WP T2 INNOVATION ON TEXTILE WASTE MANAGEMENT

ACTIVITY A.T2

Deliverable: Environmental evaluation

Additional ENTeR pilot case: Textile waste coming from medical devices concerning COVID-19 emergency

Version 1

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Responsible partner:

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Summary

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ENTeR – Expert Network on Textile Recycling

ENTeR works in five central European countries that are involved in the textile business, to promote innovative solutions for waste management that will result in a circular economy approach to making textiles.

The project will help to accelerate collaboration among the involved textile territories, promoting a joint offer of innovative services by the main local research centres and business associations ("virtual centre"), involving also public stakeholders in defining a strategic agenda and related action plan, in order to link and drive the circular economy consideration and strategic actions.

The approach of the proposal and the cooperation between the partners are oriented to the management and optimization of waste, in a Life Cycle Design (or Ecodesign) perspective.

1. Introduction

The COVID-19 pandemic has revealed the urgent need for large number of disposable textile medical devices both for the healthcare workers (surgical gowns, medical masks, respirators, surgical drapes, gloves) as well as for the citizens (protective face masks). The dramatic increase in their use is leading to significant increase of waste production worldwide.

The additional pilot case of the ENTeR project "Textile waste coming from medical devices concerning COVID-19 emergency" aims to define a potential new way for medical textile waste management in order to favour their recycling and /or reuse. The aim is to study the medical textile waste materials (material, chemicals, biological contamination), to define current procedures for medical textile waste management, to study the removal of chemicals and biological decontamination, to evaluate economic and environmental benefits of reuse / recycling and to create guidelines and best practices for a new and more sustainable waste management.

With this purpose in mind, a theoretical study was conducted to evaluate both the economical and the environmental aspects of medical textile waste management. The study focuses on the comparison between the state-of-art (i.e. incineration/landfill) and a recycling action for the fabric.

In Italy, a monthly demand of 100 million mask is estimated. If we divide this amount by the number of citizens (i.e. ~60.350.000 people), then we obtain a per capita consumption of 2 masks/month (Benedetti, 2020). This data is probably underestimated because it fails in representing also the face protection masks used by the national health system.

On a world basis, a monthly use of 129 billion face masks and 65 billion gloves is estimated. With such a high number of items, a mismanagement of personal protective equipment (PPE) waste during the COVID-19 pandemic is resulting in widespread environmental contamination (Prata et al., 2020).

Concerning the increase in plastic pollution, Silva et al (2020) identified different challenges:

- Need for a proper use and disposal of personal protective equipment: the use of PPE, especially of face masks, has been incentivised and quickly spread to the worldwide population. The demand of PPE by ordinary citizens increased. As a rule, PPE will probably end up disposed in regular municipal solid waste, or discarded in the environment.
- Increased use and demand of single-use-plastics: The increased waste generation identified with PPE is mainly due to the single-used plastics (SUP).
- Improvement of municipal waste-management: waste management is of paramount importance in the pandemic context, due to the risk prevent related to pathogen transmission and the increase of household waste generation. It is additionally crucial to continue following the hierarchy of waste management aimed at resource circularity and preservation (i.e. reduce, reuse, recycle, and recover).

2. Respiratory PPEs related to the COVID-19

2.1. Respiratory protection masks

A respiratory protection mask (Hohenstein, 2020) is a personal protective device used to protect the wearer from inhaling hazardous airborne particles (dust, infectious agents, gases, vapours). It covers at least the nose and mouth. Respiratory protection masks must comply both the European Personal Protective Equipment Regulation 2016/425/EU and the European standard EN 149:2001+A1:2009 – Respiratory protective devices – Filtering half masks to protect against particles – Requirements, testing, marking. They must wear the CE certification label

There are 3 types of respiratory protection masks (Centexbel, 2020):

- FFP1 mask – the lowest level of performance; efficiency of at least 80% against airborne particles, the side leakage (around the face) must not exceed 22%. It is used when norovirus is present.
- FFP2 mask – average category of protective masks; efficiency of 94% solid and liquid irritant aerosols, the side leakage must not exceed 8%. It is used when TBC is present.
- FFP3 mask – high protection against solid and liquid toxic aerosols; minimum efficiency of 99%, the side leakage must not exceed 2 %. It is used when working with cytostatics.

In addition to the penetration levels mentioned above, there are still other requirements which must be met by masks of these three types.

2.2. Medical masks

The medical masks (Hohenstein, 2020) are the disposable face coverings used by infected persons, healthcare workers or public to ensure a barrier that reduce transfer of body fluids which may spread infection and protects other people around the wearer; they are not designed to protect the wearer against entry of infection. They are designed to fit loosely over the nose and mouth of the user. These masks are subject of approval and certification; they are not respirators and they undergo a different regulatory and certification process (Institute of Medicine, 2006).

2.3. Materials

The materials which are typically used for manufacturing of disposable medical masks are a 20 g/m2 polypropylene spunbond non-woven fabric and a 25 g/m2 polypropylene melt-blown non-woven sheet. The thickness of fibre is from < 1 to 10 µm (Chellamani et al., 2013).

Polystyrene, polycarbonate, polyethylene or polyester are some of the other commonly-used materials in surgical masks. While they keep out bacteria effectively (although not necessarily that of the virus), the masks are plastic-based, liquid-resistant products that have a long afterlife after they are discarded, ending up in landfill or oceans.

The common single-use medical masks are made from three or four layers of non-woven fabrics. The inner layer is a common non-woven fabric; it absorbs the moisture from the wearers´ breathe. The outer layer is made from the waterproof non-woven fabric used to isolate the liquid sprayed by the wearer. In the middle, there is a filter layer which has a barrier function against germs; this middle layer is made from the polypropylene melt-blown non-woven fabric. The core material of medical masks is polypropylene melt-blown non-woven fabric after electret treatment. The thickness of a layer is 1 μm (Chellamani et al., 2013).

The spunbond non-woven textiles are manufactured by direct spinning of polymeric granulates into endless fibres (filaments).The melted polymer is extruded through a spinneret and slightly cooled in the air. The spinneret can be rotated to deliver fibres in different arrangements. The filaments are subsequently deposited onto a conveyor belt in a random manner and bonded to form a flat continuous web; bonding is performed thermally by applying heated rolls (calendaring), chemically (impregnation) or mechanically (needling)[1,2] (Lokesh, 2020). The benefits of this process are simplicity, high specific productivity and solvent-free operation (Lokesh, 2020)[3].

2.4. Chemical finishing

As already mentioned, most of these protection systems consist of disposable non-woven fabric, which must provide protection against any reasonable professional exposure expected and must not allow blood or other materials to pass through or reach work clothes, undergarments, skin, eyes, mouth or other mucous membranes of the operators in normal conditions of use. For this reason, a water-repellent coating is applied to most of the products in the healthcare sector, usually hydrocarbons, silicones and fluorocarbons coatings. The most commonly used are fluorocarbon-based coatings. Fluorocarbon repellents give the fabric high water repellence and simultaneously they lower the surface tension of the fabric. This property is important because there are low surface tension liquids, such as blood and alcohol, that can be blocked. The application of these finishes with liquid technology requires the impregnation of the fabric through a bath where the finishing chemicals are present, including catalysts and crosslinkers, and the application of wetting agents to the fabric in order to increase wettability.

3. Life Cycle Assessment: methodology overview

The Life Cycle Assessment is a methodological approach for assessing products, processes, industrial systems, and the like. The whole product’s life cycle is considered, from the raw materials extraction to the end-of-life (EoL) stage, where all the materials are dismantled, disposed, or recycled. It enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle and, as a result, it allows selecting the path or process that is preferable from the environment point of view.

The LCA helps decision-makers to select the product, process, or technology that results in the least impact to the environment. This information can be used with other factors, such as cost and performance data to find optimal solutions. The LCA supports in identifying the shifting of environmental burdens from one media to another, from one impact indicator to another, and

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[1] https://en.wikipedia.org/wiki/Nonwoven_fabric#Spunlaid_nonwovens

[2] http://www.nonwoven-material.cn/spunbond-nonwoven/what-is-spunbond.asp?m=k&m1=k1&m2=k1k

[3] https://en.wikipedia.org/wiki/Melt_blowing

between different life cycle stages. The standardized LCA framework encompasses four phases (ISO 2006a, b).

Goal definition and scope: this is the first level of the study; the purpose, scope and main hypotheses considered are defined here. Firstly, the goal must be specified, as well as the set of decisions that will be made based on the results obtained. Secondly, the scope of the study is determined. The latter should be well defined to ensure that the extent, robustness, and detail of the study are compatible and consistent to address the stated goal. This action implies defining the system, its limits, quality of data, the main assumptions, and the study limitations. The definition of the functional unit is a key step. This is the unit of the product or service whose environmental impacts will be assessed and on which the comparison will be performed. Finally, the system boundaries are outlined. They determine which stages, processes and flows will be included in the study.

Inventory analysis: this is a technical process of data collection aimed at quantifying and measuring all the inputs and the outputs of the system, as it is defined in the scope. The emissions released to the environment and the consumed resourced along the production life cycle are collected and calculated with reference to the functional unit. The main steps are: (1) data collection; (2) relevant and non-relevant element identification; (3) mass and energy balances, and (4) system burdens allocation.

Impact assessment: during this phase, the data are translated into environmental impacts, through the application of one or more impact assessment methods. Briefly, it is the procedure to identify and characterize the potential effects produced in the environment by the analyzed system. Suitable software will be used for this purpose (GaBi software[4]). The environmental pressures are characterized for several impact categories, e.g. global warming, acidification, eutrophication, resource depletion, human health, cumulative energy demand, etc. These impact categories and potential environments impact are described in section.

Data interpretation: in this phase, the findings obtained are presented in a synthetic way, identifying, and examining the critical sources of impacts and the possible options to decrease them. The interpretation is useful to indicate the results consistency according to all the aspects defined during the goal and scope stage. The interpretation requires consistency checks, ensuring that there is complete information.

3.1. LCA application in this study

As already specified, the present study is theoretical evaluation. This means that it is based on exploring and testing different theories and its purpose is to provide valuable information to be used in a wider decision-making process. This framework aims at introducing and describing a number of relevant scenarios for medical textile waste management. It is meant to examine the problem and to help brainstorming on what could be considered as relevant variables.

The study focuses on the comparison between the state-of-art (i.e. incineration/landfill) and a recycling action specific for the fabric. Therefore, different options were taken into account with the goal of initially screening them and spotting possible issues or criticalities.

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[4] http://www.gabi-software.com/international/index/

As a part of decision-making, the Life Cycle Assessment (LCA) methodology was applied, in accordance with the ISO standard series (ISO, 2006a, b). The Life Cycle Impact Assessment is carried out by means of Environmental Footprint method (EC, 2013) as in its last update (Fazio et al., 2018). Further references for the methodology are the Product Environmental Footprint (PEF) method for the transition phase (Zampori and Pant, 2019), which was used to model the end-of-life of medical fabric waste, and the LCA guidelines provided by the Joint Research Centre (EC-JRC-IES, 2010).

For the present study, data were retrieved and processed by means of the LCA software GaBi 9.5.1.46 (distributed by Thinkstep, a Sphera company) and its implemented database, i.e. GaBi Professional service pack 40 (Sphera, 2020) and ecoinvent 3.6 (Ecoinvent, 2019).

4. Goal and scope definition

4.1. Goal

The present LCA study aims at evaluating the environmental performance of the face medical masks end-of-life (EoL), as this step was identified as a critical issue during the COVID-19 pandemic, both from the resource efficiency and environmental impact sides.

For reasons of completeness, the study considers the mask entire life cycle, even if in a simplified version.

A comparison is analysed, to assess the environmental benefits of textile recycling compared to landfilling and incineration. Concisely, the analysis aims to:

- To compare the recycling scenario with the current practice.
- To assess the environmental performance of the treatment and recovery system of textiles.

The main goal of this comparison is to evaluate how the environmental performance of the face masks can change when the EoL is modified. In particular by assessing the following scenarios:

1. The fabric is entirely sent to incineration as it should be when medical waste is involved. Currently, many face masks are disposed as municipal waste, thus ending up both in landfills and incinerating plants.
2. The fabric is mechanically recycled, i.e. it is collected, shattered, re-polymerized, and used again to replace virgin textile material.
3. The fabric is chemically decontaminated and then mechanically recycled.

This evaluation is meant to identify the main environmental pressures and, consequently, possible the impact hotspots.

To meet the listed goals of the analysis, the LCA will be conducted on medical masks made in 100% virgin polypropylene fabric composed as follows:

- OUTER LAYER: non-woven fabric produced with spunbond technology; this layer has the function of giving mechanical resistance to the mask.

- INTERMEDIATE LAYER: non-woven fabric produced with melt-blown technology and consisting of microfibers with a diameter of 1-3 microns; this layer performs the filtering function.
- INTERNAL LAYER: non-woven fabric produced with spunbond technology; this layer has a protective function for the face, avoiding direct contact of the skin with the intermediate filtering layer.

For the purpose of this study, the potential occurrence of a metal part (i.e. the nose clip) is not considered, as it its amount was deemed negligible compared to the fabric mass.

4.2. Scope

According to the guidelines provided by the PEF methodology (Zampori and Pant, 2019) and by the Joint Research Centre (EC-JRC-IES, 2010), each aspect of the scope is described in the following sections.

In order to mirror the Interreg area situation, the analysis is based on the amount of medical masks imported in the Interreg Central Europe countries[5] in the first semester of 2020 (Eurostat, 2020). The import is considered from all the countries in the World, both intra- and extra-EU.

4.2.1. Functional unit and Reference flow

The functional unit of the analysis qualitatively and quantitatively describes the functions and duration of the product. In the present study, the functional unit of this analysis is the following: **the amount of imported face masks imported in the Interreg Central Europe area considered in the ENTeR project for the first six months of the year 2020 (Eurostat, 2020a), assumed to be used and disposed as waste.** The imported amount per Country is listed in Table 1.

Table 1 Total import of face masks (January 2020 - June 2020). Source: Eurostat, 2020a.

Country	Amount (kg)
Czechia	6,16E+06
Germany	9,07E+07
Italy	2,38E+07
Hungary	4,63E+06
Poland	1,53E+07
TOTAL	**1,41E+08**

The functional unit also provides the definition of the function, the extent of the function, the expected level of quality and the lifetime of the product. In Table 2, this further information is detailed; together with the amount of materials needed (i.e. the reference flow).

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[5] https://interreg.eu/programme/interreg-central-europe/

Table 2 Functional unit definition.

Feature	Description
What	To produce and to manage the end-of-life of the face masks used to fight COVID-19.
How much	The amount of imported masks in the Interreg area (Czechia, Germany, Italy, Hungary, Poland only).
How well	100% virgin polypropylene fabric (no metal parts are considered). Treated with a hydro-repellent finishing.
How long	Single use.
Reference flow	The total amount of imported face masks. Polypropylene fabric final amount = 1,41E+08 kg.

Additionally, to give a broader range of information, the authors decided to include also the environmental performance of the single face mask, in terms of absolute values.

For this reason, the impact assessment was carried out for a mass amount equal to the weight of a single mask. According to data from literature, it is possible to find mask weighting from 5 to 15 grams. Then, an average value could be 8-9 grams. For this study, in order to be compliant with the previous economical evaluation conducted within this project, the average value is 9 g for each mask.

4.2.2. System boundaries

The system boundaries specify the unit processes that will be considered in the studied analysis. The system boundaries are defined through the stages of the products' life cycle. It is essential to define where to stop tracking energy and material uses of upstream processes, otherwise the analysis would be endless, and the environmental impacts would be altered in the several processes studied. These boundaries shall be adapted to the potential accuracy that could be obtained from the available data.

The present LCA study is cradle-to-grave and it considers the whole life cycle of the imported masks, from their production to the end-of-life (EoL), including fabric finishing and distribution. This choice allows evaluating all the possible aspects linked to design and recycling process, to give support in the decision-making process.

4.2.3. Environmental impact indicators

The Environmental Impact Indicator (or Category) is the class of resource use or environmental impact to which the resource use and emission profile data are related. The impact category is the quantifiable representation of type of environmental impact. A so-called "life cycle impact assessment method" can gather one or more environmental indicators, thus providing a wide range of evaluated types of impacts.

In the present study, the impact indicators adopted are the ones recommended by European Commission when conducting a Product Environmental Footprint (EC, 2013). The version selected is the most updated one (Fazio et al., 2018). The indicators were used as in the version implemented into the GaBi software, where the method is named EF 3.0 (Environmental Footprint 3.0). The general description of each indicator is briefly reported in Table 3.

To complete the analysis, a set of resource use indicators is added. Namely, the consumption of energy from both renewable and non-renewable sources as well as the net water use are included in the impact assessment reported in section 6.

Table 3 Environmental Impact Categories as in the EF v.3 LCIA method.

Impact category	Indicator	Unit	Description
Climate Change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	Capacity of a greenhouse gas to influence changes in the global average surface-air temperature and subsequent change in various climate parameters and their effects, such as storm frequency and intensity, rainfall intensity and frequency of flooding, etc. The values adopted for the Global Warming Potentials with time horizon 100 years (GWP-100) includes the carbon feedbacks for different substances.
Ozone Depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	Degradation of stratospheric ozone due to emissions of ozone-depleting substances, for example long-lived chlorine and bromine containing gases (e.g. CFCs, HCFCs, Halons).
Human Toxicity, Cancer Effects*	Comparative Toxic Unit for humans (CTUh)	CTUh	Adverse health effects on human beings caused by the intake of toxic substances through inhalation of air or food/water ingestion, insofar as they are related to cancer.
Human Toxicity, Non-Cancer Effects*	Comparative Toxic Unit for humans (CTUh)	CTUh	Adverse health effects on human beings caused by the intake of toxic substances through inhalation of air or food/water ingestion, insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.
Respiratory Inorganics/ Particulate matter	Human health effects associated with exposure to particulate matter	Disease incidences	The indicator assesses damage to human health from outdoor and indoor emissions of primary and secondary PM2.5, in urban and rural areas. The impact category is characterising is the change in mortality due to PM emissions.
Ionizing Radiation	Human exposure efficiency relative to U-235	kBq ^{235}U eq	Adverse health effects on human health caused by radioactive releases.

Impact category	Indicator	Unit	Description
Photochemical Ozone Formation	Tropospheric ozone concentration increase	kg NMVOC eq	Formation of ozone at the ground level of the troposphere caused by photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts, and manmade materials through reaction with organic materials.
Acidification	Accumulated Exceedance (AE)	moli H^+ eq	The indicator addresses impact due to acidifying substances in the environment. Emissions of NOx, NH3 and SOx lead to releases of hydrogen ions (H+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.
Terrestrial Eutrophication	Accumulated Exceedance (AE)	moli N eq	Nutrients (mainly nitrogen) from sewage outfalls and fertilised farmland accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen resulting in oxygen deficiency.
Freshwater Eutrophication	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	Nutrients (mainly phosphorus) from sewage outfalls and fertilised farmland accelerate the growth of algae and other vegetation in the freshwater. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death.
Marine Eutrophication	Fraction of nutrients reaching marine end compartment (N)	kg N eq	Nutrients (mainly nitrogen) from sewage outfalls and fertilised farmland accelerate the growth of algae and other vegetation in seawater. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death.
Freshwater Ecotoxicity	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	Toxic impacts on freshwater ecosystems, which damage individual species and change the structure and function of the ecosystem.

Impact category	Indicator	Unit	Description
Land Use	Soil quality index	Dimensionless aggregated index (pt)	Use (occupation) and conversion (transformation) of land area by activities such as agriculture, roads, housing, mining, etc. The category considers different indicators for several soil properties (erosion, mechanical and physicochemical filtration, groundwater replenishment). These indicators have been pooled and re-scaled, to obtain a dimensionless soil quality index, accounting for the different properties evaluated by the original model.
Water Use	User deprivation potential	m^3 world eq. deprived	Deprivation-weighted water consumption. The indicator assesses the impact in terms of quantity of water deprived. Characterisation factors are recommended for blue water (i.e. the freshwater: surface and groundwater) consumption only, where consumption is defined as the difference between withdrawal and release of water.
Resource Use, mineral and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	Use of natural resources, either renewable or non-renewable, biotic, or abiotic.
Resource Use, energy carriers	Abiotic resource depletion, fossil fuels (ADP-fossil)	MJ	Use of fossil fuels. Uranium is included in the list of energy carriers.

4.2.4. Assumptions and limitations

In section 5.5, the overall data quality is analysed, whereas all the assumptions related to the study are indicated in the list below:

- Interreg Central Europe area: Italy and Germany are not entirely included in the Interreg Central Europe area. Indeed, only some of the regions within these countries are part of the considered area. Given that data concerning the face masks import were available for the whole country, Italy and Germany were considered as the entire country.
- Facial masks: Covid-19 facial protection measures include many types of masks and respirators. In the present study, the authors decide to take into consideration the face masks, which are now being widely worn not only by medical professionals, but by common people in their daily lives (Eurostat, 2020). These devices can be made of a variety of materials, but the most used is polypropylene (OECD, 2020), both for medical masks and N95 respirators (O’Dowd, 2020; WHO, 2020). For this reason, the authors deemed polypropylene the most representative material and assumed the whole masks amount composed by this fabric.
- Materials: due to the theoretical nature of the study, the main focus is the fabric. This means that the potential occurrence of a metal part (i.e. the nose clip) within the face masks is not considered, as its amount was deemed negligible compared to the fabric mass.

- Recycling rate: the face masks recycling rate is assumed to be 100%, as the hypothetical scenario is building on a separate collection fully dedicated to medical masks. The authors acknowledge that the actual recycling rate of the fabric material could be lower, especially if current statistics on PET recycle are investigated: for instance, PlasticsEurope reports a 42% packaging recycling rate for EU 28+2 in 2018 (PlasticsEurope, 2019), whereas around 60% of PET bottle waste was effectively recycled in Europe in 2018, when looking at the data retrieved for the economical evaluation.
- Mechanical recycling: due to lack of primary data regarding the mechanical recycling of polypropylene fabric, this step was included in the current study by means of a secondary source.
- Chemical agents: when dealing with chemicals, data gaps occurred for some of the reagents in the database used as source for secondary data. In these cases, proxy substances were retrieved from the ones available, based on an expert judgement that considered the function of the reagents and their molecular structure.
- Calorific values and efficiency rates: when dealing with the incineration process within the end-of-life scenario of the face masks, the low heating value and the efficiency rate are requested. With no primary data available and given the difficulties in finding this information, the values adopted were the ones indicated in the datasets used to model the process. For the incineration, the efficiency rate was not clearly reported but the documentation related to the dataset states that it is a country-specific parameter taken into account.

5. Life Cycle Inventory

The LCA is a compilation of the inputs and the outputs of a considered product system, and the evaluation of the potential environmental impacts throughout its life cycle, including all stages from raw material extraction through processing, production, distribution, storage, use stage and end-of-life treatment of the product (from cradle to grave).

The Life Cycle Inventory (LCI) analysis includes the collection of the data and the calculation procedures to quantify the inputs and outputs related to a product system. Generally, the inventory analysis process is iterative. As data are collected and the practitioner becomes more familiar with the system, new requirements and limitations can be identified and can involve changes of the procedures of data collection, so that the objectives of the study are still satisfied.

In this chapter, the data collection is described, together with data sources and the gap filling procedures. Data are elaborated to obtain an inventory related to the face masks life and final treatments (disposal, incineration and recycling).

The collection of data on virgin polypropylene fabric manufacturing and final treatments was conducted mainly on secondary sources (i.e. literature) and on technical outputs from previous projects (i.e. confidential data). The remaining input and output data necessary to complete the LCI were retrieved from LCA databases.

5.1. General modelling choices

The reasoning and calculations underpinning the general modelling aspects are illustrated below.

Firstly, to model the medical masks only the fabric is considered, as it is the highest fraction by mass as well as the fraction that can be recycled. For the purpose of this study, the potential occurrence of a metal part (i.e. the nose clip) is not considered, as it its amount was deemed negligible compared to the fabric mass.

For the water used in manufacturing activities, the dataset "*EU-28: Process water*" from GaBi Professional sp40 was considered. This dataset models the treatment from groundwater (ion-exchange) and was used to represent a generic treatment applied to withdrawn water before using it.

Considering grid energy consumption, when the energy input was not already included in the aggregated datasets, the one representing the European grid electricity mix was chosen. The source of this dataset is GaBi Professional sp.40.

To determine the production process of chemical products, it was decided to take the composition from the safety data sheets (SDS) and to recreate it in the model. Section 3 of the SDS generally provides information on the compound composition. The information usually reported includes the name and / or commercial name and other identifying elements (such as CAS number, registration number etc.) of substances, ingredients, or impurities which:

- contribute to the overall hazard classification; or
- are present in concentrations above certain risk levels; or
- are subject to occupational exposure limits.

In addition, for mixtures, the concentration or concentration range of the constituent is indicated. Chemical suppliers can choose whether to list the complete composition of the substance or mixture by reporting all the constituents or components, even those that are not dangerous. The choice of use of the data from the SDS constitutes a first approximation. Other criteria chosen for the modelling of chemical products are:

- Where there are concentration ranges, it was decided to take the higher value, thus placing itself in the most significant case.
- Where there was a percentage of water, it was added with the EU-28 process: Process water (GaBi Professional sp.40) to reach 100%.

For the chemical compounds for which generic data were not available, assumptions were made motivated by chemical analogy and synthesis methodologies.

To properly model the transports, the guidelines of the Product Environmental Footprint (Zampori & Pant, 2019) are taken as main reference. In the analysed system, this aspect accounts for the transportation of the manufactured fabric to the finishing plant, the distribution of the face masks sold on the market, and then the fabric waste collection and its transportation to the EoL facility.

According to the guidelines by Zampori & Rana (2019), an extra-EU scenario was built both for the transport to the finishing plant and for the distribution:

- Transport to the finishing plant:
    - 1000 km by truck (>32 t, EURO 4), for the sum of distances from harbour/ airport to factory outside and inside Europe; and
    - 18000 km by ship (transoceanic container).
- Product distribution on the market (100% international supply chain):
    - from factory to final client: 1000 km by truck (>32 t, EURO 4) and 18000 km by ship (transoceanic container).
    - from factory to retail: 1000 km truck (>32 t, EURO 4), and 18000 km by ship (transoceanic container).
    - from retail to final client:
        - 62%: 5 km, by passenger car (average).
        - 5%: 5 km round trip, by van (lorry <7.5t, EURO 3 with utilisation ratio of 20%).
        - 33%: no impact modelled.

In absence of a cargo process representing a passenger car, a light duty vehicle (<3.5 t, EURO 4) was used.

A default 5% material loss was considered during distribution, as indicated for healthcare products in Zampori and Pant (2019).

5.2. Raw materials and face masks production (upstream)

The upstream processes that were modelled are the following:

- Polypropylene fabric production (i.e. it corresponds also to the masks manufacturing)
- Reagents production (both for the finishing and the decontamination process)

To model the production of the polypropylene fabric, a dataset from GaBi Professional sp40 was selected. The production technology related to this material is well-established and no significant variation occurs from the geographical and temporal point of view. The dataset selected is defined as "*Polypropylene (PP) - fabric*" and its inventory was compiled by Thinkstep, including yarn production from PP granulate, weaving and washing. The dataset is representative for the EU-28 situation, focusing on the main technologies. The general comment describing the dataset is the following: *"The data set covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. For the modelling of PP, yarn and weaving industry data are used."*.

Concerning the chemical reagents, as already mentioned, the section 3 of the safety data sheets (SDS) was the reference for the composition. As primary data were not available, GaBi Professional sp.40 and ecoinvent 3.6 database were adopted as data sources for the production of the chemical compounds.

Specifically for the finishing process, a hydro-repellent treatment was modelled, with the following features:

- The main impregnating agent is C6 fluorocarbon-based resin.
- The concentration in the solution stands at 50-100 g/L.
- The resin applied to the final product ranges from 5% to 10%.
- Every kilogram of fabric absorbs ca. 700-900 g of impregnating solution.
- The ratio fabric/solution is 1:1.

As the study is a theoretical exercise, no primary data were available. However, the information underpinning this step in the mask manufacturing comes from a previous project where the same treatment was applied to another type of fabric to provide it with hydro/oil repellence.

5.3. Recycling process (downstream)

The recycling process is of the polypropylene fabric was modelled by means of two different activities:

1. Fabric mechanical recycling (i.e. cutting, shredding, regranulation).
2. Fabric decontamination.

The recycling scenarios built for the analysis take into account the mechanical recycle as an individual procedure or as combined with a preliminary decontamination step.

As this study has the purpose to give an overview of the potential impacts related to recycling, and to be an initial screening, the recycling rate is assumed to be 100% (see section 4.2.4 for further details).

5.3.1. Mechanical recycling

As reported in the economical evaluation, we assume that mask waste must be treated with a similar approach used with PET bottles:

- waste collection and sorting with a specific minimum geographical area;
- industrial facilities to recycle waste and produce secondary raw material;
- distribution of this secondary raw material in new industrial process for new goods.

Coming directly to the second point, plastic waste recycling is a well-known activity at least for a certain type of polymers, and it is usually composed by several steps.

As described Bora et al. (2020), the plastic is transported to the recycling plant where it is shredded, washed, and then dried to remove contamination. Then, the shredded plastic flakes are transformed into recycled granulates.

In European Bioplastics (2020) a similar process is described. The plastic waste passes extensive manual and/or automated mechanical sorting processes in specialised facilities, designed to separate the different materials. For this purpose, various technologies such as near infrared (NIR), laser, or x-ray-based techniques are available. NIR-units are widely used and form the state of the art in several European countries for sorting mixed post-consumer packaging. After cleaning and grinding processes, the materials are recovered through remelting and re-granulating. The resulting recycled material can be processed with all common technologies for plastics conversion.

The recycling process modelled in this study is based on the one described in Bora (2020). Data for this step are exclusively from secondary sources. The datasets designed to represent the PET recycling are assumed to be suitable for the polypropylene fabric coming from medical masks collection. As for the production step, in the recycling stage the presence of a metal part within the mask is disregarded.

The datasets used were retrieved in the GaBi Professional sp.40 database and are listed in Table 4. The process can be summarized as follows, based on the dataset documentation: “Grinding is done via cutting mills. They are used to shred massive as well as hollow parts, foils, compounds, carpets and even copper cable. The material particles are then stirred until the desired particle size is reached and the particles descend through a sieve. The washing takes place to remove small particles, dirt, oil and fat residues, followed by a further grinding process. The final step in the plastics recycling is pelletizing and compounding of the ground polymer by extrusion”.

Table 4 Mechanical recycling steps and corresponding datasets.

RECYCLING STEP	Dataset
SHREDDING	DE: Granulator
WASHING	DE: Washing (plastic recycling)
GRINDING	DE: Granulator
RE-POLYMERIZATION	DE: Pelletizing and compounding

5.3.2. Fabric decontamination

The decontamination is carried out by means of three decontamination solutions (A, B, C) heated up to 98°C. The fabric passes through this 3-steps process in a specific order (A, C, B).

In the following tables (Table 5, Table 6, Table 7) the chemical reagents are presented for each solution (A, B, C). To model the solution heating to 98°C (considering an initial temperature of 20°C), an energy input of 0.334 MJ for 1 L was assumed.

The underpinning calculation is based on the following figures:

- heat capacity (C) of water: 4.18 J/g °C
- mass of water (m): 1000 g (i.e. 1L)

- Temperature difference (ΔT) = 100°C – 20°C = 78°C
- Final formula: E (J) = m*C*ΔT = 1000*4.18*78 = 326352 J = 0.326 MJ

Table 5 Solution A (decontamination).

SOLUTION A	Concentration (g/L)
DETERGENT AGENT	25
WETTING AGENT	8

Table 6 Solution B (decontamination).

SOLUTION A	Concentration (g/L)
WETTING AGENT	8
Chelating agent	30
Emulsifying and dispersing agent	4

Table 7 Solution C (decontamination).

Solution A	Concentration (g/L)
Wetting agent	8
Detergent agent	30
Alkaline agent	15

5.4. End-of-Life

This step in the medical masks life is the most important from the point of view of the ENTeR project. Indeed, the analysis is going to assess different scenarios, both for the baseline and for the recycling option:

1. Baseline
    a. The medical masks are sent to both incineration and landfill. This scenario represents the situation mirroring the EoL of masks collected as Municipal solid waste (MSW), i.e. the waste type consisting of everyday items that are discarded by the public. **Situation 1-a.**
    b. The medical masks are sent to incineration only. This scenario represents the situation mirroring the EoL of masks separately collected from health, industry and public sector, as well as quarantined people. **Situation 1-b.**
2. Recycling
    a. The medical masks are sent to decontamination and mechanical recycling. **Situation 2-a.**
    b. The medical masks are sent to mechanical recycling only. **Situation 2-b.**

The innovation scenario assumes a 100% recycling rate for the face masks’ fabric. Additionally, it assumes that a 10% loss occurs during distribution and transportation.

According to Zampori and Pant (2019), two transport routes have been included in this life cycle stage:

- Consumer transport from home to sorting place: 1 km by light duty vehicle (<3.5 t, EURO 4), as proxy for passenger car.
- Transport from sorting place to incineration plant or recycle site: 100 km by truck (>32 t, EURO 4).

The end-of-life scenarios for both the polypropylene fabric was modelled according to the Circular Footprint Formula (CFF), indicated in Zampori and Pant (2019). The CFF is composed as presented in Figure 1.

Material

$$(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_p}\right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E_V^{*} \times \frac{Q_{Sout}}{Q_P}\right)$$

Energy

$$(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$$

Disposal

$$(1-R_2-R_3) \times E_D$$

Figure 1 The Circular Footprint Formula

In Table 8, the parameters are introduced and explained. In Table 9, all the parameters adopted for the innovation scenario are reported, both as values and as datasets. As regards the different scenarios, a colour code is applied:

- Black colour = baseline 1-a.
- Blue colour = baseline 1-b.
- Orange colour = recycling 2-a.
- Green colour = recycling 2-b.

Table 8 Parameters of the Circular Footprint Formula

PARAMETER	EXPLANATION
A	Allocation factor of burdens and credits between supplier and user of recycled materials.
B	Allocation factor of energy recovery processes. It applies both to burdens and to credits.
Q_{Sin}	Quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.
Q_{Sout}	Quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.
Q_P	Quality of the primary material, i.e. quality of the virgin material.
R_1	It is the proportion of material in the input to the production that has been recycled from a previous system.

R_2	It is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.
R_3	It is the proportion of the material in the product that is used for energy recovery at EoL.
$E_{recycled}$ (E_{rec})	Specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.
$E_{recyclingEoL}$ (E_{recEoL})	Specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.
E_v	Specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.
E^*_v	Specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.
E_{ER}	Specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, etc.).
$E_{SE,heat}$ $E_{SE,elec}$	Specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.
E_D	Specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analyzed product, without energy recovery.
$X_{ER,heat}$ $X_{ER,elec}$	The efficiency of the energy recovery process for both heat and electricity.
LHV	Lower heating value of the material in the product that is used for energy recovery.

Table 9 CFF parameters as used in the current study (colour code applied to identify the different scenarios).

PARAMETER	VALUE	DATASET	FURTHER DETAILS
			POLYPROPYLENE FABRIC
A	0	-	0.8 is the default value for textiles material (Annex C in Zampori and Pant). However, to consider the overall impacts related to the EoL, it was decided to allocate all the burdens and credits to the supplier. According to Zampori & Pant (2019), an A factor equal to 0 would reflect a 0:100 approach (i.e. credits are given to the recyclable materials at the end of life). **Applied to all scenarios.**
R_1	0	-	No recycled content in the product. **Applied to all scenarios.**
R_2	0 (1-a) 0 (1-b)	-	Default value for textiles material = 0.11 (Annex C in Zampori and Pant, 2019).

PARAMETER	VALUE	DATASET	FURTHER DETAILS
	1 (2-a) 1 (2-b)		In this study we assumed that the fabric is 100% sent to recycling.
$E_{recyclingEoL}$ (E_{recEoL})		Decontamination + mechanical recycling + 100 km transport by truck (EURO 4) Mechanical recycling + 100 km transport by truck (EURO 4)	Decontamination source: This project. Mechanical recycling source: GaBi Professional sp40.
Q_{Sout}/Q_P	0.9		Default value (Annex C in Zampori and Pant, 2019). **Applied to both recycling scenarios.**
E^*_v		EU28: Polypropylene granulate (PP)	Source: GaBi Professional sp40. **Applied to both recycling scenarios.**
B	0	-	Default value in PEF studies (Zampori and Pant, 2019).
R_3	0.6 (1-a) 1 (1-b) 0 (2-a) 0 (2-b)	-	Default value for EU-28 = 0.45 (Annex C in Zampori and Pant, 2019). In the 1-a scenario we assumed that the fabric is 60% sent to incineration. The value is calculated as fraction of waste sent to incineration and energy recovery within the Interreg Central Europe countries, based on the most recent year in the source, i.e. 2018 (Eurostat, 2020b; 2020c). In the 1-b baseline scenario the waste is 100% sent to incineration.
E_{ER}		EU-28: Textiles in municipal waste incineration plant	Source: GaBi Professional sp40. **Applied to both baseline scenarios.**
LHV	21 MJ/kg		Source: GaBi Professional sp40. **Applied to both baseline scenarios.**
$X_{ER,heat}$ $X_{ER,elec}$	44%		Source: GaBi Professional sp40. **Applied to both baseline scenarios.**
$E_{SE,heat}$		EU-28: Process steam from natural gas 95%	Source: GaBi Professional sp40. **Applied to both baseline scenarios.**

PARAMETER	VALUE	DATASET	FURTHER DETAILS
$E_{SE,elec}$		EU-28: Electricity grid mix	Source: GaBi Professional sp40. **Applied to both baseline scenarios.**
E_D	0.4 (1-a) 0 (1-b) 0 (2-a) 0 (2-b)	-	Default value for EU-28 = 0.55 (Annex C in Zampori and Pant, 2019). In the 1-a baseline scenario we assumed that the fabric is 40% sent to incineration. The value is calculated as fraction of waste sent to landfill within the Interreg Central Europe countries, based on the most recent year in the source, i.e. 2018 (Eurostat, 2020b; 2020c). In the 1-b baseline scenario no waste is sent to landfill.

5.5. Data quality

Within the current study, the data used were from secondary sources, primarily from literature and previous projects (lab-scale outputs).

Concerning the secondary data, apart from literature, they were taken from:

- the GaBi database (GaBi Professional, service pack 40; Sphera, 2020) and its Extension databases:
    - Ia: Intermediates organic.
    - Ib: Intermediates inorganic.
    - IXa: End of life.
    - XV: Textile finishing.
- the Ecoinvent v3.6 database (Ecoinvent, 2019).

With reference to these data from secondary sources:

1. **Geographical representativeness (GeR)**: where possible, data representative of the geographical area of reference (Europe) has been privileged, both from the technological point of view and from the energy mix.
    a. In case of specific European data failure, Country-specific data (i.e. Italy, given the two Italian partners) have been privileged and lastly those, which represent a global average.
2. **Technological representativeness (TeR)**: the technologies used in the datasets are equivalent to those used in the processes where the activity takes place; in particular, data sets with the following wording were privileged: *"The dataset covers all relevant process steps / technologies over the supply chain of the represented cradle-to-gate-inventory with good overall quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data. The dataset is based on primary data*

from internationally prevalent production process, connected with regional precursor chains ".

3. **Time-related representativeness (TiR)**: the datasets used have a temporal validity as recent as possible so that they can represent the situation of the reference year (2019).
4. **Data quality**: all the datasets chosen within the model have a “good” overall quality as stated from the data providers. For specific datasets, scores are reported:
   a. Polypropylene production:
      i. GaBi = 2,0 interpreted into "good overall quality" in the GaBi quality validation scheme.
      ii. ILCD = 2,4 interpreted into "basic overall quality" in the ILCD quality validation scheme.
      iii. PEF = 2,0 interpreted into "very good overall quality" in the PEF quality validation scheme.
   b. Process water:
      i. GaBi = 1.7 interpreted into “good overall quality” in the GaBi quality validation scheme.
      ii. ILCD = 1.8 interpreted into “basic overall quality in the ILCD quality validation scheme.
      iii. PEF = 1.7 interpreted into “very good overall quality” in the PEF quality validation scheme.
   c. Transports means (trucks and light duty vehicle):
      i. GaBi = 1.5 interpreted into “good overall quality” in the GaBi quality validation scheme.
      ii. ILCD = 1.7 interpreted into “basic overall quality in the ILCD quality validation scheme.
      iii. PEF = 1.5 interpreted into “excellent overall quality” in the PEF quality validation scheme.
   d. Mechanical recycling process (granulator, washing, pelletizing):
      i. GaBi = 1,7 interpreted into "good overall quality" in the GaBi quality validation scheme.
      ii. ILCD = 1,8 interpreted into "basic overall quality" in the ILCD quality validation scheme.
      iii. PEF = 1,7 interpreted into "very good overall quality" in the PEF quality validation scheme.

5.5.1. Data completeness

Concerning the polypropylene fabric production and the process water, the overall completeness of the dataset used is stated as follows: *“Coverage of at least 95% of mass and energy of the input and output flows, and 98% of their environmental relevance (according to expert judgement)”*.

Face masks distribution is based on established indications (i.e. Zampori and Pant, 2019), by means of default scenarios. Datasets used to model this phase are the ones indicated by the guidelines with the following coverage reported: *“Coverage of at least 95% of mass and energy of the input and output flows, and 98% of their environmental relevance (according to expert judgement)”*.

Data coverage for the EoL is based on established indications (i.e. Zampori and Pant, 2019), by means of default scenarios in order to cover most of possible aspects.

5.6. System model

To build a model in GaBi v.9 representing the whole system (background + foreground) within the system boundaries, a few sub-models were created and then linked in a general scheme. The diagram illustrating the whole model is shown in Figure 2.

Within each step in the scheme, all the inputs and outputs are considered and modelled as explained in the previous sections. The only differences in the system between the baseline and the innovation scenarios could be found in the EoL step.

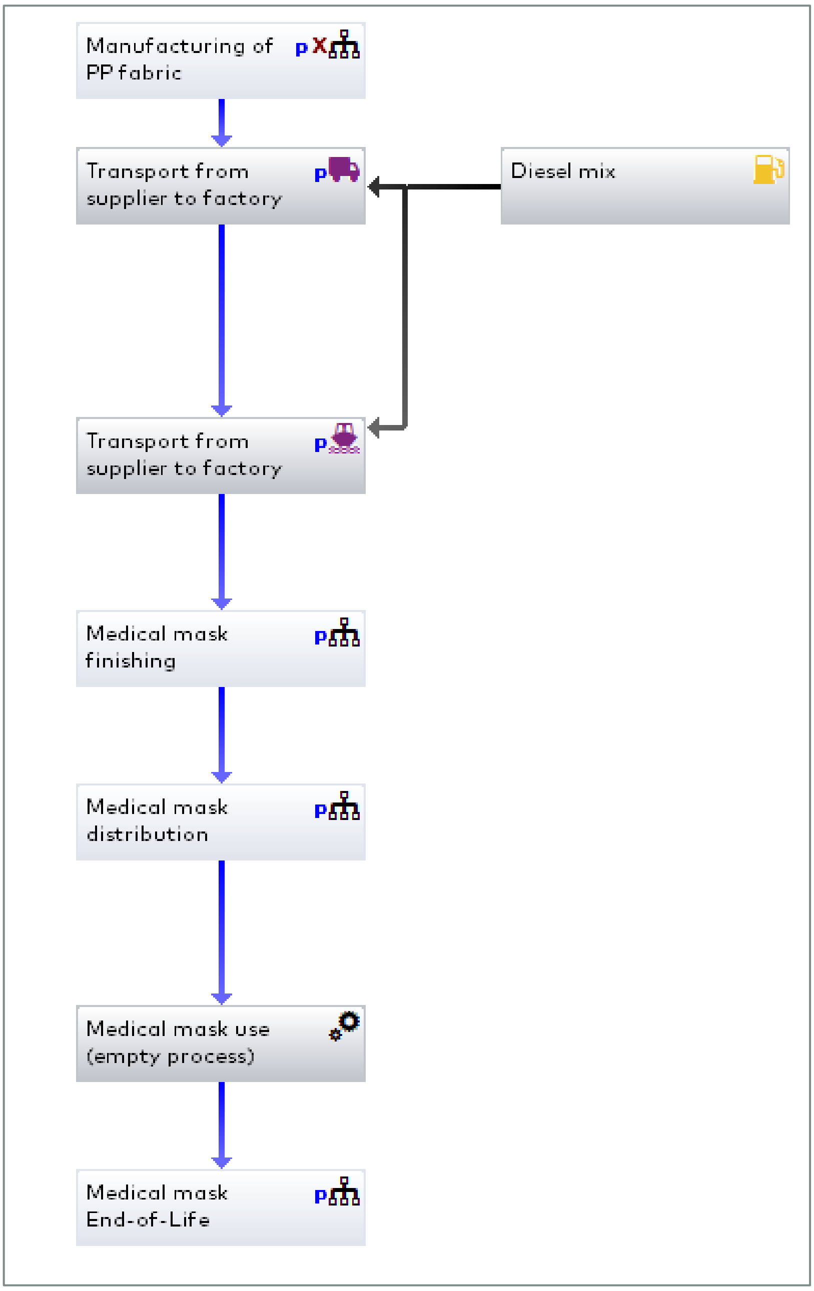

Figure 2 System model (upper level).

5.7. Allocation rules

The following allocation rules as reported in Table 10 were used.

Table 10 Allocation rules.

PROCESS	ALLOCATION RULE	DETAILS
Transport	Mass	The allocation of impacts is based on the distance and the mass of the good being transported.

PROCESS	ALLOCATION RULE	DETAILS
Manufacturing of chemical agents	Mass	An allocation based on physical relationship (mass) was done to obtain the actual amount of inputs and outputs.
Fabric manufacturing	Mass	

6. Life Cycle Impact Assessment

The goal of the Life Cycle Impact Assessment (LCIA) is to quantify the environmental impacts resulting from the environmental pressures arising from the system analysed, i.e. resulting from the emissions in water and air and the resources consumptions related to a specific productive activity.

In this step of the study, the data calculated in the inventory, are converted to “impact scores” according to different indicators. Each indicator has its own model underpinning the scoring, based on the environmental pressure that considers. The output of this calculation allows for an in-depth evaluation about the hotspot in the system, i.e. the main contributors to the impact, and it better shows where to intervene to enhance the environmental performance.

The objective therefore consists in attributing the energy/material consumption and emissions obtained in the inventory phase to specific impact categories through a classification process and then in characterizing their environmental impacts (see section 4.2.3). This step of the study may include an iterative process of reviewing the scope of the analysis initially defined, to determine when and how much the objectives of the study have been achieved, or to modify them, if the evaluation indicates that they cannot be achieved.

6.1. Results overview

In this section the general results are presented, by considering the whole system quantified environmental performance.

This is done by reporting two different type of results:

- Quantified impact (Table 11, Table 12)**Errore. L'origine riferimento non è stata trovata.**: the set of indicators recommended by European Commission when conducting the Product Environmental Footprint studies in the most recent version (v.3).
- Resource consumption (Table 13,

> RESOURCE TYPE	UNIT	BASELINE 1-A	BASELINE 1-B	RECYCLING 2-A	RECYCLING 2-B
Non-renewable energy	MJ	1,98E+10	1,90E+10	2,43E+10	1,20E+10
Renewable energy	MJ	1,31E+09	1,16E+09	2,71E+09	1,60E+09
Use of net freshwater	m^3	7,45E+06	7,53E+06	1,84E+07	7,03E+06

- Table 14)**Errore. L'origine riferimento non è stata trovata.**: resources accounting in terms of water and energy inputs (both as renewables and non-renewables).

- Percentage variation of the impact for each scenario and each impact category.

The values shown in the following tables are reported as the sum of the impact derived from the upstream and downstream.

Table 11 LCIA results for EF v.3, total amount of imported face masks (baseline vs recycling scenarios).

IMPACT CATEGORY	UNIT	BASELINE 1-A	BASELINE 1-B	RECYCLING 2-A	RECYCLING 2-B
Acidification	mol H+ eq.	3,91E+06	3,91E+06	5,33E+06	3,53E+06
Human Tox cancer	CTUh	7,87E-01	7,80E-01	9,25E-01	6,83E-01
Climate change	kg CO_2 eq.	1,29E+09	1,20E+09	1,57E+09	1,04E+09
Ecotoxicity freshwater	CTUe	1,83E+10	1,80E+10	5,43E+10	1,37E+10
Eutrophication, freshwater	kg P eq.	7,93E+04	7,84E+04	8,76E+04	7,84E+04
Eutrophication, marine	kg N eq.	1,16E+06	1,14E+06	1,49E+06	1,01E+06
Eutrophication, terrestrial	mol N eq.	1,19E+07	1,20E+07	1,38E+07	1,06E+07
Ionising radiation	kBq U^{235} eq.	7,58E+07	6,73E+07	1,30E+08	8,52E+07
Land use	Pt	1,83E+09	1,71E+09	4,61E+09	1,97E+09
Human Tox, non-cancer	CTUh	1,83E+01	1,80E+01	2,74E+01	1,30E+01
Ozone depletion	kg CFC-11 eq.	2,47E+04	2,47E+04	2,47E+04	2,47E+04
Photochem. ozone formation	kg NMVOC eq.	3,85E+06	3,85E+06	4,84E+06	3,37E+06
Resource use, energy carriers	MJ	1,97E+10	1,90E+10	2,43E+10	1,20E+10
Resource use, mineral and metals	kg Sb eq.	2,08E+04	2,08E+04	2,47E+04	2,08E+04
Particular matter	Disease incidences	5,90E+01	5,86E+01	8,84E+01	5,69E+01
Water scarcity	m^3 world equiv.	1,69E+08	1,76E+08	6,42E+08	1,77E+08

Table 12 LCIA results for EF v.3, 1 face mask (baseline vs recycling scenario).

IMPACT CATEGORY	UNIT	BASELINE 1-A	BASELINE 1-B	RECYCLING 2-A	RECYCLING 2-B
Acidification	mol H+ eq.	2,50E-04	2,50E-04	3,41E-04	2,26E-04
Human Tox cancer	CTUh	5,04E-11	5,00E-11	5,92E-11	4,37E-11
Climate change	kg CO_2 eq.	8,24E-02	7,69E-02	1,01E-01	6,68E-02
Ecotoxicity freshwater	CTUe	1,17E+00	1,15E+00	3,47E+00	8,78E-01
Eutrophication, freshwater	kg P eq.	5,08E-06	5,02E-06	5,61E-06	5,02E-06
Eutrophication, marine	kg N eq.	7,40E-05	7,28E-05	9,54E-05	6,48E-05
Eutrophication, terrestrial	mol N eq.	7,60E-04	7,71E-04	8,86E-04	6,77E-04
Ionising radiation	kBq U^{235} eq.	4,85E-03	4,31E-03	8,30E-03	5,45E-03
Land use	Pt	1,17E-01	1,10E-01	2,95E-01	1,26E-01
Human Tox, non-cancer	CTUh	1,17E-09	1,15E-09	1,76E-09	8,33E-10
Ozone depletion	kg CFC-11 eq.	1,58E-06	1,58E-06	1,58E-06	1,58E-06
Photochem. ozone formation	kg NMVOC eq.	2,47E-04	2,47E-04	3,10E-04	2,16E-04

Resource use, energy carriers	MJ	1,26E+00	1,22E+00	1,56E+00	7,67E-01
Resource use, mineral and metals	kg Sb eq.	1,33E-06	1,33E-06	1,58E-06	1,33E-06
Particular matter	Disease incidences	3,78E-09	3,75E-09	5,66E-09	3,65E-09
Water scarcity	m^3 world equiv.	1,08E-02	1,13E-02	4,11E-02	1,13E-02

Table 13 Results for resource indicators, total amount of imported masks (baseline vs recycling scenario).

Resource type	Unit	Baseline 1-A	Baseline 1-B	Recycling 2-A	Recycling 2-B
Non-renewable energy	MJ	1,98E+10	1,90E+10	2,43E+10	1,20E+10
Renewable energy	MJ	1,31E+09	1,16E+09	2,71E+09	1,60E+09
Use of net freshwater	m^3	7,45E+06	7,53E+06	1,84E+07	7,03E+06

Table 14 Results for resource indicators, 1 face mask (baseline vs recycling scenario).

Resource type	Unit	Baseline 1-A	Baseline 1-B	Recycling 2-A	Recycling 2-B
Non-renewable energy	MJ	1,27E+00	1,22E+00	1,56E+00	7,68E-01
Renewable energy	MJ	8,40E-02	7,43E-02	1,74E-01	1,03E-01
Use of net freshwater	m^3	4,77E-04	4,82E-04	1,18E-03	4,50E-04

In the next tables (Table 15 for the impact indicators, Table 16for the resource indicator) the percentage variation of results is presented. The variation is calculated by taking the Baseline 1-A as the 100% reference, and consequently scaling up the other scenarios' results.

Table 15 Percentage variation of the results (impact indicators).

Impact category	Baseline 1-A	Baseline 1-B	Recycling 2-A	Recycling 2-B
Acidification	100%	0%	36%	-10%
Human Tox cancer	100%	-1%	18%	-13%
Climate change	100%	-7%	22%	-19%
Ecotoxicity freshwater	100%	-2%	197%	-25%
Eutrophication, freshwater	100%	-1%	8%	-33%
Eutrophication, marine	100%	-2%	842%	-1%
Eutrophication, terrestrial	100%	-1%	3%	-7%
Ionising radiation	100%	-1%	10%	-1%
Land use	100%	-2%	29%	-12%
Human Tox, non-cancer	100%	2%	17%	-11%
Ozone depletion	100%	-11%	71%	12%
Photochem. ozone formation	100%	-6%	152%	8%
Resource use, energy carriers	100%	-2%	50%	-29%
Resource use, mineral and metals	100%	0%	0%	0%
Particular matter	100%	0%	26%	-12%
Water scarcity	100%	-4%	24%	-39%
Acidification	100%	0%	19%	0%
Human Tox cancer	100%	-1%	50%	-4%
Climate change	100%	4%	281%	5%

Table 16 Percentage variation of the results (resource indicators).

IMPACT CATEGORY	BASELINE 1-A	BASELINE 1-B	RECYCLING 2-A	RECYCLING 2-B
Non-renewable energy	100%	-4%	23%	-40%
Renewable energy	100%	-12%	107%	22%
Use of net freshwater	100%	1%	147%	-6%

6.2. Contribution analysis

Starting from the results presented in section 6.1, a further analyses was conducted to highlight the contribution of each step in the face mask life cycle to the total impact of the system considered in the study. Results for this analysis are presented in Table 18 (impact indicators) and Table 18 (resource indicators).

Table 17 Contribution analysis: impact indicators.

IMPACT INDICATOR	SCENARIO	TOTAL	MASK PRODUCTION	MASK FINISHING	MASK-DISTRIBUTION	MASK END-OF-LIFE
Acidification	1-a	100%	25%	59%	14%	2%
	1-b	100%	25%	59%	14%	2%
	2-a	100%	19%	43%	10%	28%
	2-b	100%	28%	66%	15%	-9%
Human Tox cancer	1-a	100%	23%	76%	1%	0%
	1-b	100%	23%	77%	1%	-1%
	2-a	100%	19%	65%	1%	15%
	2-b	100%	28%	66%	15%	-9%
Climate change	1-a	100%	45%	47%	5%	4%
	1-b	100%	48%	50%	5%	-3%
	2-a	100%	37%	38%	4%	22%
	2-b	100%	56%	57%	6%	-19%
Ecotoxicity freshwater	1-a	100%	38%	60%	3%	0%
	1-b	100%	38%	61%	3%	-2%
	2-a	100%	13%	20%	1%	66%
	2-b	100%	50%	79%	4%	-33%
Eutrophication, freshwater	1-a	100%	3%	96%	0%	1%
	1-b	100%	3%	97%	0%	0%
	2-a	100%	3%	87%	0%	10%
	2-b	100%	3%	97%	0%	0%
Eutrophication, marine	1-a	100%	23%	48%	23%	6%
	1-b	100%	23%	48%	24%	5%
	2-a	100%	17%	37%	18%	28%
	2-b	100%	26%	54%	27%	-6%
Eutrophication, terrestrial	1-a	100%	23%	48%	25%	4%
	1-b	100%	23%	47%	25%	5%
	2-a	100%	20%	41%	22%	18%

	2-b	100%	26%	53%	28%	-7%
Ionising radiation	1-a	100%	50%	44%	13%	-8%
	1-b	100%	102%	29%	0%	-31%
	2-a	100%	53%	15%	0%	32%
	2-b	100%	81%	23%	0%	-3%
Land use	1-a	100%	50%	44%	13%	-8%
	1-b	100%	54%	47%	14%	-15%
	2-a	100%	20%	18%	5%	57%
	2-b	100%	47%	41%	12%	0%
Human Tox, non-cancer	1-a	100%	44%	50%	4%	2%
	1-b	100%	44%	51%	4%	0%
	2-a	100%	29%	33%	3%	35%
	2-b	100%	61%	70%	5%	-37%
Ozone depletion	1-a	100%	0%	100%	0%	0%
	1-b	100%	0%	100%	0%	0%
	2-a	100%	0%	100%	0%	0%
	2-b	100%	0%	100%	0%	0%
Photochem. ozone formation	1-a	100%	25%	52%	20%	3%
	1-b	100%	25%	52%	20%	3%
	2-a	100%	20%	41%	16%	23%
	2-b	100%	29%	59%	22%	-10%
Resource use, energy carriers	1-a	100%	77%	24%	3%	-5%
	1-b	100%	81%	25%	4%	-9%
	2-a	100%	63%	19%	3%	15%
	2-b	100%	128%	39%	6%	-73%
Resource use, mineral & metals	1-a	100%	0%	100%	0%	0%
	1-b	100%	0%	100%	0%	0%
	2-a	100%	0%	84%	0%	16%
	2-b	100%	0%	100%	0%	0%
Particulate matter	1-a	100%	18%	56%	26%	0%
	1-b	100%	18%	56%	26%	-1%
	2-a	100%	12%	37%	17%	33%
	2-b	100%	19%	58%	27%	-4%
Water scarcity	1-a	100%	-20%	113%	0%	6%
	1-b	100%	-19%	109%	0%	10%
	2-a	100%	-5%	30%	0%	75%
	2-b	100%	-19%	108%	0%	10%

Table 18 Contribution analysis: resource indicators.

RESOURCE INDICATOR	SCENARIO	TOTAL	MASK PRODUCTION	MASK FINISHING	MASK-DISTRIBUTION	MASK END-OF-LIFE
	1-a	100%	77%	24%	3%	-5%
	1-b	100%	81%	25%	4%	-9%

Non-renewable energy	2-a	100%	63%	19%	3%	15%
	2-b	100%	128%	39%	6%	-73%
Renewable energy	1-a	100%	95%	18%	3%	-17%
	1-b	100%	108%	21%	3%	-32%
	2-a	100%	46%	9%	1%	44%
	2-b	100%	78%	15%	2%	4%
Use of net freshwater	1-a	100%	37%	61%	1%	2%
	1-b	100%	37%	60%	1%	3%
	2-a	100%	15%	24%	0%	61%
	2-b	100%	39%	64%	1%	-4%

7. Conclusions and discussion

The present study is theoretical evaluation based on testing different scenarios for medical textile waste management. Its purpose is to provide valuable information to be used in a wider decision-making process.

The LCA study focused on the comparison between the state-of-art (i.e. incineration/landfill) and a recycling action specific for the fabric, and different options were taken into account with the goal of initially screening them and spotting possible issues or criticalities.

When considering the overall outcome, results are quite variable.

As a general consideration, it is worthy to highlight that the greatest contribution to the overall impact of the masks come from the production and the finishing process (i.e. about 80% in the baseline 1-a). The second in particular covers a significant fraction of the impact (about 50% in the baseline 1-a) due to the chemicals used in the process. This could be read as a reason to boost the recycling of the material, in order to avoid at least the production of new virgin polypropylene.

Looking at the EoL scenario, the possible considerations are the following,

Starting from the baseline, the incineration scenario shows potential improvement in waste management environmental impact: by incinerating the whole amount of medical masks, the energy recovery (and the avoided generation of electricity) decrease the impact scores of about 5%. This results is not very significant because the baseline representing the current MSW treatment already takes into account an high fraction of incineration (i.e. 60%).

Coming to the recycling options, the mechanical recycling is potentially the best scenario from the environmental performance point of view. When compared to the other recycling scenario is it clear that the amount and the type of chemicals hypothetically used to treat the fabric before the mechanical step have an additional impact. This significantly affects the overall performance of the recycling and increases the score for several indicators by an average 15% compared to the only mechanical treatment.

The authors would like to stress that the chemicals considered in this study for the decontamination treatment did not come from real testing. However, the underpinning reasoning takes advantage from another project in which the same chemicals are successfully used to remove finishing and contamination agents from another type of fabric.

On the hand, the authors deem the decontamination step as optional when the plastic waste is washed at a high temperature (i.e. >90°C) before entering the mechanical treatment for recycling. As in the following the re-polymerization step, the plastic material is subjected to high temperatures (90°C for the washing, 200-300°C for the melting/extrusion), then most of contaminants should be removed.

As a conclusion, it is possible to say that on a theoretical basis, the mechanical recycling could be a feasible option, both from the practical and the environmental point of view. Nevertheless, some further aspects should be considered:

- The recycling rate assumed in the study (i.e. 100%) could be not realistic. A lower rate sounds more reasonable, ideally 40-60%.

- The mechanical recycling process assumed in the study (i.e. the PET process) could be not fully representative for the polypropylene material used for the medical masks. Primary data should be collected to increase the overall robustness.
- No destination is considered in the present study for the recycled polypropylene. One or more options related to the possible use of the recycled material should be accounted, especially because recycled PP is usually mixed with virgin PP at up to substantial fractions to produce new products. However, given its inherent flexibility, PP can be recycled back into many different products, including:
  - Clothing fibres.
  - Industrial fibres.
  - Food containers/bins/gardening items.
  - Dishware.
  - Speed humps.

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