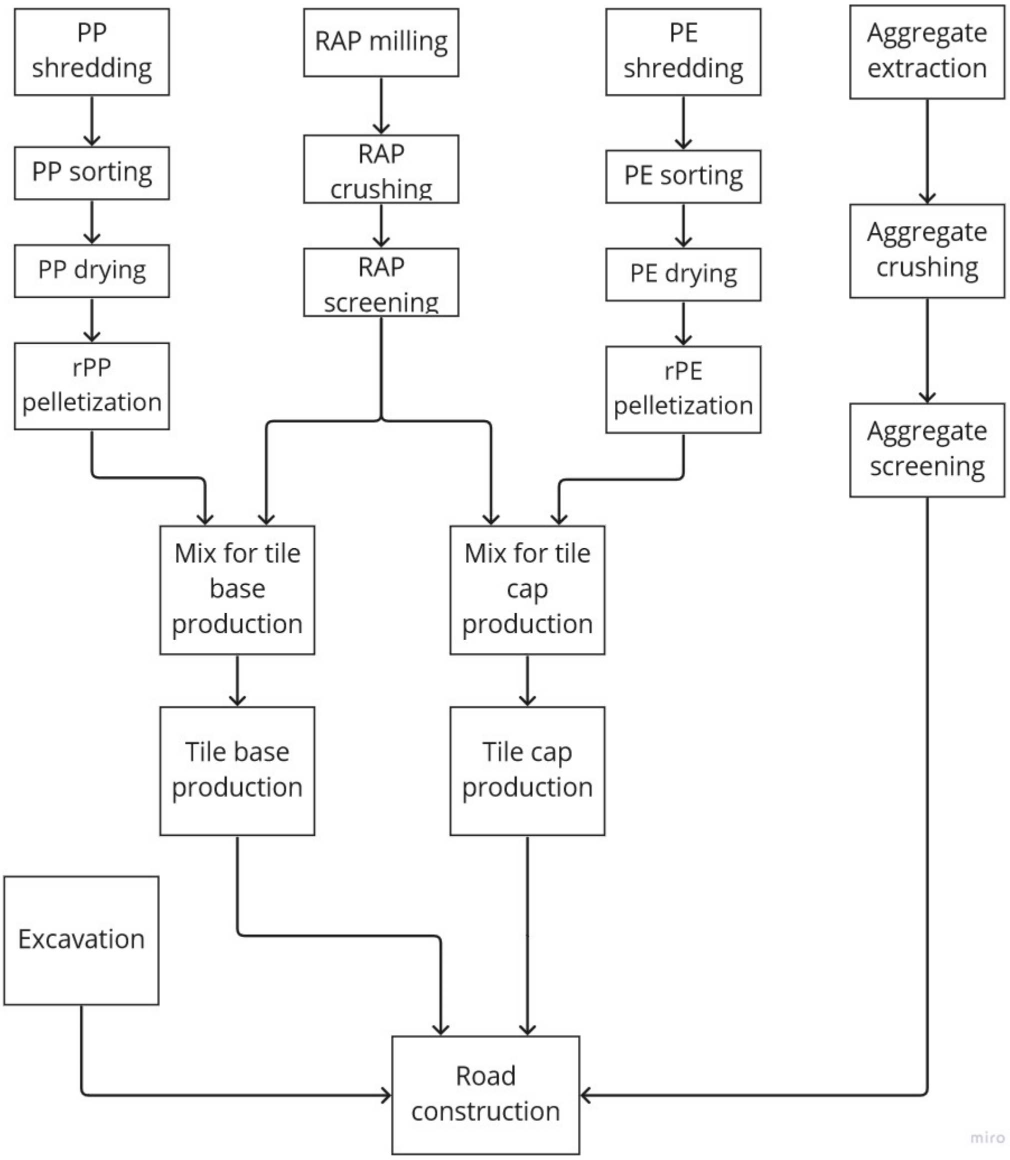


Figure 39: Flowchart of the innovative production method

Once RAP is milled, operations must be carried out to make it usable again on site. These operations include crushing, to obtain smaller pieces, and subsequent screening, in order to create separate piles based on size. The following model was used to carry out these operations: there is a wheel loader that unloads the RAP truck and makes piles of materials connected to a conveyor belt. This is used to feed the crushing machine. Between the crushing machine and the screening machine there is another conveyor belt. Finally, the size-separated material is loaded onto different trucks by the wheel loader. The estimates on commercial machines for crushing and screening systems are the same as those used for processing virgin aggregates in the classic production case (Table 9 and Table 11). Average values of energy consumption required to process one ton of material are used for the calculations. As for the consumption and emissions of the loader and conveyor belt, they are the same as those used in the previous case study (Table 10 and Table 12).

The action of reclaiming milled asphalt allows for environmental benefits, since virgin materials are not used and especially for the fact that waste materials find a new application. This possibility translates into the fact that the materials do not end up in landfills and therefore this constitutes a positive impact. A literature source, the paper by Blengini et al. [52] (Table 23), was used to estimate this impact. This paper appears to be an adequate source as it is contextualized to Piedmont; although it deals with cement aggregate and demolition waste landfills, it is reasonable to assume that the process flows are similar to those of milled asphalt in landfills.

Table 23: Positive impacts of avoided landfill for RAP [52]

Land use		
Transformation, from pasture and meadow	0.08	m^2
Occupation, dump site	0.08*16	m^2a
Transformation, to industrial area, vegetation	0.08	m^2
Materials/fuels (operation of the landfill)		
Electricity	1.14	kWh
Diesel	20.23	MJ
Water	2.6	m^3
Construction of landfill facility		
Concrete	13.85	kg
Waterproof barrier	0.47	kg
Reinforcing steel	0.34	kg
Bentonite	9.93	kg
Gravel	47.10	kg
Polyethylene mesh	0.43	kg
Polyethylene pipe network	0.02	kg
Excavation, hydraulic digger & loader	1	m^3

Polymer processing represents another process flow. In fact, it is necessary for polymers to be recycled before being reprocessed and mixed with RAP. In this case, a mechanical recycling process is used since the materials are thermoplastics. The model boundaries assume that the plastics are already at a recycling center, so the collection stage was not analyzed.

The following operations need to be performed: shredding the plastics, sorting them using separators that operate with various technologies, washing them to remove any dirt, drying them from the moisture introduced, and finally proceeding with pelletizing to obtain workable grains in blending.

Consumption for all these processes was estimated from the data in the tables below (Table 24, Table 25, Table 26 and Table 27), which give details of the industrial machinery; as in the other cases, the average energy consumption to process one ton of material was used. These process flows are present for both PE and PP. A conveyor belt is used in order to move the materials through the different machines; the consumes are the same of the Table 10. Again, for each process, the average consumption to process a quantity of material equal to one ton was calculated.

Table 24: Shredding machines details

Shredding	**Model**	**Throughput (t/h)**	**Power (kW)**
Coparm	TR30	1	22
Forrec	TBS 100	1,4	22
PRT Innovation	Tm40120	0,75	55
Wedomachine	S3063	0,5	30

Table 25: Sorting machines details

Sorting	**Model**	**Throughput (t/h)**	**Power (kW)**
Angelon	A221C4-256V6	0,75	5
Anhui Optic-electronic Color Sorter Machinery	Z1-64 6SZM-64	0,75	1

Co., Ltd			

Table 26: Drying machines details

Drying	Model	Throughput (t/h)	Power (kW)
ASG	HXJ400	0,6	37
PRT innovation	UPEF250	0,375	15

Table 27: Pelletizing machine detail

Producer	Model	Throughput (t/h)	Power (kW)
Maag	Primo 60E	0,35	2,2
Promeco	PES	1,5	92
Beier	SJ-100	0,3	100
Suzhou ACC Machine	SJ-50	0,08	29,5

The recycling process has positive environmental impacts, as it allows waste to be reused, ensuring that it can be put to new use. From an LCA perspective, this translates into avoiding landfilling and avoiding the production of new virgin materials.

The asphalt module consists of two parts:

- The base is composed of 50 % by weight recycled PP (rPP) and 50 % RAP.
- The cap or cover plate is composed of 50 % by weight recycled PE(rPE) and 50 % RAP.

Module dimensions (0.19x1.25x1.25 m) are shown in the Figure 40; depth is omitted as the same for all of 1.25 m. The cap plate is laid on a structure of 11 bottom plate cores.

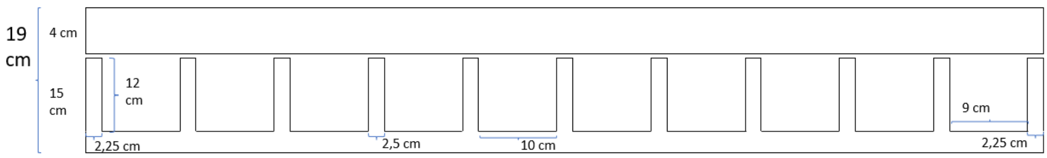


Figure 40: Model and dimensions of the road block

Once the polymers have been recycled and the RAP has been processed, it is possible to proceed with the preparation of the material mixture, to be used later in injection molding. RAP must be transported from the SAM plant, where they were processed, to the mixing and molding site located in Alessandria. The distance is 62.8 km. The mixing process takes the recycled polymer granules and RAP powder to form a homogeneous compound. The resulting mixture consists of 50 percent by weight of Rap and 50 percent of recycled polymers. Obviously, two different mixtures are made, one for the module base and the other for the cap.

The electrical consumption of the mixing stage of 1 ton of material was reconstructed on the average of the properties of the machinery presented in Table 28.

Table 28: Inventory data for the mixer machine

Producer	**Model**	**Throughput (t/h)**	**Power (kW)**
Plastic systems	M1	0,114	0,37
Wam Group	MLH06	0,0285	1,22

Once the material mixtures are ready, it is possible to move on to the injection molding stage. To understand the required amount of the two mixtures, the volume of the plates (upper and lower) was calculated. This volume was multiplied by the resulting density of the mixtures. A density of 1660 kg/m^3 (half of PP and 2390 kg/m^3 of RAP) was considered for the mixture formed from rPP and RAP, and 1665 kg/m^3 for that of rPE and RAP (using the same reasoning). Thus the weight of a tile is 249.1 kg, resulting from the 145 kg of the base and the 104.1 kg of the lid.

For the injection molding phase, values from the Ecoinvent database were considered, with the detail derived from the [59] work. These values refer to consumption per 1 kg of molded product, and accordingly were multiplied by the weight of the two finished products. Of course, a margin of waste material from production was considered.

Table 29: Inventory data for the injection molding of the tile base, based on [59]

Flow	Quantity for kg	Quantity for 1 tile	Unit
Electricity	1,48	214,66	kWh
Grease	0,0007	0,10	kg
Kaolin	0,0076	1,10	kg
Lubricating oil	0,0000167	0,00242	kg
Thermal energy	4,2327	613,92	MJ
HMA mix for tile base	145,047	145,77	kg
Plastic waste	0,005	0,73	kg

Table 30: Inventory data for the injection molding of the tile cap, based on [59]

Flow	Quantity for kg	Quantity for 1 tile	Unit
Electricity	1,48	154,01	kWh
Grease	0,0002	0,02	kg
Kaolin	0,0076	0,79	kg
Lubricating oil	0,00303	0,32	kg
Thermal energy	4,2327	440,47	MJ
HMA mix for tile cap	104,06	104,79	kg
Plastic waste	0,007	0,73	kg

Once the modules have been printed for injection, it is possible to head to the site area to do the installation. It is necessary to bring all materials and machinery to the site location; to do so, the values in the Table 31 were considered. Some of the machinery presented in Table 20 is needed for the paving phase to perform cleaning, excavation, lime spreading and compaction.

The module will be laid on a foundation layer composed of stone aggregates. This layer is 0.10 deep, 1.25 m wide and 20 m long. Aggregates are used to fill this layer, which follows the process flow already outlined in case study 1, thus extraction, crushing and screening. The density that was considered is equal to 1420 kg/m^3.

Table 31: Distances and weight for installation

	Distances (km)	**Weight (kg)**	**t*km**
Modules	62,8	3985,68	250,30
Aggregates	24,8	3550	88,04
Elevating cranes	62,8	523,75	32,89
Machines	24,8	8350	207,08
People	24,8	320	7,94

The construction process involves an excavation phase and the deposition of aggregates, which are then compacted. Once the aggregate layer has been compacted, the lower forms can be deposited, and later the upper forms will be deposited. Because the weight of the modules is high, these steps are carried out with the help of a hydraulic crane mounted on one of the trucks moving the material. Such types of cranes operate through the aid of a hydraulic pump that puts pressure on the hydraulic oil used to move the piston.

This type of crane to operate must consistently have a certain flow rate of oil held at a certain pressure. Below are examples (Table 32), on which the average was calculated to have a more representative figure. To ensure these working conditions, a Plunger Metering Pump Makro TZ hydraulic pump from Prominent, capable of operating in these ranges and with an overall consumption of 1 kW, was considered.

Table 32: Properties of hydraulic crane

Producer	**Model**	**Weight (kg)**	**Pressure**	**Flow (l/min)**
Fassi	M10A.11	/	180	6
CPS	FS 44 Z	920	230	30
Hyva	HA10E1	145	180	5

Cormach	40000	690	260	14
Ing. Bonfiglioli	P2300L2	340	250	10

Consequently, the consumption for this phase is that for the pump, and it was estimated based on the turn-on time. The operating times are shown in the Table 33. The loading time on the truck involves 5 minutes per piece for the total of 32 pieces, the unloading of the basic module a time of 3 minutes per piece; different is the case of the upper module which takes 15 minutes per piece, as this is the time needed to connect the sensors and carry out the electrical wiring.

Table 33: Times of work for the pump

	Time(min)	**Time (h)**	**Consumption (kWh)**
Load	96	1,6	1,6
Dumping tile base	48	0,8	0,8
Dumping tile cap	240	4	4

Once the data inventory phase is completed, the quality of the data can be judged. For this reason, a pedigree matrix (Table 34) was compiled for each process analyzed in order to evaluate the data according to the required criteria.

The data used during the analysis are mainly the result of estimates based on commonly used machinery in the technological world analyzed. Average consumption of state-of-the-art machinery was considered. Consequently, a strong technological, temporal and geographical correlation is present.

It should be noted that data from a reprocessing of the Ecoinvent database were used for the injection printing process. These data refer only to the molding of the individual materials (i.e., PP and PE); due to the impossibility of estimating the actual consumption of the machinery during the printing of the mixture of recycled polymers and RAP, data for the polymers alone were used. Nevertheless, the data used for the required quantities of materials are the result of calculations conducted by structural engineers, so they can be considered primary. In general, the data present good quality, but the results of the analysis can be improved by including primary data on some of the processes involved in the future.

Table 34: Pedigree matrix for data quality evaluation in the innovative case

Data	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation
Aggregate extraction	1	1	4	2	1
Aggregate crushing	3	1	1	1	1
Aggregate screening	3	1	1	1	1
RAP milling	3	1	1	1	1
RAP crushing	3	1	1	1	1
Rap screening	3	1	1	1	1
Polymer recycling	3	1	1	1	1
Mixing process	3	1	1	1	1
Injection molding	3	1	3	1	1
Road costruction	3	1	1	1	1

5.4 Life Cycle Impact Assessment (LCIA) and interpretation

Once the process inventory phase was completed and the quality assessment of the data used was conducted, it is possible to proceed to the evaluation phase and subsequent interpretation of the results.

The impact calculation phase is handled independently by the OpenLCA software; at this stage the impacts of each reference flow in the model are attributed to the various impact categories. As announced in Chapter 3, the analysis performed here stops at the characterization phase, not including the optional steps provided by ISO 14040, namely normalization, weight assignment and clustering. This is due because the analysis does not want to introduce further margins of subjectivity into the model, in order to keep it as objective as possible.

Consequently, it is possible to move on to the interpretation of the results of the analysis. For each impact category, the values most relevant to impact formation can be compared. The real comparison will be the comparative one between the impacts of the innovative case and the traditional case, however, the analysis of the impacts of the individual cases is also useful to understand, given the data used and the assumptions made, which processes impact the most in the various categories. Below are the impacts of the model in the main impact categories.

In terms of the climate change category, it can be seen in Figure 41 that the main impact is from electricity and thermal energy. These sources are mainly used in injection molding and polymer recycling, which require significant amounts of energy to operate. Positive impacts can be seen due to the recycling of PP and PE polymers, which saves the impact of producing new granules.

Figure 41: Climate change impact

The same comments can be applied to acidification (Figure 42) as well, in fact the negative impacts are due to energy sources, while the positive impacts are due to the polymer recycling process.

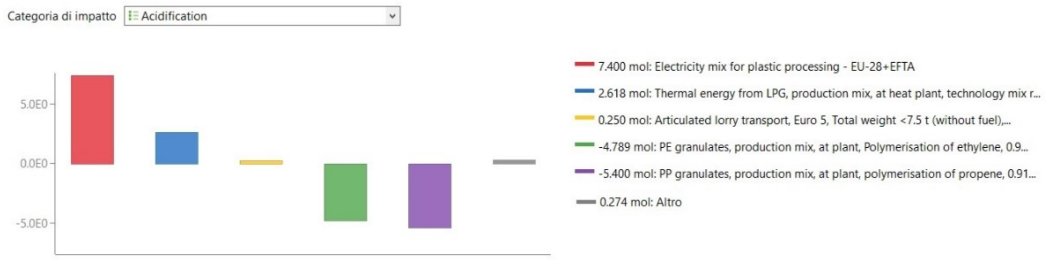


Figure 42: Acidification impact

For the Eutrophication freshwater category (Figure 43), the impacts are related to energy sources and polymer recycling. It is noteworthy that the positive impacts are far greater than the negative ones, estimating a total positive effect on this impact category.

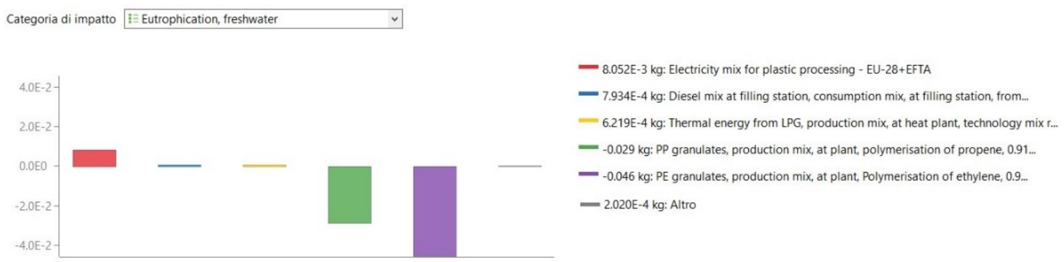


Figure 43: Eutrophication freshwater impact

The situation is different in the marine eutrophication category (Figure 44), as the impacts of electricity are significantly higher and the impacts of transporting materials between production sites are also present.

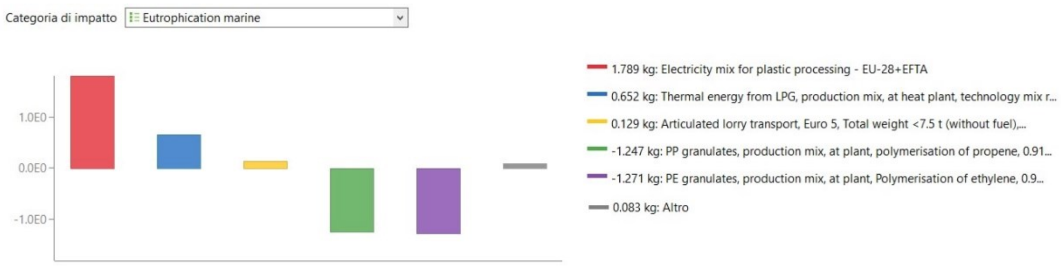


Figure 44: Eutrophication marine impact

For the Human toxicity category related to cancer and non-cancer (Figure 45 and Figure 46), it can be seen that polymer recycling allows for overall positive impacts, outweighing the negative impacts of energy sources.

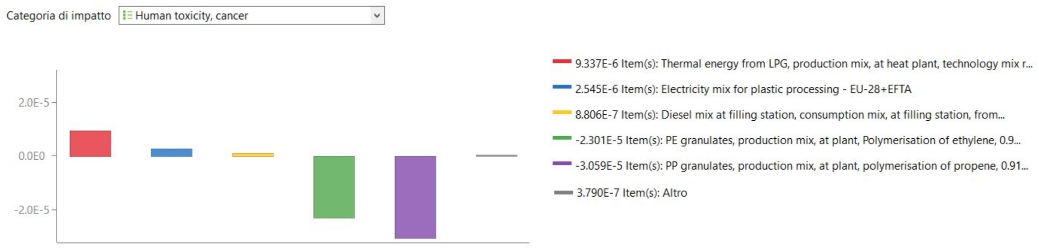


Figure 45: Human toxicity cancer impact

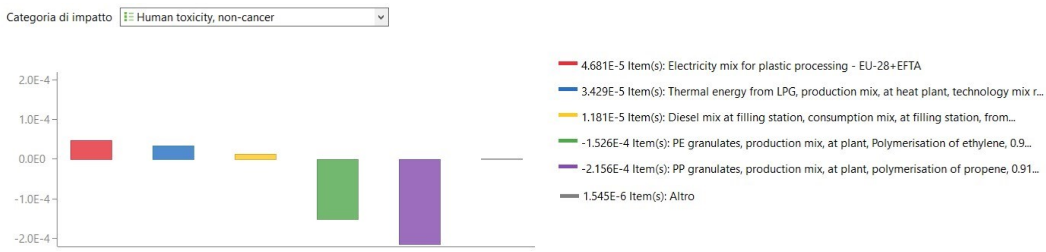


Figure 46: Human toxicity non cancer

For the impact categories Ionising radiation, land use and ozone depletion (Figure 47, Figure 48 and Figure 49), the most significant contribution is always from consumed electricity. In these categories, the effect of recycling is minimal and almost irrelevant, differing by several orders of magnitude.

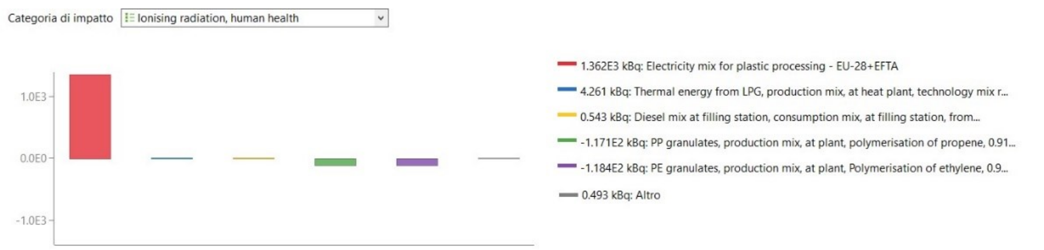


Figure 47: Ionising radiation impact

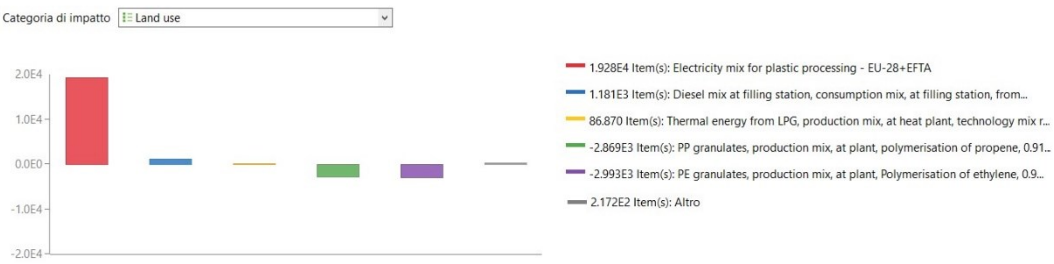


Figure 48: Land use impact

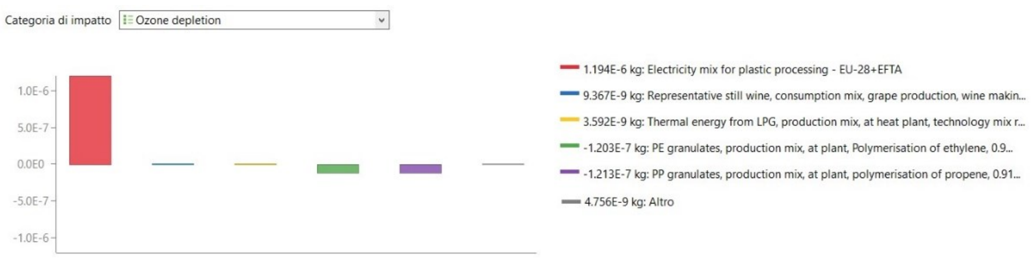


Figure 49: Ozone depletion impact

Regarding the category of particulate matter (Figure 50) creation, the most polluting processes are energy consumption of electricity and heat. Again, there is a positive impact due to recycling, but this does not compensate for the high energy expenditure.

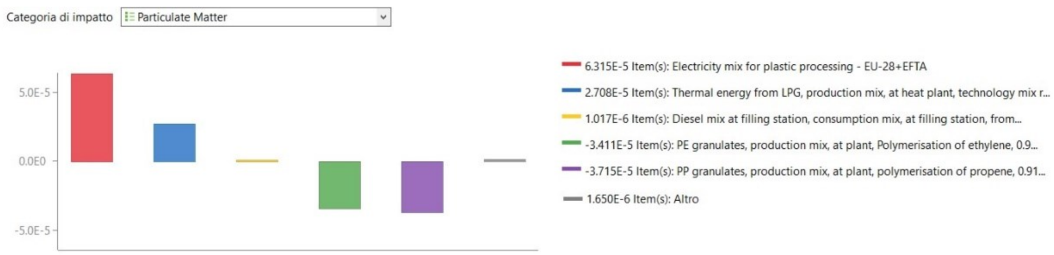


Figure 50: Particulate matter impact

In the Photochemical Ozone formation category (Figure 51), there is an overall positive impact, as the share from energy consumption is overpowered by the positive impacts of polymer recycling.

Figure 51: Photochemical ozone formation impact

The category related to water use (Figure 52) involves the extraction of aggregates for use in the road subgrade as the most impactful material.

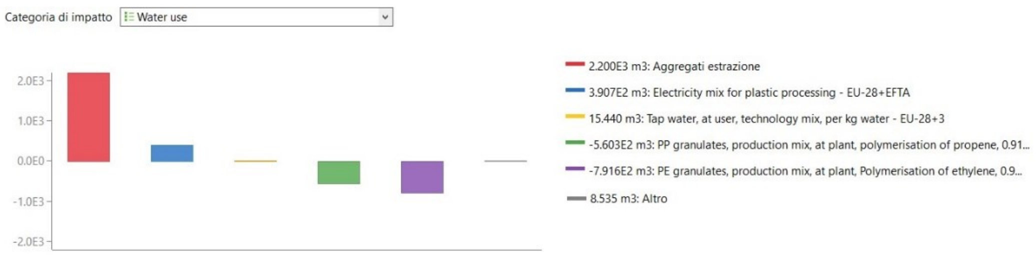


Figure 52: Water use impact

For the Ecotoxicity freshwater (Figure 53) category, there is a significant positive impact due to polymer recycling. it is noteworthy that in this impact category, thermal energy consumption is more impactful than electricity.

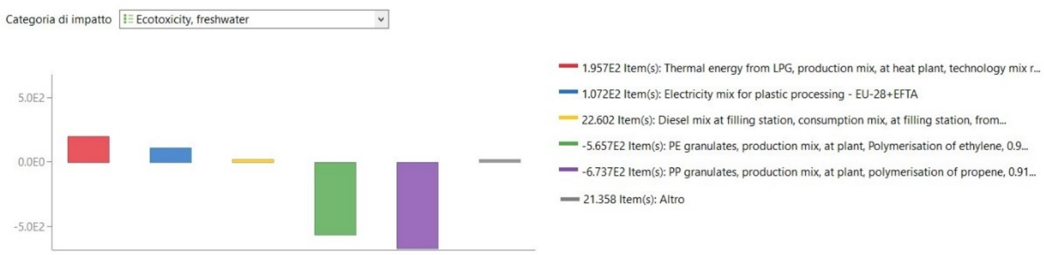


Figure 53: Ecotoxicity freshwater impact

From the analysis of these impacts, some more general conclusions can be drawn about the development of the new process. First of all, the innovative process has good estimated impacts, which come mainly from polymer recycling.

An aspect that was not taken into consideration concerns the production of the molds to carry out the molding of the modules. This process was not considered, as its impacts would have been homogeneously assigned to all printed products during their useful life. Since the prototype case foresees the molding of only 16 modules per type, it was not considered an added value to estimate the useful life, inserting numbers in an arbitrary manner. Consequently this aspect has been omitted.

However, it should be emphasized that material recycling may risk hiding the characteristics of the process. In fact, the innovative process is highly energy intensive, with the highest consumption occurring in the case of injection molding and polymer recycling. The energy that is used in these two processes is mainly related to heating the plastics to obtain a molten state that is processable by extrusion to obtain the recycled granules or by molding. It should be noted that actual estimates of these energy consumptions may be even higher than those produced by the analysis. This is due to the fact that the molding process was estimated through the Ecoinvent database, which is for individual polymers (PP and PE), not taking into account that a mixture of RAP and recycled polymers will have to be processed. Since RAP has a significantly higher density, it is reasonable to assume that the blend will have higher density and therefore higher viscosity, thus requiring greater amounts of energy to be melted. Consequently, the analysis on this aspect can be improved through the use of primary data measured directly on the injection molding machine. Since the process consumes a lot of energy and this greatly affects all the impacts analyzed, a possible solution could be to diversify energy sources. In fact, the analysis was conducted using the electricity flow characteristic of Italy, however if the producing company had energy from renewable sources, such as photovoltaic panels, it could be a great way to reduce impacts.

Despite this drawback, the effect of recycling is remarkable, as a reuse of materials through new processing means that materials are not sent to landfills, preventing consumption and related emissions.

Chapter 6

Case comparison and conclusions

After conducting the two case studies, it is finally possible to conduct the comparison between the two production methods on the various environmental impact categories of interest. This comparison, the ultimate goal of the analysis, is useful in understanding the environmental performance of the new process. Through this tool, it is possible to understand whether the new production technology allows for a more environmentally sustainable process. This chapter presents the comparison, commenting for the various impact categories on the behavior of the two production methods.

6.1 Impacts comparison

A summary diagram showing the comparison, for the various environmental impact categories of the Environmental Footprint methodology, of the two cases is shown in the Figure 54. The innovative case is shown in blue color, while the classic case is shown in red. It is emphasized that in this image the results are shown in percentages, without units of measurement; for each individual category the values of the impacts have been reported on a percentage from 0 to 100, with positive and possibly negative values.

From the results shown in the table it can be seen that in general the behavior of the innovative production case allows for better performance under several categories of environmental impact, while for others the results are comparable with the classical one.

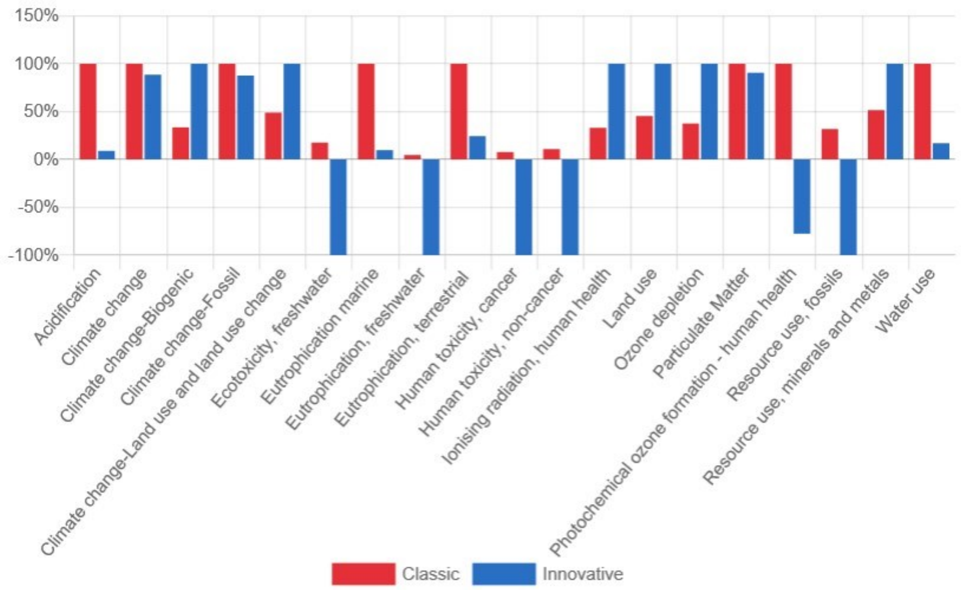


Figure 54: Comparison impacts between classical and innovative production case.

Going into detail, individual environmental impact categories can be analyzed. For the Acidification category (Figure 55), it can be seen that the innovative case shows considerable preference, emitting fewer pollutants. This indicator concerns the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides.

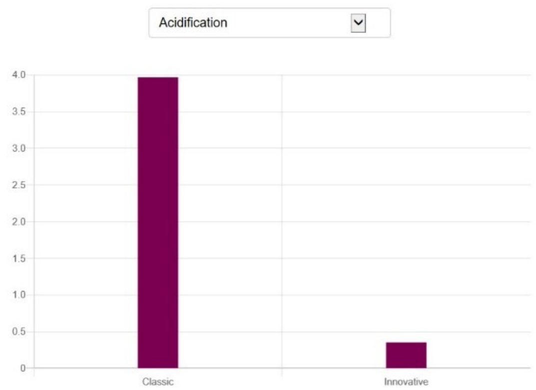


Figure 55: Comparison Acidification impact

A more complicated discussion concerns the climate change (Figure 56) category. In fact, in this case the innovative case is favored, but the pollutant emission is slightly lower. Consequently, it can be argued that the innovative case estimates a smaller impact, but that the environmental gain is not so net.

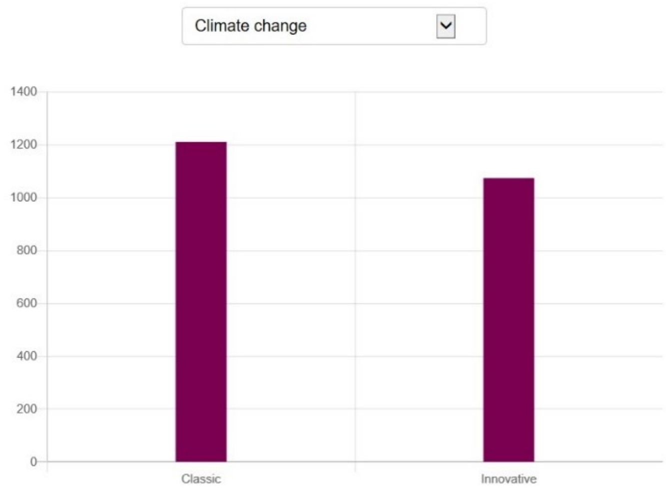


Figure 56: Comparison climate change impact

For the Ecotoxicity freshwater (Figure 57) category, the innovative process is clearly favored, as it even allows an environmental benefit, resulting from the recycling of polymers. This category concerns the impact on freshwater organisms of toxic substances emitted to the environment. The same consideration can be applied to the Eutrophication freshwater category, that relates the enrichment of the fresh water ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds.

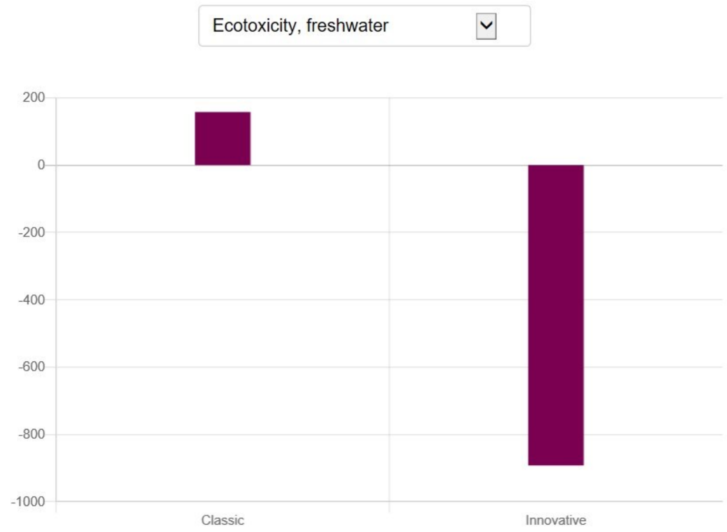


Figure 57: Comparison Ecotoxicity freshwater

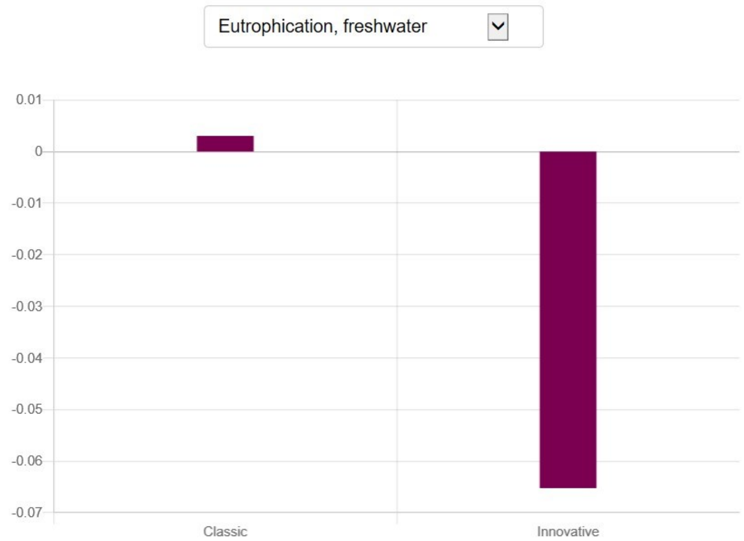


Figure 58: Comparison Eutrophication freshwater

For the marine and terrestrial Eutrophication categories, the innovative case performs well, generating significantly lower impacts than the traditional case. Thus, fewer equivalent kilograms of nitrogen are prospectively emitted for the marine category.

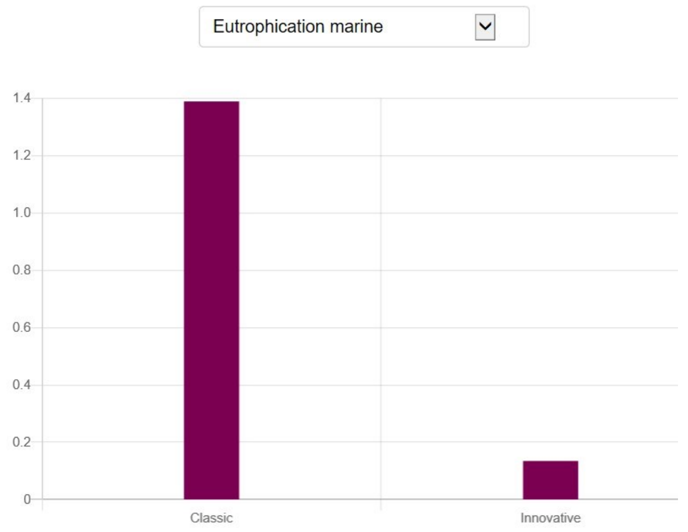


Figure 59: Comparison Eutrophication marine impact

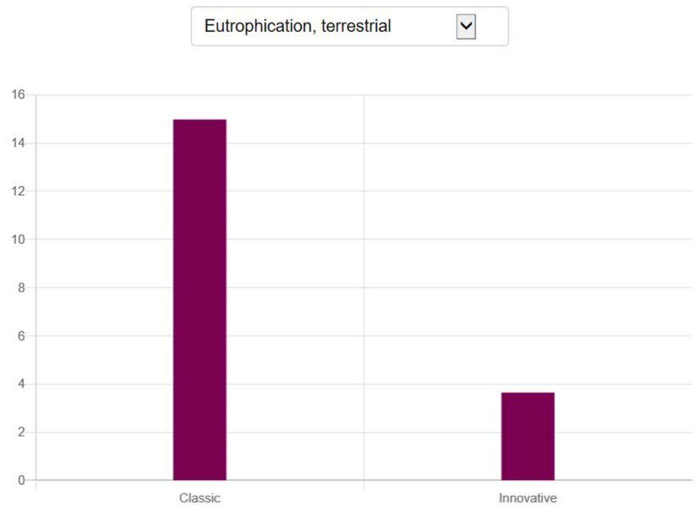


Figure 60: Comparison Eutrophication terrestrial impact

For the human toxicity categories with cancer effects and non-cancer effects, it can be seen that the innovative case has environmental advantages, thus making it preferable to the classical case. These categories concern the impacts on humans of toxic substances emitted to the environment.

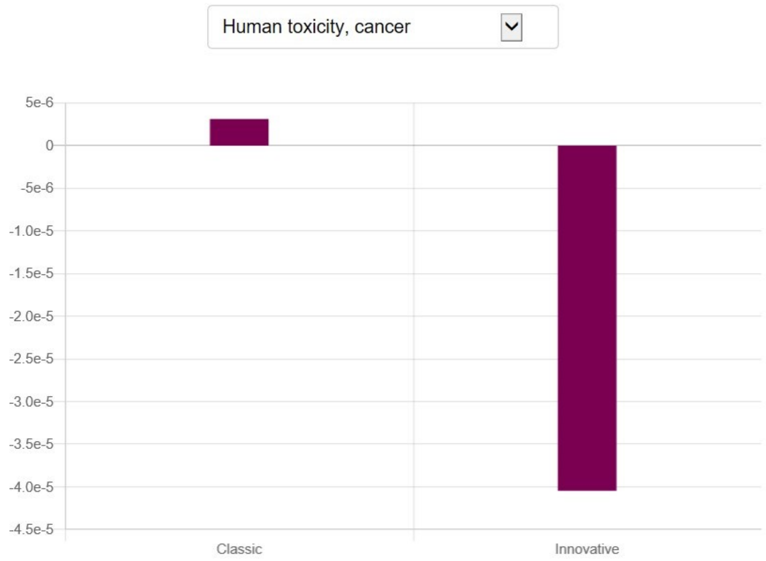


Figure 61: Comparison Human toxicity cancer impact

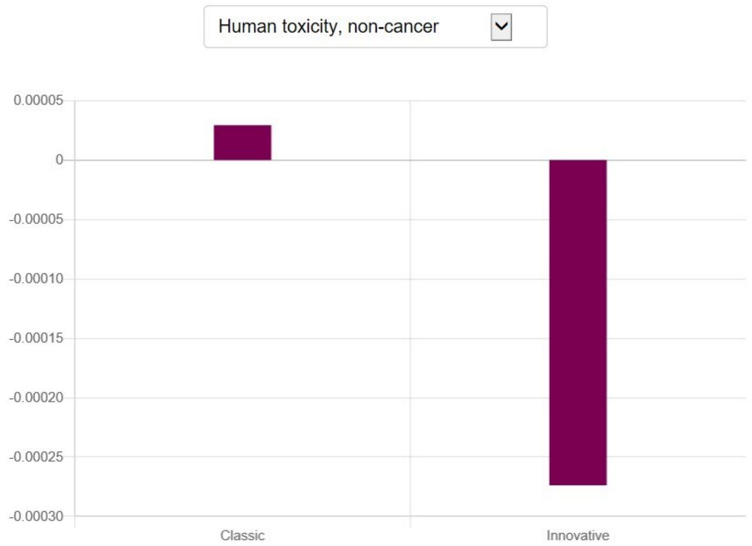


Figure 62: Comparison Human toxicity non cancer impact

For the particulate matter formation category (Figure 63), it can be seen that the two production processes have similar emission levels of kg of PM2.5 equivalent. The innovative case shows a slight preference, however, the performance can be considered very similar.

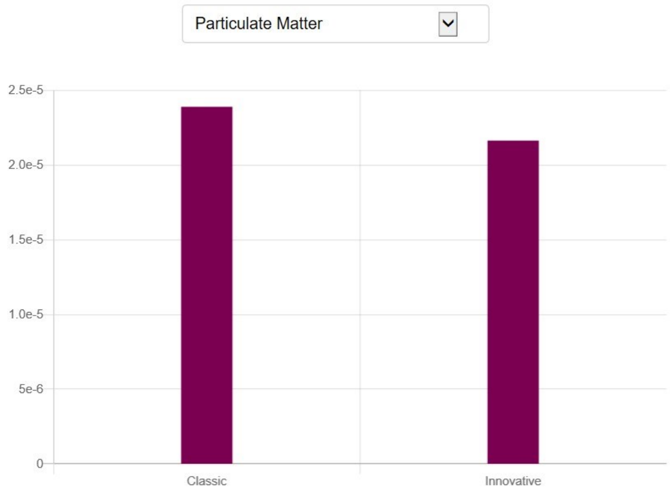


Figure 63: Comparison Particulate matter impact

For the Photochemical ozone formation category, the innovative process has an environmental advantage, proving preferable to the classical process. As a result, fewer kilograms of equivalent nitrogen oxides are emitted. This category relates the emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalyzed by sunlight.

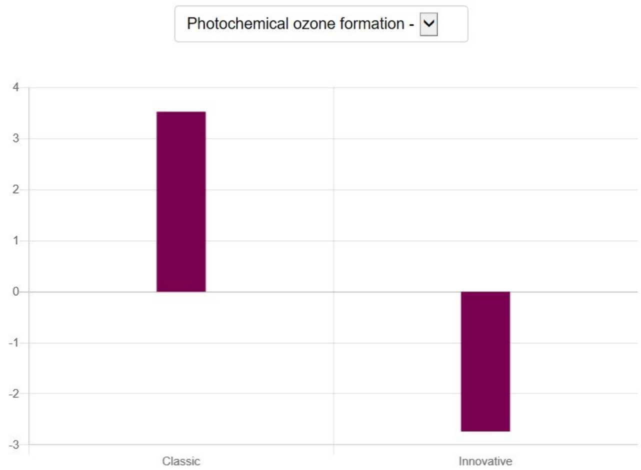


Figure 64: Comparison Photochemical ozone formation impact

In terms of the fossil resource consumption category (Figure 65), expressed in MJ of energy, the innovative case has a significant advantage due to the reuse of polymers, which means that energy is not consumed from virgin materials.

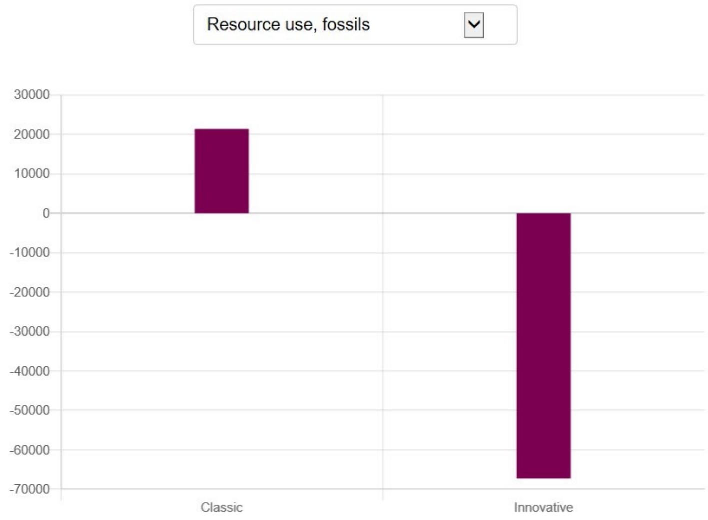


Figure 65: Comparison resource use fossils impact

The category on water use (Figure 66) refers to cubic meters of water used by processes. In this case, the impact of the innovative production case is significantly less, as much more water is used in the classical process, for example, for the production of asphalt mix.

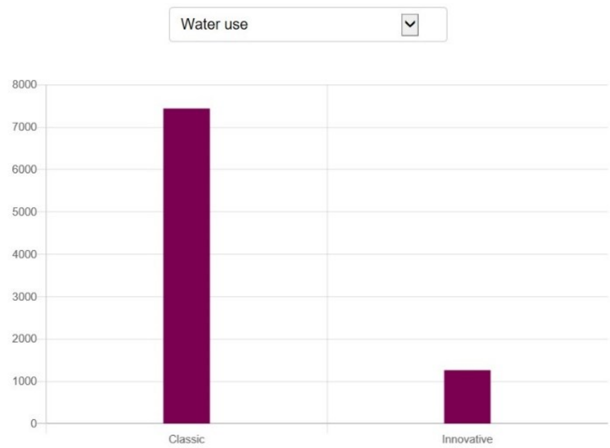


Figure 66: Comparison water use impact

There are also categories in which the classical case is preferable, such as in land use and ozone depletion. However, the better result shown by the innovative process on the majority of environmental impact categories remains significant.

6.2 Conclusions

In this study, a life cycle assessment was conducted on a new road construction process. This process in particular concerns the construction of a cycle path in Piedmont in 2022. The analysis had a comparative nature, assuming two case studies: one concerning the classic production process of bituminous conglomerate and the other concerning the innovative production process with molding of modules composed of RAP and recycled polymers.

After analyzing and comparing the two case studies, some final conclusions can be drawn about the work done. Both processes are very energy intensive, the classical one for asphalt processing and the innovative one with polymer recycling and module molding. As analyzed in the conclusions of the innovative production case, the energy consumption of the process is offset by the positive impact due to recycling, a factor not present in the classic case.

It should be emphasized that the analysis conducted was done to obtain an evaluation benchmark for the new methodology. The choices made included a comparison between a case with entirely virgin materials and a case where recycling is involved.

In reality, even in the case of asphalt production, recycling of some materials such as RAP is possible, even with the inclusion of polymers that serve as additives. Consequently, the classic case could have benefits from these kinds of materials. However, the useful life phase of these processes, which is necessary for their inclusion, would have introduced additional room for subjectivity to the analysis. However, this reasoning can also be applied in the case of innovative production, as the aggregates used as a basis for the modules can come from recycling and not necessarily from quarries.

This analysis has produced estimates that testify, according to the assumptions made and the data used, how the innovative process is preferable from the point of view of different environmental categories. Obviously these results are subject to change when the analysis is repeated by varying some aspects, for example using other databases or perhaps introducing more detail with primary data.

Starting from the results achieved, some suggestions and needs for future work can be defined. First of all, it may be interesting to repeat the analysis of the innovative production case using primary data, especially for the injection molding phase. Another aspect to consider, perhaps on other larger case studies, concerns the comparison between bituminous conglomerate containing RAP and the modules of recycled polymers and RAP, thus introducing recycling in the classic case of production.

The evaluation that was carried out can only be used as an analysis from an environmental point of view, as the costs of the new methodology and the production times of such large molds are not dealt with.

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