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Microplastic emissions from disposable type I and FFP2 face masks used in the Netherlands

An exploration for further research and emission mitigation measures

Ham, S; Landman, H; Lieben, M; Veen, I

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Microplastic emissions from disposable type I and FFP2 face masks used in the Netherlands

AN EXPLORATION FOR FURTHER RESEARCH AND EMISSION MITIGATION MEASURES

ADVIESRAPPORT

InCompany Milieuadvies

Maarten Lieben, Ingrid Veen, Harm Landman & Sonja Ham
RESEARCH COMMISSIONED BY OPEN UNIVERSITEIT, FACULTY OF MANAGEMENT SCIENCES, CHAIR 'CLOSED LOOP SUPPLY CHAINS'
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Projectteam (auteurs)	Sonja Ham, ing. Harm Landman, Maarten Lieben, Ingrid Veen
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Projectgegevens

Titel (nl)	**Microplastic emissies van type I en FFP2 wegwerpmondmaskers die gebruikt worden in Nederland Een verkenning voor verder onderzoek en mitigerende maatregelen**
Title (in English)	**Microplastic emissions from disposable type I and FFP2 face masks used in the Netherlands An exploration for further research and emission mitigation measures**
Opdrachtgevende instantie	Open Universiteit, faculteit managementwetenschappen, leerstoel Closed Loop Supply Chains
Opdrachtgever	prof. dr. Harold Krikke, faculteit Managementwetenschappen (vakgroep Marketing en supply chain management)
Omschrijving opdracht (nl)	In kaart brengen waar in de productketen van een bepaald product emissies van microplastics plaatsvinden. Dit wordt gerealiseerd aan de hand van de integratie van de productketenbeschrijving en een MSA van Type I en FFP2 wegwerp mondmaskers. Verder zoeken we naar mogelijke proxies waar eventueel verder onderzoek naar verricht kan worden en naar eventuele emissie mitigerende maatregelen.
Description of the order (in English)	Mapping of the product chain of a certain product to reveal potential locations where microplastics enter the environment. Through the use of a product chain description and an MSA, microplastic emission locations of disposable Type I and FFP2 face masks will be uncovered. Provided this knowledge, the team will look for possible proxies that can be the topic of further research in the field of microplastics and possible emission mitigation measures.
Trefwoorden	Microplastics, micro deeltjes, microplastic emissie, Type I, FFP2, SCOR model, Material Flow Analysis (MFA), Material System Analysis (MSA), proxies
Key words	Microplastics, microparticles, microplastic emission, Type I, FFP2, SCOR model, Material Flow Analysis (MFA), Material System Analysis (MSA), proxies
Betrokkene(n) bij opdrachtgevers-organisatie	Prof. dr. Harold Krikke Sija Hoeke, MSc
Projectleider team IM	Maarten Lieben, cursus Virtueel milieuadviesbureau, NB9906, wo-bachelor Milieu-natuurwetenschappen (BSc) Maarten Lieben
Projectmedewerker team IM	ing. Harm Landman, cursus Virtueel milieuadviesbureau, NB9906, wo-bachelor Milieu-natuurwetenschappen (BSc) Harm Landman
Projectmedewerker team IM	Sonja Ham, cursus Virtueel milieuadviesbureau, NB9906, wo-bachelor Milieu-natuurwetenschappen (BSc) Sonja Ham
Projectmedewerker team IM	Ingrid Veen, cursus Virtueel milieuadviesbureau, NB9906, wo-bachelor Milieu-natuurwetenschappen (BSc) Ingrid Veen
Projectcoach	dr. Jikke van Wijnen, faculteit Bètawetenschappen, vakgroep Environmental Science, Open Universiteit Nederland, Heerlen
Examinator	dr. ir. Angelique Lansu, Open Universiteit Nederland – InCompany Milieuadvies
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	FFP2 face masks used in the Netherlands: an exploration for further research and the use of proxies. Research commissioned by Open Universiteit, faculty of Management Sciences, chair 'Closed Loop Supply Chains' [Unpublished Bachelor's thesis, Environmental Sciences, Open Universiteit, Heerlen, NL], Open Universiteit research portal https://research.ou.nl/

Preface

This report includes the study done by InCompany Milieuadvies (team Microplastics) commissioned by the Open Universiteit, research project MinPlas (Minimising the environmental impact of (micro) plastics through integrated modelling of supply and source-to-impact chains). For this project both collaborative and individual research was done. Four individual reports were written and the results of these reports are combined into this report.

Microplastic pollution has gained more importance as the effects of these small particles on human health and the environment are becoming apparent. A global surge in the use of disposable face masks due to the COVID-19 pandemic rapidly introduces a new source of pollution affecting the ecosystems of our planet.
This study aims to contribute to the understanding of microplastic pollution pathways by studying the product chain and material flow of Type I & FFP2 face masks. We do this by mapping the product chain using the SCOR model and making a system flow analysis of the different types of plastic involved throughout the lifecycle of the two types of face masks.

The product chain of both types of face masks will be mapped in a level 2 detail of the SCOR model. The flows of the plastics present in the face masks will be revealed through two Material System Analyses. Differences might be found in the product chain of both types of masks. Highlighting these differences potentially offers better solutions to mitigate microplastic pollution.

Furthermore, the similarities and differences of the emission pathways of both face masks will be used to find potential proxies to reduce the timeframe in which a potential source of MPs emissions can be discovered. In the field of microplastic research, technological advances are still in their infancy. Pollution is often not visible to the naked eye and effects are not immediate. Therefore, the use of proxies is of utmost importance to assess the potential dangers of the dormant risks that might occur when plastic products such as face masks are suddenly used globally in massive numbers.

Abstract

Plastic pollution of microplastics has become a major issue in recent years in the aquatic and terrestrial environment. During the COVID-19 pandemic, a new plastic item emerged in the environment: disposable face masks. In this study, we research Type I surgical face masks, the masks used in public spaces and public transport in the Netherlands, and FFP2 face masks, in the Netherlands mainly used in hospitals. The masks contain plastic and their production, use and disposal can cause microplastic emissions. To get more insight into the product and possible plastic emissions we investigated how the production of both types of face masks works and where emissions of plastic can take place among the whole product- and supply chain from suppliers to end-users. To describe the product chain we used the SCOR model. With two Material System Analyses, we calculated the annual total microplastic emissions to the environment in the Netherlands. Most microplastic emissions from type I masks are caused by the mismanagement of waste. Microplastic emissions from FFP2 masks used in Dutch hospitals only occur due to pellet loss. Proxies to estimate microplastics entering the environment should consist of a combination of the following variables: location (hot spots and polluted areas), population density, waste management, policies, culture, institutions and the presence of friction.

Definitions

Microplastics: particles of synthetic plastic polymers that are smaller than 5 mm (Anik et al., 2021).

Primary microplastics: microplastics that are intentionally added to products, such as pre-production pellets.

Secondary microplastics: fragments of larger plastic products that have become separate particles through degradation processes.

Medical face mask: medical device covering the mouth and nose providing a barrier to minimise the direct transmission of infective agents between people (source: EN 14683:2019+AC).

Personal Protective Equipment: products that are designed to protect the user from health and safety risks (Health and Safety Executive, n.d.).

Plastic Pellets: small plastic particles that are used as the raw materials for plastic products (OSPAR commission, 2018).

SCOR model: Supply Chain Operations Reference-model. a management tool used to address, improve, and communicate supply chain management decisions within a company and with suppliers and customers of a company (Supply Chain Council, 2004)

Material System Analysis: a research method to study the physical flows of a specific material into, out of and through a system (OECD, 2008).

Unused flows: flows of materials in a Material Flow Analysis that are not priced goods in the economy (OECD, 2008). This includes pollutants and waste that is generated outside of the system (OECD, 2008)

Abbreviations

MPs: Microplastics

SCOR: Supply Chain Operations Reference

MFA: Material Flow Analysis

MSA: Material System Analysis

PPE: Personal Protective Equipment

LCH: Landelijk Consortium Hulpmiddelen

PET: Polyethylene Terephthalate

PP: Polypropylene

PES: Polyester

1. Introduction: The problem

Plastic materials are omnipresent in modern-day life. Plastic is light, durable and impenetrable. From an economic perspective, these characteristics form the base of their popularity in a globalised world where transportation and storage of goods became vitally important. From an ecological perspective, these characteristics form a base of concern as it means the substance can remain in the environment for centuries (Ryberg et al., 2019). In recent times, specific attention has been paid to microplastics (MPs).

MPs can be deliberately made or originate from weathered plastic products, respectively called primary and secondary MPs. It involves all sorts of synthetic plastic materials smaller than 5mm. Due to their small size, they are often not visible and can be inhaled or ingested. The consequences for human life are still being studied. Some studies suggest that they cause inflammation, oxidative stress and lipid metabolism disorders in the liver (Murashov et al., 2021). MPs have also been found in other biota, sediments, air and water (Geyer, Jambeck & Law, 2017). Due to their persistent nature, bioaccumulation in animals has been suggested to occur. However, because of their small size, little is known about this so far (Kawecki & Nowack, 2019). An important knowledge gap in MPs pollution is the measurements of their presence. So far, there are no validated analytical methods that can properly identify and quantify MPs (Murashov et. al., 2021). The lack of these methods creates difficulties in regulating MPs emissions and conducting risk assessments. This suggests further research is inevitable to assure that human and ecosystem health does not suffer from consequences attributed to the use of plastic materials.

Due to the COVID-19 pandemic, an increase in disposable face mask production has emerged. Wang et al. (2021) estimate that a staggering 129 billion face masks are consumed globally every month. Face masks are made of polypropylene (PP) and Polyethylene terephthalate (PET) & polyester and can degrade to MPs (Prata, Duarte & Rocha-Santos, 2021). In this report, the focus will be on Type I & FFP2 masks. Type I masks are often worn by the general public and protect the environment from themselves. FFP2 masks are used by health professionals and are primarily used to protect themselves from the environment. Inhalation is the critical point in FFP2 masks, in contrast to the Type I masks, where exhalation is key (Militky, 2021). While used in fighting a pandemic that caused millions of deaths and set back entire economies, little attention has been paid to the direct and indirect effects of the use of disposable face masks on the environment and human health regarding their MPs' pollution. Therefore, the focus of this study will be to uncover the microplastic emissions that the mass production and use of type I and FFP2 face masks release into the environment.

1.1 Plastics in the environment

After the 2nd world-war, global plastic production increased rapidly from 1.5 million tons in 1950 to 367 million tonnes in 2020 (Tiseo, 2021). Annual production volumes are expected to continue rising in the following decades, up to approximately 590 million tons by 2050 (Tiseo, Statista, 2021). According to CE Delft, 1.9 million tons of plastic were used in the Netherlands in 2017. Thereof, 1.65 million tons ended up as waste which was partly recycled (CE Delft, 2021). Law et al (2020) calculated a yearly plastic litter amount of 25,000 tons. Other estimates of yearly litter in the environment in the Netherlands are of the same order of magnitude, although slightly higher. Staatsbosbeheer estimates the yearly total plastic litter in the environment in the range of 50,000 to 300,000 tons (Staatsbosbeheer, 2021). Milieucentraal estimates the number at 35,000 to 140,000 tons of litter (Milieucentraal, 2021). Based on the world cleanup day 2021 about 70 % of the litter consists of plastic (Plastic Soup Foundation, 2021). Combining these three data sources, we can estimate that around 70,000 tons of plastic litter enter the environment every year. See table 1.1.

Table 1.1: Estimation of plastic litter entering the environment

Source	Total litter (tons/year)	Conversion factor litter to plastic litter (plastic soup foundation, 2021)	Plastic litter (tons/year)
Law et al (2020)	35,700	0.7	25,000
Milieucentraal (2021)	87,500	0.7	61,300
Staatsbosbeheer (2020)	175,000	0.7	122,500
Average	**99,400**	0.7	**69,600**

So far, it is still not clear where all this plastic ends up eventually. This was first clearly brought to the attention by researcher Richard Thompson(Thompson, et al., 2004) in his article" lost at sea: Where is all the plastic?'' in which the problem with plastic objects degrading into MPs is also mentioned . MPs are particles of synthetic plastic polymers that are smaller than 5 mm (Anik, et al., 2021). What we slowly start to understand is that MPs may have a severe ecological impact in both marine (Khalid, et al., 2021) and terrestrial environments (Lahive, et al., 2019). They have been found in all the environmental compartments, this includes soil, arctic ice, deep oceans and remote terrestrial locations (Anik, et al., 2021). This means there are plenty of reasons to prevent the emission of MPs to the environment including those that are caused by the degradation of plastic objects. Figure 1.1 shows an overview of microplastic problems in the marine environment.(Khalid, et al., 2021).

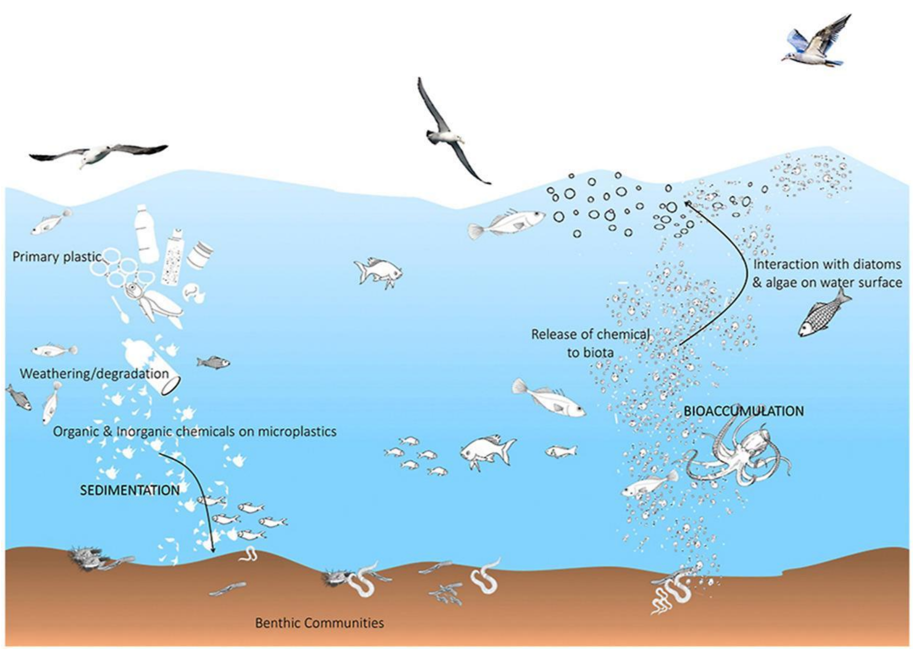

Figure 1.1 Overview of microplastic problems in the marine environment (Khalid, et al, 2021).

1.2 Face masks in the environment as a result of the COVID-19 pandemic

On December 31, 2019, a new coronavirus was discovered in Wuhan, China. The novel virus, Covid-19, causes severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) in humans (Noorimotlagh, et al., 2021). Among the protection measures worldwide was the use of face masks in public transport and public places. As a result of the use of face masks by the public, disposable face masks showed up in the Dutch environment during the COVID-19 pandemic. Figure 1.2 shows some examples (Nederland Schoon, 2020). Also, the use of face masks in hospitals increased drastically because of the many COVID patients in these health facilities.

Figure 1.2: Some examples of face masks in litter in the Netherlands (Nederland Schoon, 2020).

Data from the world clean-up day in The Netherlands in 2020 reveals that face masks made up 2.1% of all litter items that were found in the environment (Plastic Soup Foundation, 2021). This might not seem like much, but it is still a significant percentage. In comparison, plastic bottles made up 3.5% of all litter items.

Considering the ''plastic soup'' problem in the oceans, which contains lots of items originating from litter, one can assume that a fraction of the face masks also ends up in the marine environment. Plastics are very resistant to degradation under natural conditions but will eventually break down into MPs. Exposure to sunlight, especially to ultraviolet light, seems to be the most important driver of plastic degradation (Bajt, 2021). Another recent study addresses the release of MPs into the environment. The melt-blown cloth in the middle layer of masks was found to be particularly sensitive to UV irradiation. A single weathered mask can release more than 1.5 million MPs to the aqueous environment. The physical abrasion caused by sand further exacerbated the release of microplastic particles from masks, with more than 16 million particles released from just one weathered mask in the presence of sand. (Wang, An, Chen, Lee, & Zhang, 2021).

As witnessed during the COVID-19 pandemic, the use of face masks and the quantity thereof in the environment has risen drastically. Therefore, it is important to investigate how and why these end up in the environment to take possible emission measures.

1.3 Face masks used in the Netherlands

1.3.1 In public use (type I)

During the Covid 19 pandemic, wearing face masks was mandatory in public transport, supermarkets, schools, universities and other public indoor spaces. Most people used homemade cloth masks or type I masks. The latter, the well-known (often blue) single-use face masks, is the type that was sold by supermarkets and drugstores.

In this paragraph, we focus on the medical face masks (type I) that were found in terrestrial litter since the COVID-19 pandemic. These face masks are in the media often wrongly described as non-medical.

The criteria for medical face masks are described in EN 14683:2019+AC:2019. This European standard specifies construction, design, performance requirements and test methods for medical face masks intended to limit the transmission of infective agents from staff to patients during surgical procedures and other medical settings with similar requirements (EN 14683:2019+AC:2019, 2019). Face masks imported and used in the Netherlands have to comply with this standard. In this standard, a medical facemask is described as a medical device covering the mouth and nose providing a barrier to minimise the direct transmission of infective agents between staff and patient.

The use of washable non-medical face masks or medical face masks that comply with EN 14683:2019+AC:2019 were obligated in public transport and public buildings from December 1st 2020.

The EN 14683:2019+AC:2019 describes three categories of face masks. Type I, type II and type IIR. All these face masks look the same and are very similar. However, minor differences in performance requirements can be distinguished. Type I has the least strict requirements while type IIR has the strictest requirements. A summary of the performance requirements for medical face masks is presented in table 1.2.

Table 1.2: Performance requirements for medical face masks according to EN 14683:2019+AC:2019

Test type	**Type I**	**Type II**	**Type IIR**
Bacterial filtration efficiency (BFE), (%)	≥ 95	≥ 98	≥ 98
Differential pressure (Pa/cm2)	< 40	< 40	< 60
Splash resistance pressure (kPa)	Not required	Not required	≥ 16,0
Microbial cleanliness (colony forming units/g)	≤ 30	≤ 30	≤ 30

Depending on pandemic measures, the face masks used per country may differ. In most countries, including in the Netherlands, the simplest disposable face masks type I is recommended to be used in public during the COVID-19 pandemic. Figure 1.3 shows the type I face mask.

The type I face mask consists of five parts. There are three different layers of protection, namely:

- An inner layer of non-woven fabric.
- A middle layer of melt-blown cloth (filter)
- An outer layer of non-woven fabric

Figure 1.3 shows these three different layers.

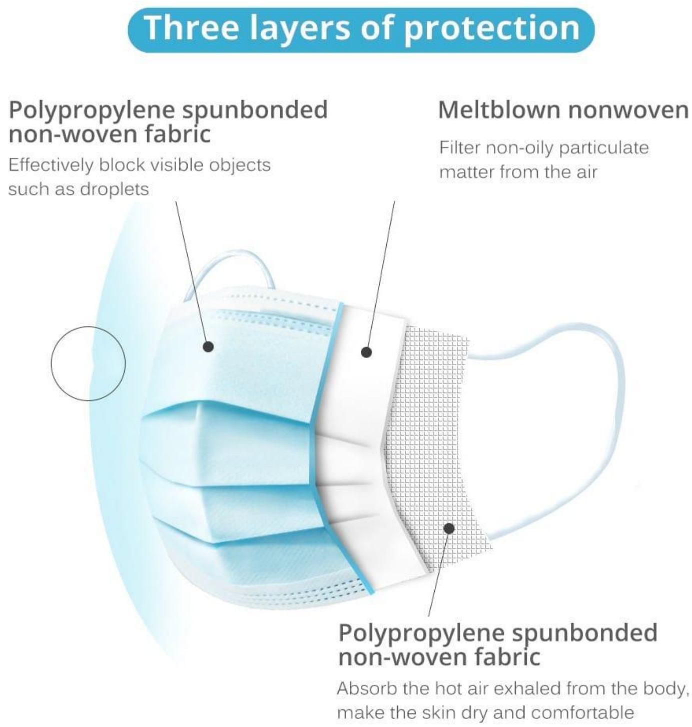

Figure 1.3: Three layers of protection in type I face masks (unhcrs.org, 2021).

The 4th plastic element is the ear loop that is mainly made of PES. The 5th element of the face mask consists of an aluminium nose clip.

1.3.2 In hospitals (FFP2)

In hospitals, several types of face masks are used for different purposes. Here we focus on Filtering Facepiece 2 masks, also known as FFP2 face masks, which are used by medical professionals.

FFP2 face masks have been in use in medical and industrial settings since long before the pandemic. The reason to use these masks is mainly to protect the user from its environment. One can think of situations where a health professional is at constant risk of catching infectious diseases. Since the start of the pandemic, many patients have been admitted to hospitals with Covid-19: an infectious disease. As a consequence, the need for FFP2 face masks by medical professionals also increased.

FFP face masks can be divided into FFP1, FFP2, and FFP3 masks. The latter provides the best protection against aerosols, dust, viruses and bacteria (99% of the particles in the air are blocked). However, the downside of FFP3 face masks is their low breathability which can result in shortness of breath and/or dizziness when used for a prolonged period of time. The FFP2 masks filter out 95% of the particles in the air and are also effective in filtering out COVID-19. The protective function of the product is standardised in the Netherlands according to the EN 149 standard.

The two main reasons for the success of FFP2 masks in blocking out particles from entering the body are the quality of the filter and the shape of the mask. In contrast to type I facemasks, the FFP2 face masks have four protective layers instead of three.

The quality of the filter depends on the chemical and physical properties that the plastic fibres have. These plastic fibres are made of PP (Park & Lee, 2021). One can often describe the working of a filtering system as a strainer, where particles are blocked if they are too big to fit through the holes. The filters in face masks also work as a strainer for the big particles but they also need to filter out micro -and nanoparticles. These are filtered out by getting attracted to the fibres under the influence of van der Waals-forces. The medium particles are not filtered out by these two mechanisms but are filtered out because the fibres have been ionised. Even neutral plastic particles will create an internal electric field that attracts them to these fibres. By these three mechanisms, the FFP2 face mask can effectively block out 95% of particles entering the filtering system.

One can see that the proper fitting of the mask on the face of the user, however, is an equally important indicator of the number of particles entering the human body. Figure 1.4 shows the shape of the FFP2 face mask.

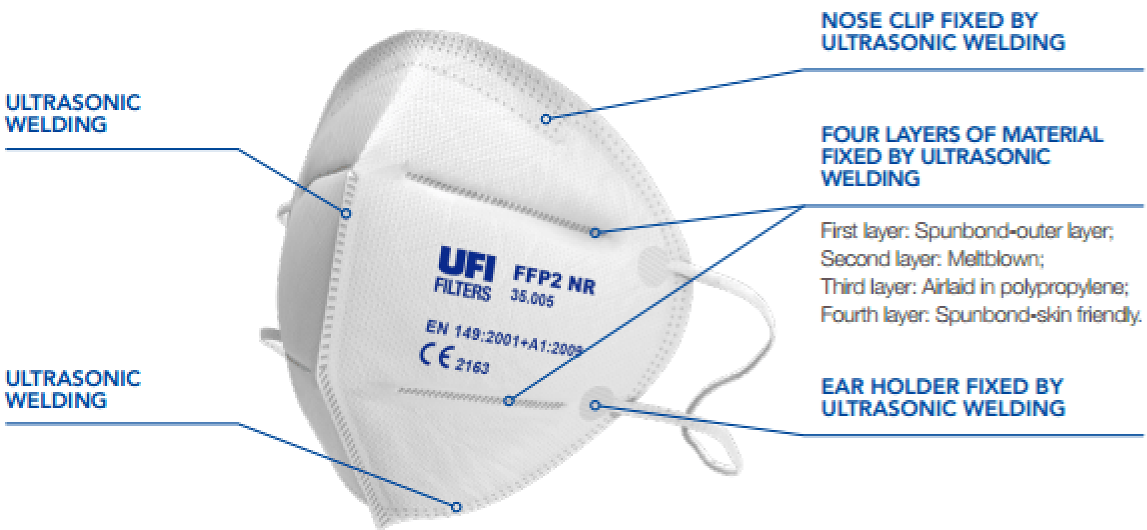

Figure 1.4: Four layers of protection in FFP2 face masks (www.ufihyd.com, 2021).

1.4 The importance of product chain knowledge

MPs are being found almost everywhere on the planet. To get an insight into the impact of this problem, it is important to perform research on the ecotoxicological and human toxicological effects of MPs. It is however equally important to investigate how these MPs end up in the environment and which products are contributing to this problem. It might seem obvious that an important route of microplastic emission is terrestrial litter ending up in the marine environment, but there might also be other plastic emissions in the product chain. Therefore, it is important to quantify the plastic emissions from single products at all stages of the product chain. Clearly, this product chain differs from product to product in the way it is produced, how the raw materials are produced and transported, how the products are distributed, how the products are used and how waste management takes place. In order to be able to map the plastic emissions from a product chain, first, the product chain has to be described in detail. Thus far, for Type I and FFP2 face masks, no detailed description of the product chain and quantitative estimates of the plastic flow exist.

1.5 Goal & Scope

This research is a subpart of the project Miniplas, that focuses on two potential important plastic polluters: the disposable type I medical face masks and the FFP2 face mask.

With the increasing production, use and disposal of single-use type I medical face masks and FFP2 masks, it is possible that a big environmental challenge lies ahead. A better understanding of plastic flows is important in order to address the environmental challenge of littered face masks. Identifying and mapping areas of inefficiency, material losses and potential emissions to natural systems is important in order to mitigate plastic pollution. Knowledge of the full production chain of the face masks can therefore improve our understanding of its releases to the environment (Kawecki et al., 2018). Therefore, a detailed description of the full product chain of both face masks is important. Even though knowledge about the pollution sites and the toxic effect of MPs on public health and on flora and fauna is important, to prevent or mitigate pollution it is necessary to fill in the knowledge gap of how plastics enter the environment and the underlying mechanisms. An important and hardly researched step towards achieving this is making reliable estimates of the quantity of microplastic emissions from the potential new source of plastic pollution: the face masks and in particular the Type I medical face masks and FFP2 medical face masks (Plastics Europe, 2018; Hsu, Domenech & McDowell, 2021).

In this context, the objectives of this study are:

- Describe the full product chain of type I medical face masks and FFP2 face masks.
- Quantify the plastic flows in the product chains of type I medical and FFP2 face masks from production to waste using a Material System Analysis.
- Identify possible emission sites of MPs to the environment within the product chains and predict them using proxies.
- Describe possible solutions to mitigate plastic emissions in the product chains.

In this study, we focus on the major processes in the product chain. Use of plastic packaging materials for face masks or use of chemicals packed in plastic to perform maintenance on machinery for example are not included in this study. We focus on all plastic emissions from these major processes. No distinction is made between plastic and microplastic because eventually emissions of plastic will lead to the formation of MPs and direct emission of MPs will lead to the formation of even smaller MPs.

1.6 Research Question

Due to the relatively new and possible extensive source of plastic pollution that could have an enormous burden on the aquatic and terrestrial environment worldwide, it is important to describe the product chain of type I and FFP2 face masks, to identify emissions locations and to provide reliable numbers of the plastic flows into the environment. To achieve this goal, the following research question is formulated:

- Where does the emission of MPs to the environment take place in the product and environmental chain of type I medical and FFP2 face masks and how big are these emissions?

In this research, the following environmental science sub-questions are linked to the main question in order to be able to answer the main question:

- How do the product and environmental chains of Type I and FFP2 face masks look like?
- Where in the product and environmental chain can plastic emissions be identified?
- What is the share of type I and FFP2 face masks in the total emission of MPs into the environment?
- What suggestions can be made for a quick-scan method based on proxies?
- What recommendations can be made to mitigate emissions?

2. Method

External data collection through online surveys, site visits and systematic literature reviews were used to achieve the objectives of this research. We executed a traditional literature research making use of databases like Sciencedirect and Google Scholar. We made use of the search terms SCOR models and product. Among the scarce publications, there were no studies about the SCOR model in relation to plastic items or materials. Though, several publications were found that pinpointed the success, advantages and disadvantages of the SCOR model. In some cases, an application of the SCOR model on a certain product was described. This literature research on the SCOR model is attached in appendix E.

Literature about production processes and materials was also found in databases like Sciencedirect and Google Scholar and used to describe the production processes in the product chain. This was done by using simple search terms like the names of the used materials in the face masks, the types of plastic used and the term production.

In order to make a detailed description of the complete product chains of type I and FFP2 face masks, aspects of a SCOR model were used. The following sub-sections describe the SCOR model used to make a description of the product chains.

In order to be able to quantify the plastic flows in the life cycle of Type I and FFP2 face masks, two different Material System Analyses were structured. The baseline model of the MSA´s and the data and information collection strategy are described in the sub-sections.

2.1 Product chain description based on SCOR model

2.1.1 SCOR model principles and literature research

To describe the full supply chain of disposable face masks, the **S**upply **C**hain **O**perations **R**eference-model (SCOR model) is used. The SCOR model was developed in 1996 by the management consulting firm PMRT and was endorsed by the Supply Chain Council to help companies better understand their processes. It has since been implemented by thousands of companies worldwide (supplychain 247, 2014). The model is used to provide a map of a product from the suppliers' supplier to the customers' customer (as shown in figure 2.1). It is free to use for members. Because of its robust and standardised framework, it can be used for comparison between product chains. Also, it provides recommendations for more efficient or best practises. The main reason companies make use of the SCOR model is to describe the business activities associated with satisfying customers' demands.

The model consists of five processes that are analysed in every step of the product chain:

- **Plan**: Alignment of supply and demand to develop a plan that meets the requirements of various stakeholders concerning purchasing, production and distribution.
- **Source**: Procurement of goods and services necessary to meet demand.
- **Make:** Transformation of raw materials and components into end products.
- **Deliver**: Delivery of end products including order management, warehouse management and transport management.
- **Return**: Returning finished products for any reason.

These processes are analysed through four indicators:

- **Performance metrics**: Standard metrics to measure process performance
- **Processes**: Standard descriptions of management processes and a framework of process relationships
- **Practises**: Management practises that produce best-in-class performance
- **People**: Training and skills requirements aligned with processes, best practises, and metrics

The processes are described from the supplier's supplier to the customer's customer. This is shown in figure 2.1.

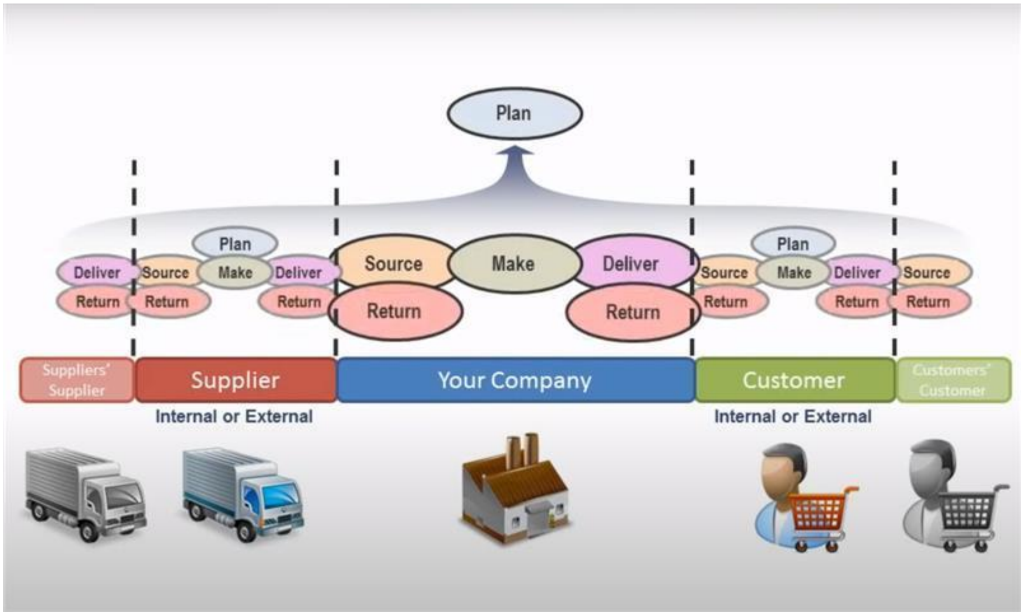

Figure 2.1: SCOR processes ((AIMS education, unknown date).

The processes as described by the Supply Chain Council are explained in more detail in appendix B and derived from (Supply Chain Council, 2010). For details, we refer to: (Supply Chain Council, 2010).

In the SCOR model, there are three different levels of detail ranging from level 1 to level 3. To get an idea of the various terms, these terms are explained with some examples that relate to the supply chain of face masks in appendix B.

Literature research on former SCOR model applications is attached in appendix E to get an idea of the pros and cons of the SCOR model.

The SCOR model was used to create an overview of relevant processes in the product chains of face masks after which a Material System Analyses could be performed to find out the microplastic emissions during these processes. By using the SCOR-model, first the whole process is described in detail with a focus on the plastic materials. This has the advantage that it reduces the chance that possible emission routes are overlooked.

2.1.2 Data and information collection strategy on Type I and FFP2 face mask production

Our research scope is the supply chain of type I and FFP2 face masks. Type I face masks are not produced in the Netherlands. However, type IIR face masks that are very similar to type I face masks are produced in the Netherlands. FFP2 masks are produced in the Netherlands. Therefore, the strategy for data collection on face mask production consists of three elements, namely:

- Gathering information from type I and FFP2 face mask producers from abroad.
- Gathering information from type IIR face mask producers from the Netherlands because they are very similar to type I face masks.
- Gathering information from FFP2 face mask producers in the Netherlands.

Unfortunately, we were unsuccessful in getting any information from type I face mask production companies. As an alternative, we focused on type IIR manufacturers. As explained in 1.3.1, type IIR face masks only differ slightly from type I face masks. The main difference is the outer layer. Type IIR face masks outer layer has to be splash resistant. For type I face masks this is not required. Apart from the splash resistant layer, the type I face masks are almost the same. So we can assume that the production process is very similar as well. We compared the production process of the biggest IIR face mask manufacturer in the Netherlands that we visited for this research to the production process of General Motors (General Motors, 2021). GM shows parts of the production process on their website. We can conclude that the same machinery is used and that the whole process looks practically identical. We can draw the same conclusion when watching an online video of one of the biggest face mask producers in China which produced 20 million face masks per day (EEXI Face Masks, 2020). Based on the video they even use identical machinery. Therefore, we assume that type IIR face masks are the same as type I face masks concerning the content of plastic.

Three type IIR manufacturers in the Netherlands were contacted of which two responded with answers to our questions. One of these two manufacturers is the biggest manufacturer in the Netherlands. With this information and as well other information from websites of different manufacturers, we were able to make an overall description of type I face mask production. To get more detailed information for a supply chain description, we visited the biggest type IIR manufacturer in the Netherlands. Also, we visited an FFP2 face mask manufacturer. The gathered information for both type I and FFP2 were found to be useful for describing the supply chain with the SCOR model.

Our first step was to gather information from type I and type IIR face mask producers in the Netherlands and abroad. Therefore we asked the manufacturers the following questions:

- Which materials are used in the type I/IIR and FFP2 face masks?
- In which way do the type I/IIR face masks you produce differ from other manufacturers?
- In which way does your type I differ from other type I manufacturers?
- Who are the material suppliers for type I/IIR and FFP2 face masks?
- How are the face masks tested?
- How much material is needed to produce one face mask?
- Who are your main customers and how many do they usually buy? And to what extent did the COVID pandemic influence these numbers?
- How does the distribution to the customers take place?
- How many masks are produced?
- How does packaging take place?
- How are stocks managed?
- Are there any plastic waste streams to the environment, if yes how big are they and how are they managed?
- How are supply and demand matched?
- What goods and services are needed to meet demand?
- Are face masks ever returned? If so, why how many?

Unfortunately, we were unsuccessful at gathering information from manufacturers abroad with our questionnaire. However, we did get answers to most of the questions from the two face mask manufacturers we visited. The gathered data is used in this research report with references to ‘’site visit’’.

2.2 Material System Analysis

To discover the sources of microplastic emissions and their quantities, we performed two Material System Analyses (MSA’s). Material System Analysis (MSA) is a subcategory of Material Flow Analysis (OECD, 2008). In a Material Flow Analysis, the physical flows of materials into, through and out of a system are studied. A Material System Analysis (MSA) focuses on individual materials and how they flow through a system (OECD, 2008). The individual materials in this study are the plastics that are used in the production of type I and FFP2 face masks. The plastic flows are followed through the entire life-cycle of both face masks.

MSA tends to identify major problem flows to the environment, tracing these back step by step to their origins in the product chain (Bureecam et al., 2018). Because the same amount of material input needs to leave the system, (hidden) leaks from processes in the chain are traced (OECD, 2008). This methodology has been applied to many products, but until now not to the materials used in face masks. Material System Analysis is used to discover and quantify the flows of plastics that are used in the production of face masks. By researching the flows of plastics, the emissions of MPs can be detected.

In this study, we are particularly interested in detecting unused plastic flows of materials. Unused flows are flows of materials that are not seen as priced goods in the economy (OECD, 2008). These include flows of pollutants (like microplastic emissions) and waste that is generated outside of the system boundaries (OECD, 2008). It is especially these flows that can contribute to the pollution burden of (micro) plastics to the environment. The materials that are studied in this research are the plastics that are contained in the face masks. The plastics used for packaging face masks and sealing the pallets in trucks during transportation are not included in this study.

The MSA's are structured through the use of the bookkeeping system. First, a flowchart is made that shows the processes, flows and stocks of the studied materials (De Haes & Heijungs, 2009). Then, empirical data can provide quantities and percentages that can be attributed to the processes, flows and stocks. The result is a flowchart that contains quantities of materials. The quantities are accounted for in percentages and masses.

MSA is not a standardised method. This means that the two methods and models used in the two different MSA´s in this paper have slight differences. The MSA's are mainly based on a guide to Material Flow Analysis from the Organisation for Economic Co-operation and Development (OECD) and on a chapter from the coursebook of the course principles of Environmental Sciences by the Open Universiteit (OECD, 2008, De Haes & Heijungs, 2009).

2.2.1 Technical framework and system boundaries

To structure the analysis, MSA should be performed within a well-defined technical framework with system boundaries. Typically, a geographic location is chosen as a system boundary. In this study, however, it is chosen to take the life-cycle of the face masks as the system boundary. This is because one specific geographical boundary is not possible as the production of plastics takes place in China but the consumption and output stages take place in the Netherlands.

The MSA for type I medical masks describes a scenario of plastic flows of a type I face mask during a one year pandemic (365 days) with flexible precautionary measures representative of the measures mandatory in 2020 and 2021 in the Netherlands. A total of 40 weeks where face masks are mandatory in public spaces, shops and transportation and where the acceptance rate of wearing the masks is 100% are chosen as important system definitions in the described scenario. An acceptance rate of 100% means that everyone mandatory to wear a face mask accepts this measure. The population with a medical reason to not wear face masks or people with different ideas about the pandemic are not taken into account in this study.

For the MSA of FFP2 masks the year 2020 is chosen as the temporal system boundary as at the time of writing this was the only full year for which information on the use of FFP2 face masks during the Covid-19 pandemic was available. Note that in that year, two different usage periods can be distinguished: A pre-Covid-19 period where regular numbers of face masks were being used, and a larger Covid-19 period in which more FFP2 face masks were used (see appendix A for the length of these periods).

The subsystems in the complete product chain will be described using the SCOR model in section 'Results'. The identified subsystems will be used to construct the MSA's of both Type I and FFP2 face masks.

3. Results

3.1 Product chain description

3.1.1 Introduction

With the combined information from websites, answers from our questions to manufacturers and site visits of type IIR and FFP2 manufacturers, we were able to describe the product chain of both type I and FFP2 face masks in general. This description was categorised into the five process categories used by the SCOR model. The description was focused on possible emission routes in the chain so that these can be used to perform an MSA in possible further research. In the next paragraphs, we follow the flow diagram that is shown in figure 3.1. The figure also shows the different actors involved in the process of manufacturing face masks.

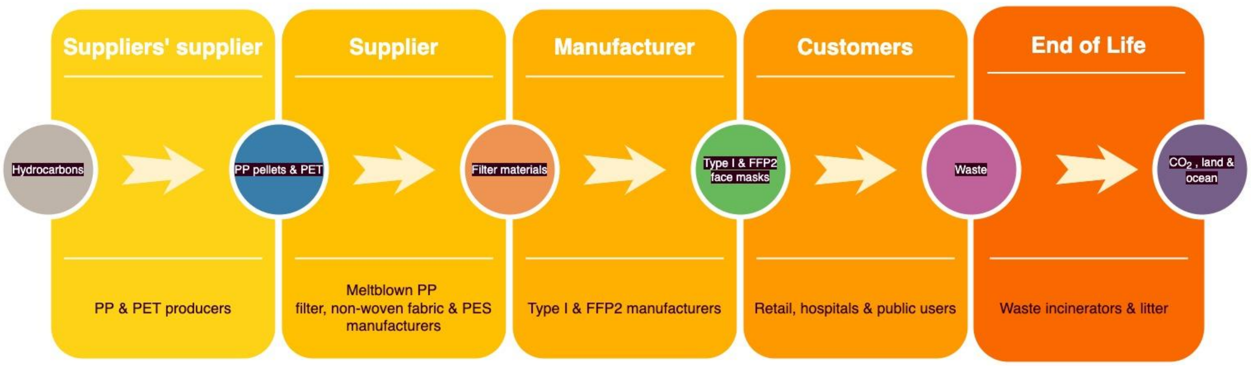

Figure 3.1: Supply Chain of materials in production of type I and FFP2 face masks

3.1.2 Pellet loss

Before going into the five stages of the product chain, we explain the phenomenon of pellet loss in this paragraph. This phenomenon is a significant emission route of plastic into the environment. Pre-production pellets are small spheres of plastic that are used by manufacturers to make plastic products by melting and moulding them. Pellets are on average smaller than 5 mm in size and therefore classified as primary MPs. Some of these pellets don't end up in the product but in the environment. This is known as the term 'pellet loss'. Pellet loss is described in detail in a background document belonging to the OSPAR convention. OSPAR is the Convention for the Protection of the Marine Environment of the North-East Atlantic and is the current legislative instrument regulating international cooperation on environmental protection in the North-East Atlantic. The Pellet loss background document (Ospar Commission, 2018) points out the following causes for pellet loss:

- **Leakage on industrial sites:** During logistic operations, pellet spills can occur during, but are not limited to, the loading and unloading of pellets using suction pipes for silos and forklifts or cranes for bags or octa bins. These processes can occur in the open air, which increases the risk of pellets escaping to the natural environment.
- **Losses during transportation**: Pellets are easily spilled during transport, including by road, ship and air.

Figure 3.2 shows the pathways in which pellets enter the environment.

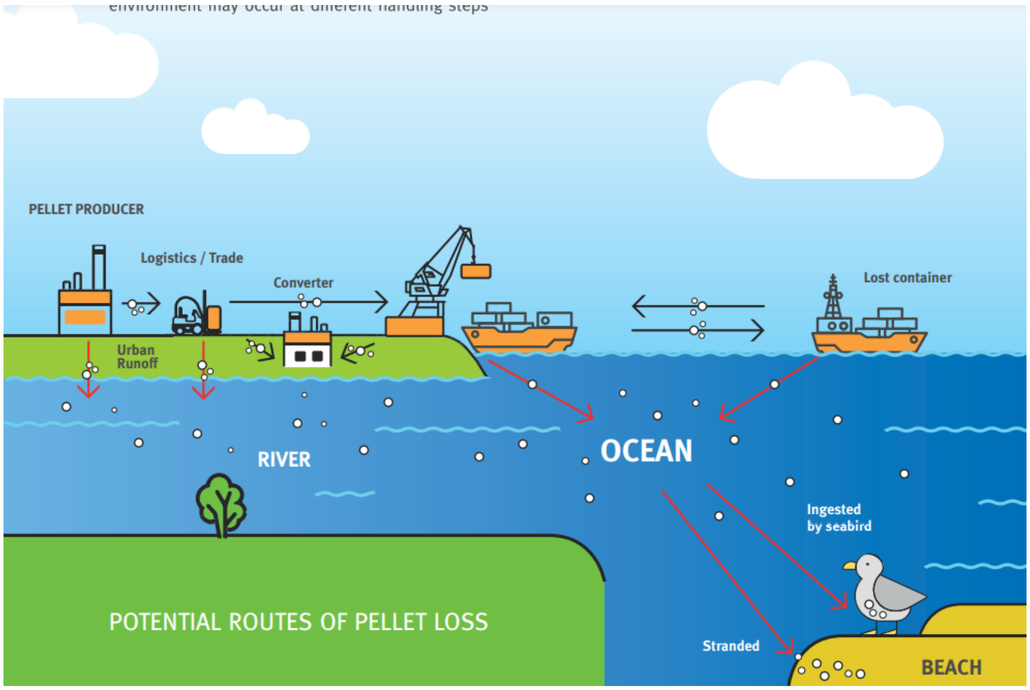

*Figure 3.*2 Pellets losses pathway on the sea *(PlasticsEurope, 2017)*

Pellets can be found all over the world, especially near production plants. However, they may also travel huge distances in rivers. Especially pellets like PP that have a relatively low density compared to water. Figure 3.3 shows an example of pellets in the environment.

Figure 3.3 Pellets on a beach in Sri Lanka (Eranga Jayawardena/AP)

According to Lassen (2018) the pellet loss rate in Europe by producers is estimated between 0.010 – 0.040 %. This is equivalent to 5.8 ktons – 28.2 ktons tons per year. Intermediary facilities also contribute 0.010 – 0.040% to pellet loss. This is equivalent to 5.3 – 106.0 ktons per year (Lassen, 2015). The pellet loss in Europe caused by transport is estimated at 0.001 – 0.0002%. This is equivalent to 141 – 225 tons per year (Marine Insight, 2014). The pellet loss rates are also shown in table 3.1. Numbers for other parts of the world are probably somewhere in the same range. Rybert et al. (2019) show that losses of microplastic in plastic production in China are about the same as in

Western Europe and North America (Ryberg, Hauschild, Wang, Averous-Monnery, & Laurent, 2019). The pellet loss most likely occurs in China as the producers of non-woven fabric and melt-blown cloth are also located in China.

Table 3.1 — Plastic pellet loss in Western Europe. Adapted from Hann et al. (2018)

	Minimum loss rate ***(% of total production)***	***Maximum loss rate*** ***(% of total production)***
Producers	0.01 %	0.04 %
Intermediary facilities, including distributors and storage facilities	0.01 %	0.04 %
Shipping	0.001 %	0.002 %
Total pellet loss	0.021 %	0.082 %
Average pellet loss	**0.052 %**	

3.1.3 Production of materials (suppliers' suppliers)

As mentioned in paragraph 1.3, face masks consist of the following five elements, of which four contain plastic:

- Inner layer of non-woven fabric (plastic - PP)
- Middle layer of melt-blown cloth (plastic - PP). In FFP2 masks two or three middle layers are present depending on the manufacturer.
- Outer layer of non-woven fabric (plastic – PP)
- Elastic ear loop (plastic – 87 % PES/ 13 % elastane)
- Nose clip (aluminium)

The face mask producer orders these materials itself but orders them from a supplier.

The producers of the non-woven fabric and meltdown cloth need PP pellets to produce these layers. The producers of ear loops need PES and elastane to produce the ear loops. PES producers need PET pre-production pellets to produce PES.

PP in non-woven fabric and melt-blown cloth and related pre-production pellet loss

PP is a thermoplastic polymer, which means it becomes soft when heated. This softening makes it able to mould PP to different shapes. Therefore, PP is one of the most produced plastics worldwide and is used for various applications. In 2018, 56 million tonnes of PP were produced and this is increasing to an estimated 88 million tonnes in 2026 (Statista, 2019). 52.6% of the global production of PP is situated in Asia. China makes 27.3% of the world's PP pellets. However, Europe also has its fair share with nearly 15% of the global production of the material (Statista, 2021).

PP is produced in a process called the Spheripol process. The Spheripol process is a modular technology consisting of three main process steps, catalyst (usually Ziegler-Natta or metallocene catalyst) and raw material feeding, polymerisation and finishing. Lee et al (2015) mentioned as one of the major advantages of this technique its unique ability to produce polymer spheres directly, in the reactor (Lee, Kofi, Kim, Hong, & Oh, 2015). Other production technologies though also exist worldwide, depending on the production company.

PP is usually considered a safe product and is suitable for recycling. Several studies show that the production process of PP however has a certain environmental impact. Alsabri et al. (2021) performed a life cycle analysis of PP production in the Gulf Cooperation Council (GCC) Region. The study showed that the PP manufacturing process releases numerous pollutants into the environment. LCA studies on the manufacturing process of polypropylene have been conducted, for example by Alsabri, Tahir & Al-Ghmadi (2021) and Harding et al (2007). The disadvantage of these LCA studies is that they do not address the problem with microplastic emissions caused by plastic production. As mentioned earlier, PP is the second most-produced plastic worldwide and PP is produced as pre-production pellets that can leak into the environment.

PES and PET in elastic ear loops and related plastic pellet loss

The elastic ear loops in the majority of face masks are made of PES. To enhance elasticity, the PES is mixed with about 13 % elastane. Elastane also goes by the brand names Spandex and Lycra.

PES is produced by a process called melt spinning. In this process, a viscous melt of polymer (PET-pellets) is extruded through a spinneret containing a number of holes into a chamber, where a blast of cold air or gas is directed on the surface of fibres emanating from the spinneret. As the airstrikes the fibres, the fibres are solidified and collected on a take-up wheel (Murase & Nagai, 1994). The melt spinning process is shown in figure 3.4.

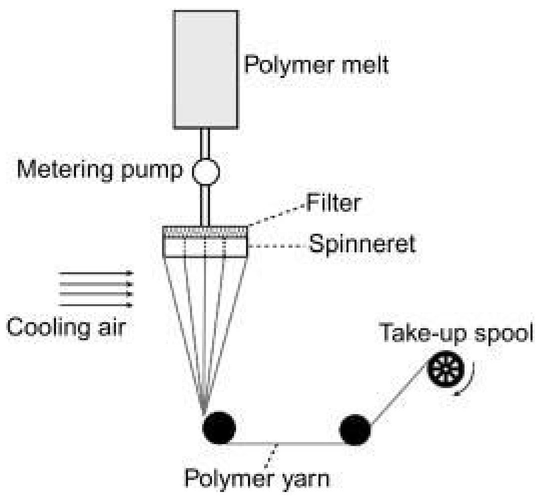

Figure 3.4 Melt spinning process (Murase & Nagai, 1994)

Unlike PP, the end-product of PES production isn’t a pre-production pellet but a fluffy yarn material (How It`s Made Polyester, 2001). The most widely used PES fibre is made from linear polymer polyethylene terephthalate(PET) (Hossain, 2021). PET is produced as pre-production pellets in a similar way as PP. Therefore, we conclude that the use of ear loops in face masks will cause an emission of PET pre-production pellets.

Spandex is made up of a long-chain polyglycol combined with a short diisocyanate and contains at least 85% polyurethane. Polyurethane polymers that are formed by the reaction between the OH (hydroxyl) groups of a polyol with the NCO (isocyanate functional group) groups of an isocyanate. The name is associated with the resulting urethane linkage (N.V., Ferreira, & Barros-Timmons, 2018)

For face masks, the elasticity is expressed as 1:3. This elasticity is achieved by mixing PES and elastane. Some producers use nylon instead of PES. The percentage of elastane is probably usually low as most online suppliers mention PES as the only ingredient. Therefore, we can conclude that face mask ear loops almost fully consist of PES.

3.1.4 Production of plastic materials (suppliers)

In the supplier's category of the SCOR model we limit ourselves to the supplier of non-woven fabric, melt-blown cloth and ear loops. The nose clips won't be discussed in this section as they are irrelevant to the emissions of plastics.

Non-woven fabric

The inner and outer layers of type I and FFP2 face masks both consist of the same material, though the outer layer usually has a different colour, mostly blue. Both layers are made of non-woven fabric of PP. In type IIR face masks, the outer layer has splash resistant properties, but in type I face masks these properties are absent and don't need to be in accordance with EN 14683:2019+AC:2019. Also, in FFP2 face masks, a splash-resistant layer is absent. A nonwoven geotextile is a manufactured sheet, web or batt of directionally or randomly oriented fibres, filaments or other elements, mechanically and/or thermally and/or chemically bonded. (Müller & Saathoff, 2015). The material used in type I and FFP2 face masks is usually called Spun bond PP nonwoven fabric. The material is made by melting PP pre-production pellets. Then the melted material is spun to form filaments. Then fibre bundles of many filaments are separated, spread and laid down to form a net. The fibres are bonded by thermal heating with a heat roll and eventually, the material is winded up (Unitika Nonwovens division, 2021). In figure 3.5 this process is visualised.

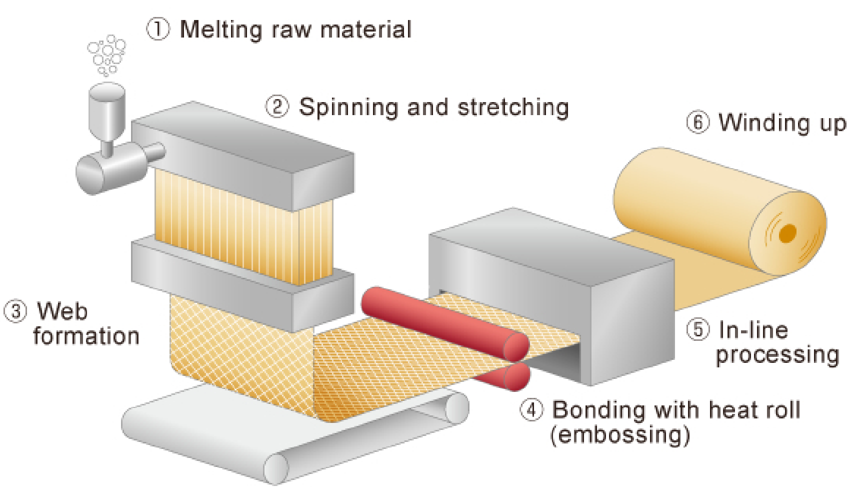

Figure 3.5 Manufacturing process non-woven material (Unitika Non-woven division, 2021)

Pellet loss of raw material is expected at intermediary facilities. Other plastic emissions in the process might occur but are most likely eliminated by waste management.

Melt-blown cloth

Melt-blown cloth is the middle layer of the type I and FFP2 face mask. FFP2 face masks usually contain two or three of such layers. This layer operates as a filter and is therefore the most important layer in the mask. Particles going through the filter are absorbed by the fibre network. Van der Waals bonding and other forces hold the particles that have been absorbed by a filter to the fibres; hence, it is hard for captured particles to escape (Bailar, et al., 2006)

Melt blowing is a simple, versatile and cost-effective extrusion-based technology that generates continuous nano/microfibres, forming a randomly oriented web ((Kara & Molnár, 2021).
This material is made by melting PP pre-production pellets. In melt blowing, the polymer melt is extruded through a die containing numerous small capillaries. This is then stretched via a jet of hot air.

The ratio of high-velocity air versus the lower velocity polymer provides a drag force that rapidly attenuates the forming fibres. Then, the fibres are collected on the surface of a collector in the form of a random web (ibid.). This process is visualised in figure 3.6.

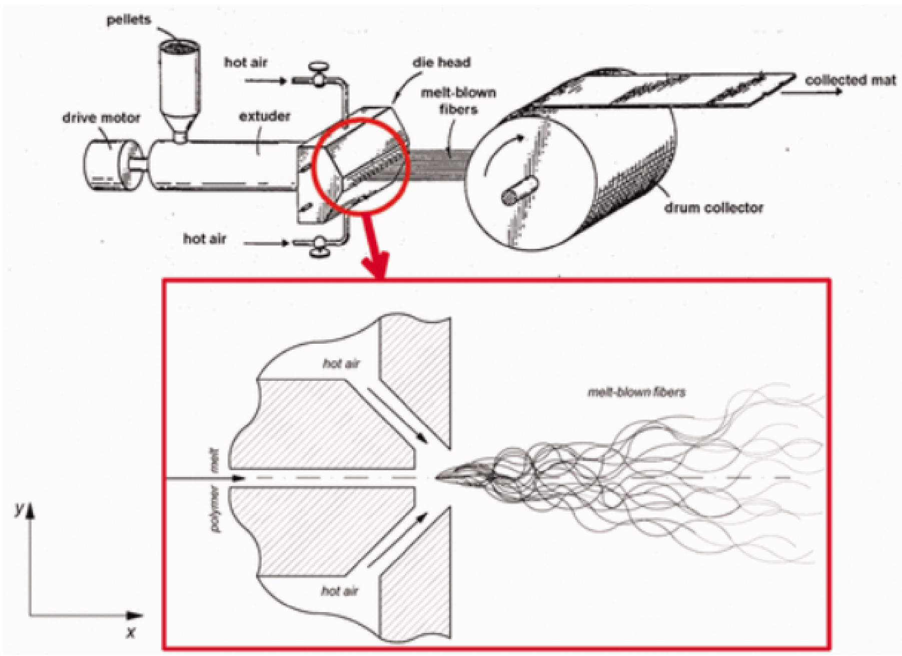

Figure 3.6 Manufacturing process melt-blown fabric (US Patentnr. US3972759A, 1976)

Because the meltblowing facility is an intermediate facility where PP pellets are used, microplastic emission because of pellet loss is expected. Other plastic emissions in the process might occur but are most likely eliminated by waste management such as waste collecting and good housekeeping.

Ear loops

The ear loops are made of a mixture of PES and spandex(elastane). In general, the material is called stretch fabric. Just like the non-woven fabric and melt-blown cloth, stretch fabric is produced by specialised textile companies. The process consists of weaving the PES and spandex in the desired ratio. The ear loops for face masks are specifically engineered for this purpose. We were not able to get information from ear loop producers, but based on information from the facemask producer in the Netherlands we visited, the percentage of spandex/elastane in the used ear loops is 13 %. The other 87 % consists of PES. Just like with the non-woven fabric and melt-blown cloth, plastic emissions out the process might occur but are most likely eliminated by waste management. Direct emissions of pre-production pellets might occur during shipping from the PET pellet producer to the PES producer as already pointed out in the supplier's supplier section. Because the percentage of spandex is low in comparison with the percentage of PES in ear loops, the production process of spandex and possible emissions of plastic during the production of spandex and production and transport of the required materials are not described in detail.

Pellet loss

The production facilities of the face mask layers can be considered intermediary facilities. According to Lassen (2015), the pellet loss rate at intermediary facilities is the same as the pellet loss at the primary plastic producer, namely 0.010 – 0.040%.

3.1.5 Production of type I face masks

In this paragraph, a general description of face mask production is given. For this research a general description is sufficient. Different producers might have production processes that differ in detail, but based on several online videos of face mask production from, for example, the Dutch producer Mondmaskerproducent (Mondmaskerproducent, 2021), EEXI Face masks (2020) and General Motors (2021), we can conclude that face mask production is almost identical for all manufacturers. This also has to do with the fact that the face masks have to be produced according to EN 14683 and are almost totally standardised. Most detailed information was retrieved from the face mask producer we visited in the Netherlands. Unlike the production of the materials, the production of the face masks itself is quite simple. We can distinguish the following steps:

- Purchasing and storing the materials
- Folding and welding the five components together
- Handling waste
- Testing
- packaging
- Distribution to customers

Purchasing and storing the plastic materials

To ensure production, manufacturers have to make sure they always have enough materials in stock to fulfil purchase orders. The essential materials are the melt-blown cloth filter, the non-woven inner and outer layer, the ear loop and the nose clip. The biggest face mask producers are located in China. Producers in other countries usually also buy their equipment and materials from Chinese suppliers.

The layers are supplied in rolls. Table 3.2 shows the characteristics of the delivered materials and the mass needed per face mask.

Table 3.2 — Characteristics of the used materials and used plastic in type I face masks (source: Site visit type I face masks factory)

Layer	**Material**	**Roll mass (kg)**	**Areal density (g/m^2)**	**Roll length ($m \times 10^3$)**	**Roll width (mm)**	**Number of Face masks produced out of 1 roll ($\times 10^3$)**	**Mass plastic needed per face mask (g)**
Inner layer	Non-woven fabric	15.0	25	3.5	175	15.0	1.0
Middle layer (filter)	Melt-blown cloth	6.8	25	1.4	160	6.0	1.1
Outer layer	Non-woven fabric	17.1	25	3.5	190	15.0	1.1
Ear loop	PES/elastane	10.0	-	-	-	14.0	0.7
Total							**3.9**

Based on this data, 3.9 g of plastic is needed for one face mask. The actual mass of type I facemasks is actually a bit lower, namely about 3.5 g based on a simple measurement using a kitchen scale. This difference can be explained because of a small plastic waste stream which is explained in the next paragraph.

Assembling the face masks out of the plastic materials and handling of plastic waste streams

China is the biggest supplier of materials and machines for facemasks, though the materials are also available in many other countries. A typical face mask machine is shown in figure 3.8.

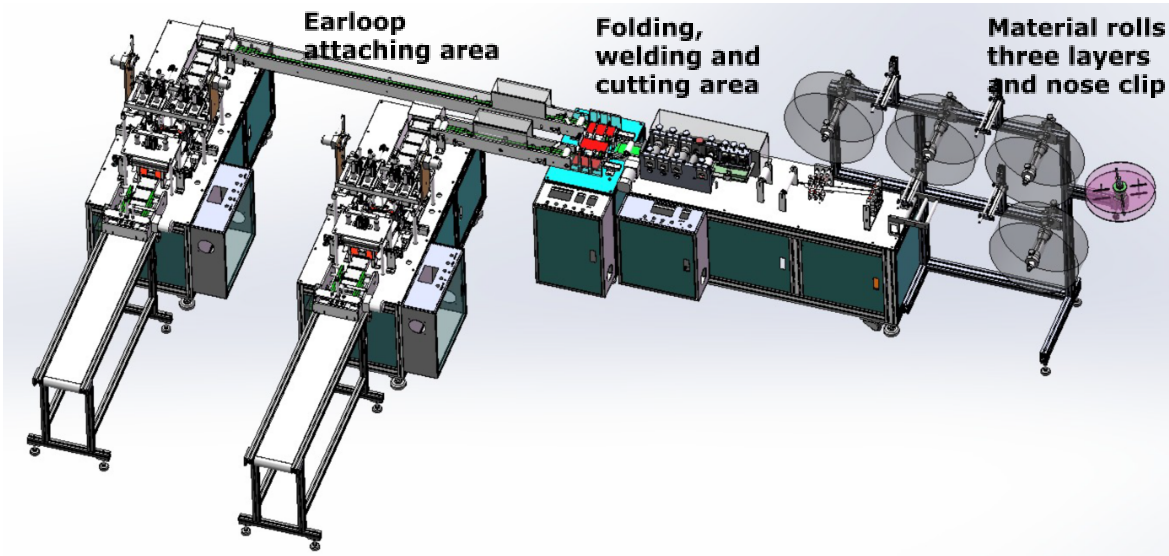

Figure 3.8 Face mask machine (Guangzhou Smart Tech Technology, 2021)

The three plastic layers are installed on the production machine. An example of the three layers in the machine is shown in figure 3.9. The materials that are shown in figure 3.9 were purchased from Chinese suppliers. Also, the machines are from Chinese suppliers.

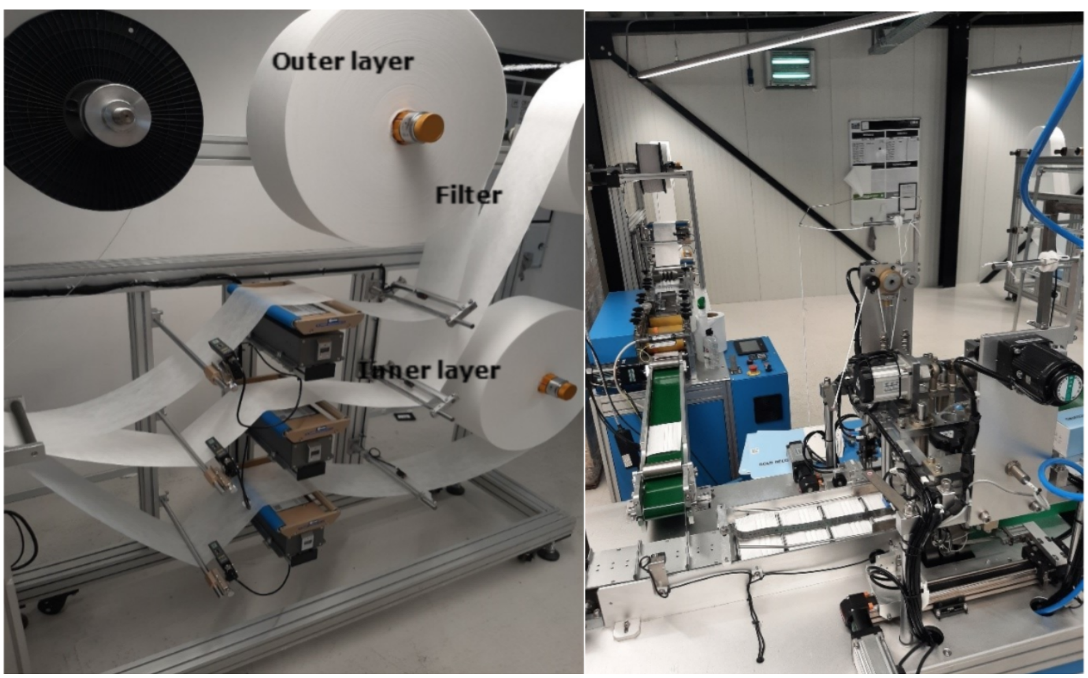

*Figure 3.*9: Left: three layers installed in the machine. Right: full view of the machine *(*source: Site visit face masks factory)

After installing the rolls with different layers, the machine folds and welds the three layers and the nose clip together. Then, these combined layers are cut to the right size. The last step consists of adding the ear loops. There are no emissions of pellets as pellets are not used. There is a limited amount of plastic waste though, which occurs when something goes wrong in the process that can influence the quality of the face mask. The machine or machine operator recognises these flaws and rejects the flawed face masks. Data about the number of rejected face masks was only gathered from one producer (Site visit face masks factory). The waste caused by the rejected face masks is about 65 face masks per hour. This is about 2.2 %. This percentage may vary a bit between producers. Lee et al (2020) mentions that during the process about 5 % of plastic waste occurs in the form of defected face masks. Because overall the same or similar machines and processes are used abroad like in China, we expect the plastic waste stream to be similar. This plastic waste stream is handled by waste management (collecting, disposal and eventually incineration).

Testing

Producers of face masks have to perform several tests on a limited number of samples in order to be in accordance with NEN-EN 14683+C1. This does not include the testing of the separate materials. Face mask producers perform several tests. For example differential pressure, splash resistance and the strength of the ear loops. During testing no plastic waste occurs apart from the fact that the tested face masks can't be used anymore and are disposed of.

Packaging

The packaging process differs slightly among producers. It is often an automated process in which the face masks are automatically packed in cardboard boxes. Some producers seal their face masks in plastic bags, which can for example be seen on the website of General Motors (General Motors, 2021). Data about the percentage of face masks that are sealed in plastic bags was not gathered. The packaging process is unlikely to cause plastic emissions during the packaging process. In the case plastic sealing bags get damaged, they are likely to be disposed of and handled by waste management.

3.1.6 User phase of type I face masks (customers)

Face masks are distributed to customers by different means of transport. They are usually distributed directly to retail sellers like drug stores and supermarkets. However, since the COVID-19 pandemic, they are also bought by governments. In the Netherlands, for example, LCH (National Consortium of medical and personal resources) buys and stores face masks to ensure there is a buffer for crisis situations. The distribution process is unlikely to cause plastic emissions to the environment.

3.1.7 End of life phase of type I face masks

As described in the introduction, the actual end-user of the face mask does emit plastics to the environment and causes litter. The current general supply chain of face masks does not include a recycling route or a waste management system in the end-user phase. The plastic emissions caused by litter seem significant. Research done in the Netherlands between April 2021 till September 2021 by the Zwerfinator in 11 different municipalities along 206 km, showed that 1.36 % of all plastic items were face masks. This represents a mass percentage of 0.5 % of all plastic waste (Groot, 2021).

3.1.8 Visualisation of product chain of type I face masks

Figure 3.10 shows a visualisation of the supply chain of type I face masks. Orange blocks show the processes where plastic emission to the environment takes place. These are the processes that should be analysed with MSA to quantify the emissions.

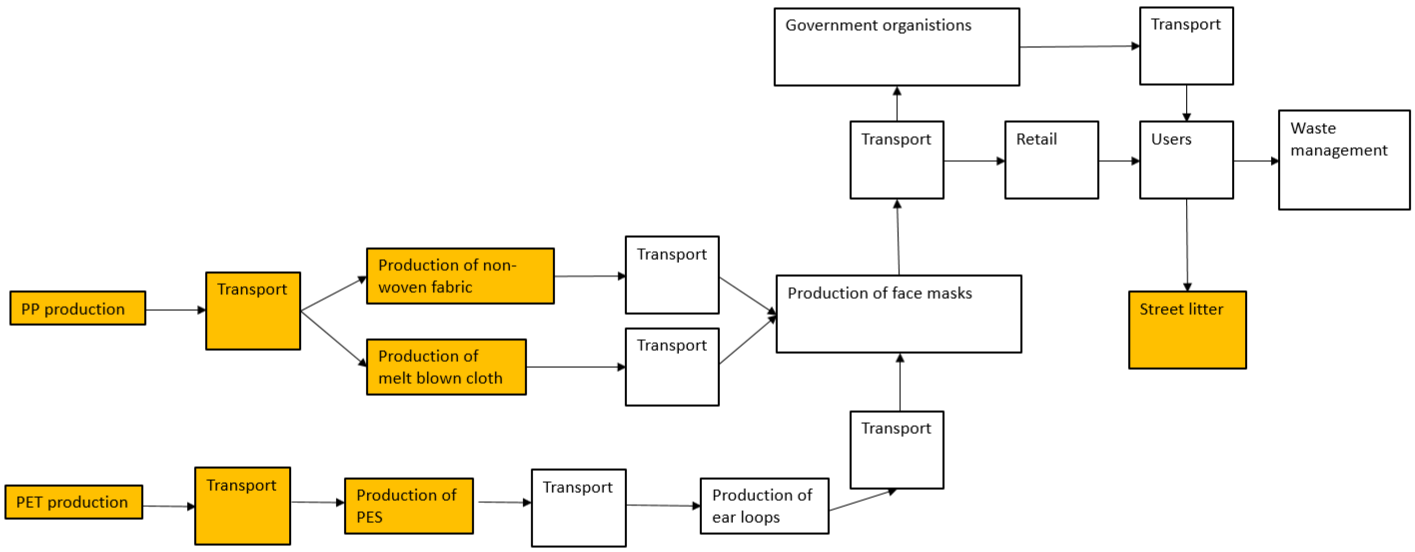

Figure 3.10: visualisation of the supply chain of type I face masks. The orange blocks represent the processes where plastic emissions occur to the environment that are not totally eliminated by waste management

3.1.9 Production of FFP2 face masks

As stated in chapter 2, a site visit to an FFP2 face mask manufacturing company (company B) provided insights into the manufacturing process of FFP2 face masks. The company is located in the Netherlands and its main customer is the LCH. One could understand that their main customer is the healthcare industry in the Netherlands, and they were provided with this clientele by the government through passing the quality checks of the LCH.

The production of FFP2 face masks is fairly straightforward. The materials necessary are:

- Filter material
- Inner - and outer layer material
- Ear loops
- Aluminium nose clip

Except for the aluminium nose clip, company B orders all these materials from the same supplier. This supplier is a company that focuses on the production of fabrics that contain plastics. The filter material used is 100% melt-blown polypropylene. The inner - and outer layers are a mix of polyester, polypropylene and traces of other fabrics. The ear loops have the same percentage of polyester and elastane as the type I face masks, respectively 87%-13% (Ferreira & Barrios-Timmons, 2018).

During the site visit to company B, we realised that the type of machine that produces FFP2 face masks is essentially the same type of machine that produces Type I face masks. The main difference found was that three filter layers were used instead of one. The type of filter was the same as in company A. However, for quality reasons, company B only purchased these filters from European manufacturers. The shape of the FFP2 face mask was imprinted into the fabric by a mould. The shape of the FFP2 masks ensures a tight fit around the face which enhances its efficiency. However, company B stated that 15% of their materials go to waste, mainly because of the shape of the mask. However, this 15% also included rejected masks and masks used for quality testing. Figure 3.11 clearly shows the fragment of the material that goes to waste because of the shape of the face mask.

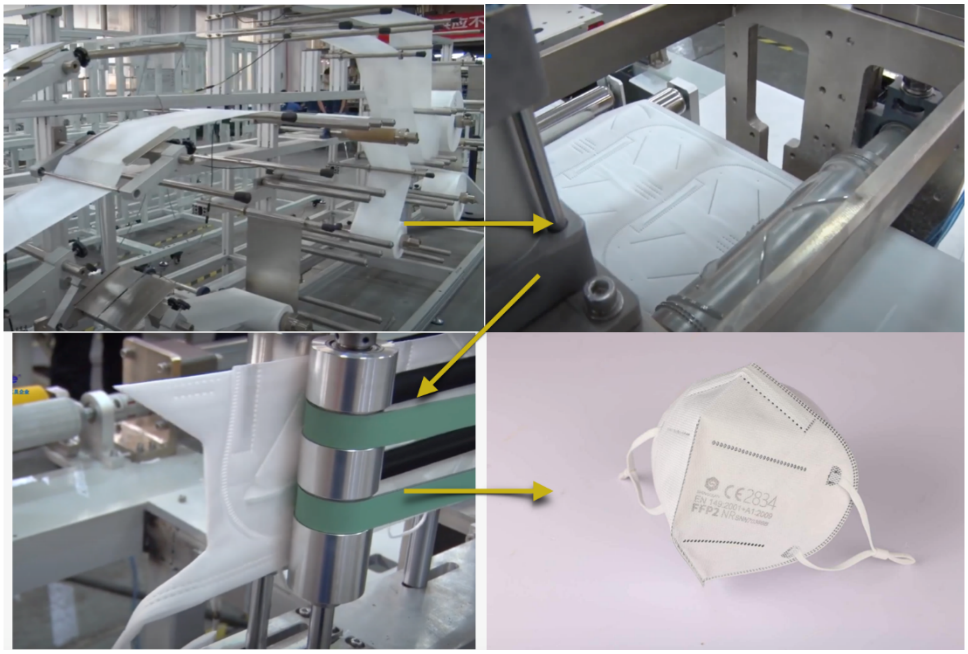

Figure 3.11 Production process of FFP2 face masks

The on-site visit also provided us with details that can exclude the manufacturing process as a potential source of microplastic contamination into the environment. The waste generated in the production process was high. However, microplastic pollution from the production site seemed highly unlikely as the excess fabric fed straight into a waste container.

The quality standards set by the LCH and the ISO13485 induce a controlled environment during the production process. This was visible as hourly samples were taken and tested on their efficiency. Moreover, every face mask was individually checked visually before being boxed. Also, due to the nature of their customers (the healthcare industry), they cannot afford to produce face masks of inferior quality. Packaging was done similarly to company A. The main difference was that every mask was once more visually inspected and manually boxed.

Table 3.3 shows an estimation of the amount of plastic used to produce one FFP2 face mask. This estimation is based on data from a face mask producer that produces IIR face masks in regards to the characteristics of the used materials (mondmaskerproducent). We used this data for the FFP2 face masks as the only differences are the lack of a splash screen and the usage of not one but three filter layers. The calculation shows that with this data, an FFP2 face mask consists of 6.2 g of plastic. In reality, the number of plastics used to produce one FFP2 face mask will differ among manufacturers.

Table 3.3 — Characteristics of the delivered materials and used plastic in FFP2 face masks (source: Site visit FFP2 face masks factory)

Layer	Material	Roll mass (kg)	GSM (g/m²)	Roll length (m x 10³)	Roll width (mm)	Number of Face masks produced out of 1 roll (x 10³)	Mass plastic needed per face mask (g)
Inner layer	Non-woven fabric	15.0	25	3.5	175	15.0	1.0
Middle layer (filter) 3 per face mask	Melt-blown cloth	6.8	25	1.4	160	2.0	3.4
Outer layer	Non-woven fabric	17.0	25	3.5	190	15.0	1.1
Ear loop	Polyester	10.0	-	-	-	14.0	0.7
Total							**6.2**

3.1.10 User phase of FFP2 face masks (customers)

As stated earlier, the main clients of the producers were hospitals. Thus, these are the main users of FFP2 face masks. Three hospitals within the Netherlands provided details on their use of FFP2 face masks by answering questionnaires. The hospitals did not mind sharing their data, but do want to remain anonymous. Therefore, we will further refer to the participating hospitals as hospitals A, B & C.

The use stage of the FFP2 masks was the same in the three hospitals. The only difference is the time of replacing the mask. In hospital A, a new mask was used for every patient, while in hospitals B and C, the mask was replaced every three hours as recommended by, among others, the WHO. Hospital A provided data on stock replenishing from which we derived the average use. Hospitals B and C did not give such data but provided the estimated numbers directly. During the heat of the pandemic, the use of FFP2 masks went up by 34 times in hospital A, and 10 times in hospitals B and C. As hospital A had different sets of rules on how to use the masks.

As FFP2 face masks can also be bought by the public, a questionnaire was sent to find out the number of FFP2 masks used outside of hospitals. Of the 131 responses, only 4 people (3.1%) used FFP2 masks in daily life. A detailed description of the questionnaire can be found in appendix D. If the sample is used to estimate the number of FFP2 face masks used in the Netherlands (17,5 million inhabitants), ≅280.000 FFP2 face masks are worn by the general public daily. We do acknowledge that the calculations made from this questionnaire might not apply to the whole population of the Netherlands as the sample size is too small. Another nuance is that even if the sample was to be random, a majority of the people who participated in this online questionnaire did so on LinkedIn. This social platform is more homogenous than, for example, Facebook. Thus, the answers provided might only reflect a subpopulation of the people in the Netherlands.

3.1.11 End of life phase of FFP2 face masks

Hospitals are controlled environments where following best practice procedures are highly important as human lives are at stake if mistakes are made. Therefore, waste disposal in such facilities is regulated, with a high compliance rate to such regulations. The used FFP2 face masks are disposed of with other plastic medical waste. Nearly all of the used medical supplies end up in a waste incinerator. According to the answers of the hospitals to the questions sent (appendix A), one can assume that the MPs leaking into the environment from hospitals are negligible.

3.1.12 Visualisation of product chain of FFP2 face masks

Figure 3.12 shows a visualisation of the supply chain of FFP2 face masks. Orange blocks show the processes where plastic emission to the environment takes place. These are the processes that should be analysed with MSA to quantify the emissions.

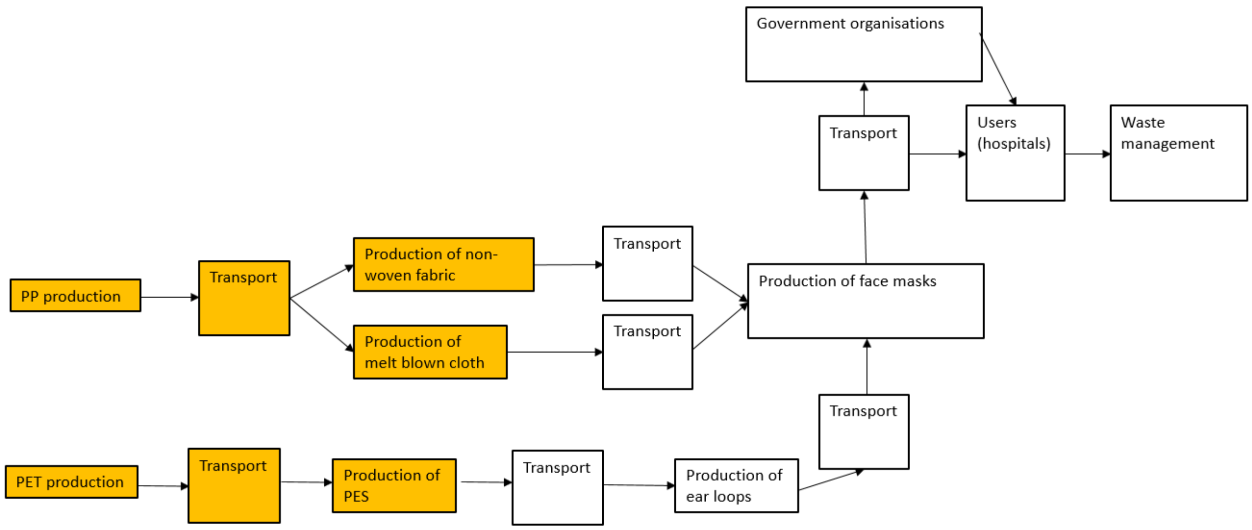

Figure 3.12: visualisation of the supply chain of FFP2 face masks. The orange blocks represent the processes where plastic emissions occur to the environment that are not totally eliminated by waste management

3.2 Material System Analyses

After collecting all data, information, survey results and the information of the supply chain using the SCOR model, two MSA's were constructed for type I and FFP2 face masks. The flow diagrams of the MSA's can be found in figures 3.13/3.14/3.15. The following sections describe step by step the steps taken to structure and quantify the plastic flows in the complete product chain of type I and FFP2 face masks in an MSA.

Both MSA's were calculated through the same calculation process. The quantification was done by calculating the flows and stocks of plastic masses from data from the user phase and percentages of material loss (see 3.2.1 and appendix A). The structure of the following MSA's does differ. The structure of the type I mask is based on the calculation process. This process begins in the consumption phase of the product chain, with the usage of type I masks in the Netherlands. The MSA of FFP2 masks is structured along with the three main phases of the product cycle in an MSA: input of plastics (the production of plastics), the consumption of plastics (the use of plastics to produce materials, masks and the use of the masks) and the output of plastics (into stocks, incineration and the environment).

3.2.1 MSA of Type I medical face mask

As described before, the most important aspect of a MSA to identify plastic emission locations, is the principle of mass balance. The amount of plastics going into the system needs to be in balance with the plastics going out of the system. When the mass input and output does not match, hidden leaks to the environment can be identified. An overview of the most important calculation results in constructing this MSA is summarised in table 2. The following sections describe step by step the different steps taken to get the calculation results to structure and quantify the plastic flows in the complete product chain of a type I medical face mask in a MSA.

Table 2: Summary of the calculation results used to construct the MSA for the product chain of type I medical face masks during one pandemic year in the Netherlands.

Type of calculation	Result	Type of calculation	Result
Type I face mask users (millions)	6.8	Complete plastic input (tons)	6,828
Mean number of weekly used face masks	3.5	Complete plastic output (tons)	6,714
Total annual used face masks (millions)	950.0	Annual pellet loss (tons)	3
Average face mask mass (g)	3.8	Annual plastic emission in consumption stage (tons)	111
Plastic used in face masks annually (tons)	3,700.0	Total plastic emission to environment (tons)	114
Stocked face masks (tons)	2,800.0		

In order to meet these criteria, the first step in structuring the MSA is to calculate the mass of plastics in one type I face mask and how many type I face masks are actually needed for the described scenario.

Calculation of plastic masses in type I medical face masks

The data received from the site visit to the face mask producer about the characteristics and masses of the materials used to fabricate the type I medical face mask is shown in table 3.3. and are similar to the masses shown in the study of Wang et al, (2020). The actual amount of plastic in one face mask is slightly different from table 3.3 because the percentage of production losses are not calculated yet, but are important in quantifying the exact amount of plastic in the environment.

With a production loss rate of 5% of the fabrics used to make the face masks, the mass of one face mask is 3.8 g. The plastics in one face mask are divided between PP and Polyester (ear loops). 87% of the face mask consists of PP, 13% consists of polyester.

Calculation of the plastic amount of all face masks used

The results from the mass plastic needed in one face mask and the results from the survey were used to calculate how many type I face masks are used every week and how much mass plastic is equivalent to that amount. The results from the survey indicate that about 45% of the general population wear type I face masks. With a face mask acceptance rate of 100%, this is equivalent to 6.8 million people who wear type I medical face masks.

The next step to calculate how many face masks are used by the population in the Netherlands is to calculate the amount of type I masks that are used every week. This quantification may vary depending on the duration of mask usage, degree of people's hygiene, visited places etc. However, a mean mask usage is calculated from these results to 3.5 type I masks usage per week. This means that for a population of 6.8 million people, 23.8 million type I face masks are used every week (950 million annually). Considering the mass of the mask (3.8g), this would mean that 90.9 tons of plastics is used every week by the population in the Netherlands and 3,700 tons of plastics for a whole pandemic year.

Littering mass

As described before, the consumer of the face mask emits plastic to the environment by causing litter. The plastic emissions caused by littered face masks seems significant. Different studies assumed a plastic littering rate of 3% of the total plastic waste generation, across all countries during non-pandemic times (Law et al., 2020; Ocean Asia, 2020; Jambeck et al., 2018). 3% of 3,700 tons means that 111 tons of plastics from littered face masks is expected to stay in the Dutch environment annually and will eventually degrade into MPs.

Retail

Consumers get the face masks from different distributors. The distributors consist for example of retail sellers like drug stores and supermarkets. In this study it is assumed that during a pandemic year the amount of face masks bought by distributors are all sold and used by consumers. No plastic emissions are found during this stage in the product chain.

Stock

During Covid-19 face masks were also bought up by the Dutch government to stock them to ensure there will be sufficient face masks in crisis situations. It is called the National Consortium of Medical and Personal Resources (LCH). In 2021, more than 700 million surgical face masks are in stock. This distribution process is unlikely to cause plastic emissions to the environment but needs to be taken into account to describe the complete plastic flow. 700 million type I face masks is equivalent to 2,800 tons of plastics being stocked.

Production process and waste

The amount of face masks stocked and distributed are produced in the Netherlands or imported from other countries like China (Eurostat., 2020). The production process in the Netherlands is exactly the same as in China. The same fabrics, the same techniques and the same machines are used in both countries. Therefore, production of face masks in the Netherlands and in China are not distinguished in this MSA.

Hardly any waste occurs during face mask production (Lee et al., 2020). There are no emissions of plastics directly to the environment. The rejected face masks during fabrication and fabric that is not needed for the face masks are disposed of directly as waste in a bin next to the production line. The waste accumulates to approximately 5% of all the used plastics (Lee et al., 2020; site visit, 2021). The amount of plastics used to fabricate the distributed Type I face masks and the face masks in stock (1.6 billion pieces) is equivalent to 6,825 tons of plastic.

Intermediary facilities and input

As described in section 3.1.2 intermediary facilities where plastic pellets are moulded in the different plastic products used to manufacture the type I face masks, do contribute to plastic emission directly into the environment. The total amount of PP used in one face mask is 3.3g which is equivalent to 87%. The type I surgical face mask consists of 13% of the total face mask of PET (ear loops). It means that the intermediary facilities that make the ear loops material and the polypropylene cloth needs 87% PP pellets and 13% PET pellets to fabricate the face mask. The direct emissions of pellets into the environment is between 0,010 -0,040% with an average of 0,025%. We assumed that the rest of the 99.975% of the pellets are all moulded into plastics and no waste is accumulated here. The total mass of pellet losses for the production of type I medical face masks for the Dutch population is 3.4 tons of plastic emission annually.

Waste

According to the results of the survey all users of type I medical face masks dispose of the face masks in general household waste. The current general product chain of face masks does not include a recycling route or a particular waste management system. The face masks together with the household waste is collected and burned in incinerators in the Netherlands. The national waste reporting point (LMA) assured that the plastics in the face masks are burned so no plastic emissions are expected in these last steps of waste management.

From plastic to MPs.

The phenomenon of MPs being released from type I face masks to the open environment compounded by natural weathering was explored in multiple studies (Wang et al., 2021; Liang et al., 2021; Saliu et al., 2021). According to the research, it is plausible that a mask dumped in the environment may completely degrade into microscopic fibre fragments and aggregates in less than two years under extreme conditions (Saliu et al., 2021). Other studies find that it could take 450 years before a face mask is completely degraded into MPs. Wang et al. (2021) found that 1.5 million MPs can be released from the weathered mask (Wang et al., 2021). Sand and mechanical abrasion (waves) are important factors influencing the speed of the degradation.
In this study, the amount of plastics emission to the open environment is estimated at 114.4 tonnes. A part of those plastics takes years to degrade into MPs and a part, the pellet losses, are directly emitted as MPs. Since 114 tons of plastic corresponds to around 30 million littered type I face masks it can be estimated that 45 billion MPs are released in our environment from the littered face masks alone.
MPs released through inhalation were significantly lower than those released to the environment. Therefore, we left this flow of emission out of the study.

3.2.2 Complete Material System Analysis of type I medical face masks in the Netherlands

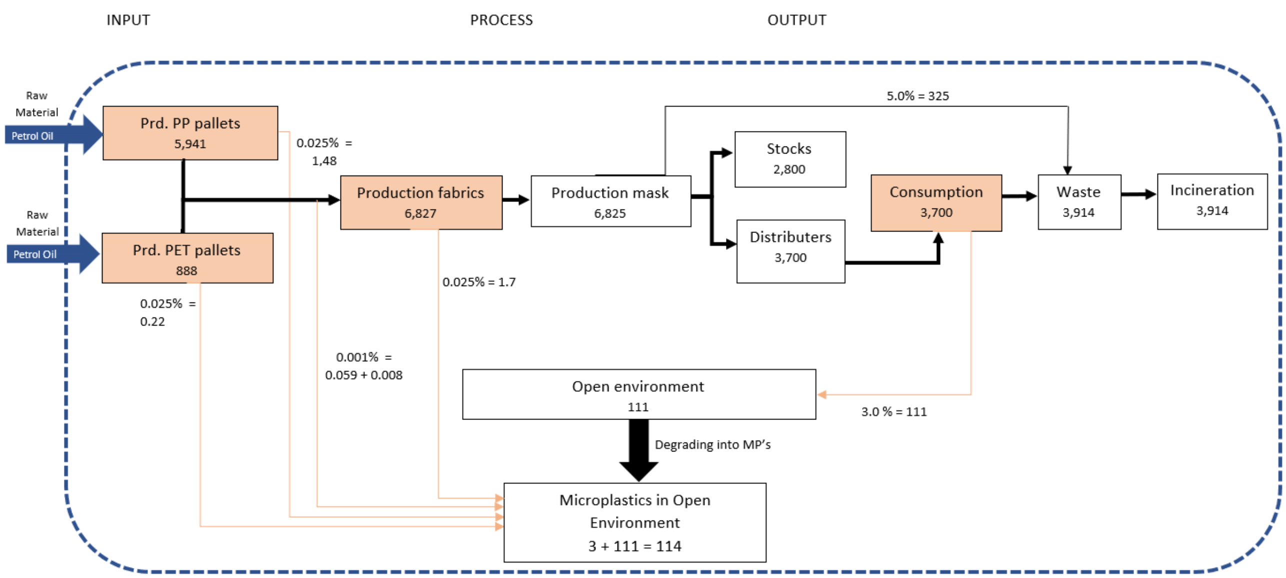

Figure 3.13: The complete Material System Analysis of Type I medical face masks in the Netherlands, calculated in tons (micro) plastic annually. The orange sub-processes and arrows are identified plastic emission stages and flows in the product chain.

3.2.3 Material System Analyses of FFP2 face masks

In the Material System Analyses of FFP2 face masks, we distinguish three separate stages in which microplastic emissions could take place: the material input, material consumption and material output stages. The following section is structured along these three stages.

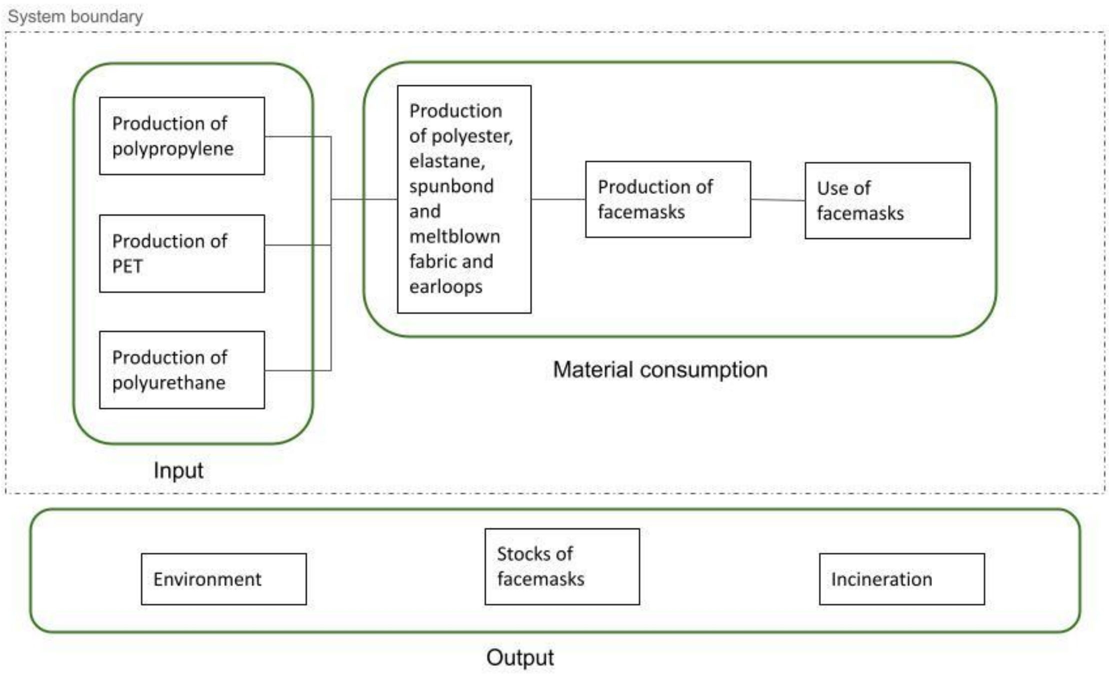

Fig 3.14: The processes in the life-cycle of FFP2 face masks and their MSA stages.

3.2.4 Plastic inputs

The material inputs into the system are the plastics that are used to produce the materials used in FFP2 face masks: polypropylene, polyethylene terephthalate (PET) and polyurethane. Losses of MPs occur during the production process of the plastics (table 3.1). These losses occur in the form of pre-production plastic pellets. Pellets that end up being spilled into the environment are not always cleaned up, because they are small and relatively expensive to clean up (Hann et al., 2018). A financial incentive for producers to remove the pellets from the environment does not exist either. This is because the pellets lose their worth and become waste when they have been spilled as they are considered to be contaminated (Hann et al., 2018). It is thus reasonable to assume that most pellets that are spilled into the environment will stay there. As most of the plastics used for the production of FFP2 face masks come from China, most pellet loss will likely occur in China. Pellet loss during transport can occur during the journey from China to the Netherlands.

The exact quantities of pellets that have been, and are, lost to the environment is still unknown. Attempts at quantifying the losses are made through the formulation of 'loss rates'. These 'loss rates' consist of percentages of plastic pellets that are lost to the environment. For this research, we have used percentages of 'loss rates' that have been mentioned in a report made by an independent sustainability consultancy firm for the European Commission (see table 3.1.) (Hann et al., 2018). The authors of this report based their 'loss rates' on a report by the Danish Environmental Protection Agency (Lassen et al., 2015). The loss rates are formulated for Western Europe. According to Ryberg et al. (2019) losses of plastic that occur during production are roughly the same in Western Europe as in China. Therefore, we can use these 'loss rates' for Western Europe as an approximation of pellet loss in China. It is important to know that 'loss rates' of pre-production plastic pellets are highly uncertain as there is little empirical evidence available to formulate them (Hann et al., 2018). Because 'loss' rates are highly uncertain, both the minimum and the maximum loss rates are used in the MSA of FFP2 masks (figure 3.15).

3.2.5 Plastic consumption

In the consumption phase of the product chain, plastics are used. PET and polyurethane are first used to produce two additional types of polymers. Then all plastics are used to produce the materials that are part of the face masks. These are melt-blown fabric, spun-bond fabric and ear loops. These materials are then used to produce the face masks. The final process in the use stage is the use of the FFP2 face masks by healthcare personnel in Dutch hospitals.

Production of materials

As stated in chapter 3.1.9, the FFP2 face masks consist of three different materials: melt-blown fabric, spun-bond fabric and ear loops. The mask itself has five layers: an inner and an outer layer made from spun-bond fabric and three filter layers made from melt-blown fabric. The inner and the outer layer of the FFP2 face mask are made from spun-bond fabric that is made from polypropylene (Ma et al., 2021). In the production of this fabric, plastic pellets are used, which leads to pellet loss (table 3.1). The filters of the mask are made from polypropylene melt-blown fabric. In the production, polypropylene pellets are used which could lead to pellet loss. The fabric is made up of thin plastic fibres with a diameter between 1 and 5 μm (Li et al., 2021). These fibres are short, and with their size fall into the category of MPs (Ma et al., 2021). Ma et al. (2021) wrote that the fabric is relatively fragile. This could mean that the fabric could release microplastic fibres. Possible microplastic emissions from spun-bond and melt-blown fabric have not been quantified yet.

The face masks have ear loops to position and hold the mask on the face. For the production of ear loops, two additional types of plastics need to be produced first: polyester and elastane. Polyester is made from PET pellets. Elastane is made from PET and polyurethane pellets. During the production process of the additional plastics, pellets of PET and polyurethane are handled, which leads to pellet loss. Each earloop consists of 87% polyester and 13% elastane. Most studies on microplastic emissions from face masks focus on losses from the fabric layers of the face masks. We have not found any information on the release of MPs from the production of ear loops.

Production of face masks

The materials that are made from plastics are used to produce face masks.

We have made an estimation of the number of FFP2 face masks ordered by Dutch hospitals in 2020. The calculated number was 12.5 million FFP2 masks (see appendix A) for the calculation). For the production of 12.5 million FFP2 face masks, 91,8 tons of plastic was needed. In reality, more plastic was used in the production of the masks than the number of plastic particles that the masks contain. This is because there is plastic pellet loss.

Material waste happens both during and after the production of materials and during and after the production of face masks. In the factory we visited that produces FFP2 face masks, 15% of every roll of fabric was lost as waste after cutting out the shapes of the face masks. This means that more plastic and more fabric was produced than was used for the production of the face mask.

As stated in chapter 3.1.9, FFP2 face masks need to abide by strict quality requirements. Not all produced face masks meet these criteria, which means that they are not allowed to be sold or used. The manufacturer of FFP2 face masks we contacted said that 15% of all produced FFP2 masks did not pass quality control. This means that 15% of all produced FFP2 face masks, and their plastic content, become waste.

Use of FFP2 face masks

In this study, we look at the use of FFP2 face masks in Dutch hospitals. The Dutch Federatie Medische Specialisten recommends that the FFP2 face mask should be worn when healthcare workers come in direct contact with suspected or confirmed patients with symptomatic Covid-19 (Federatie Medisch Specialisten, 2021). The usage times of the masks differ between hospitals (see table 3.6). An FFP2 face mask is worn for a maximum time period of three hours, but it can be worn for a shorter period of time when the hospital's policy is to replace it after every visit to a symptomatic Covid-19 patient. As FFP2 masks are intended for single-use, the short usage time results in a relatively large amount of waste generation. With data we gathered from three hospitals we calculated that Dutch hospitals used an average of about 10,5 million FFP2 face masks in 2020 (see appendix A for the calculation).

The use of FFP2 face masks can release MPs. These MPs can end up in the environment by becoming airborne, or they can be inhaled by the mask wearer. The number of MPs released from a face mask during wearing is partly determined by the behaviour of the wearer. Breathing rapidly releases the most microfibres, followed by talking and breathing, and breathing alone releases the least MPs (Ma et al., 2021).

Interestingly, wearing an FFP2 face mask seems to reduce the number of MPs inhaled by a person. MPs are already around us in the air we breathe, and the filter of an FFP2 face mask can prevent these airborne MPs from being inhaled. Li et al. (2021) discovered in their research that the inhalation risk of MPs is higher for people that don't wear a face mask than for people that wear any form of face mask. After 720 hours of face mask usage the inhalation risk of microfibers shifts, and only the use of a N95 face mask results in a lower risk of microfiber inhalation (Li et al., 2021). A N95 mask has a similar filter efficiency as a FFP2 mask, with the filter efficiency of a N95 mask being 95% and the filter efficiency of a FFP2 mask being 94%. Outcomes of studies done on N95 masks can thus be used as an approximation of FFP2 masks. It is thus likely that after 720 hours of FFP2 face mask usage the risk of microfiber inhalation will also be lower than when using another, or no mask. The fact that for type I/II the risk after 720 hours is higher than the risk when wearing no mask suggests that the type I/II masks release microfibres. For particle-like MPs, the order of inhalation risk stays the same after 720 hours. Figure 3.5 shows the order of inhalation risk of microfibers and particle-like microplastics. According to Li et al. (2021), it is likely that only a low percentage of the possible inhaled fibre MPs are released by the mask themselves.

Table 3.5: Inhalation risk of MPs. Adapted from (Li et al., 2021).

Duration of experiment	**Order of inhalation risk of microfibers**	**Order of inhalation risk of particle like MPs**
2 hours	No mask > Type I/II mask > N95 mask	No mask > Type I/II mask > N95 mask
720 hours	Type I/II mask > No mask > N95 mask	No mask > Type I/II mask > N95 mask

Table 3.6: The use and waste management of FFP2 face masks in Dutch hospitals.

	Hospital A (top clinical hospital in the East of NL)	**Hospital B (university hospital in the middle of NL)**	**Hospital C (top clinical hospital in the North of NL)**	**For all Dutch hospitals (115)**
When are the FFP2 masks used?	Direct contact with Covid-19 infected patients	Direct contact with Covid-19 infected patients	Direct contact with Covid-19 infected patients	Direct contact with Covid-19 infected patients
How long are the FFP2 masks used?	Single use with a maximum of 3 hours	Single use with a maximum of 3 hours	Replaced after every visit to a with Covid-19 infected patient	Single use with a maximum of 3 hours
How are the FFP2 masks disposed of?	Incinerated as medical waste	Incinerated as medical waste	Incinerated as medical waste	Incinerated as medical waste

3.2.6 Plastic output

The material output of the system occurs when flows leave the system. In the system of FFP2 face masks, this output consists of flows into the environment, into stocks and into waste management. In this paragraph, we will discuss intentional outputs: into stocks and into waste management.

Stocks

Not all of the FFP2 face masks that are bought are used in the same year. Because we are looking at the usage of FFP2 face masks in 2020, the masks that were not used before January 1st 2021 will be seen as being part of stocks. Both Dutch hospitals, and the Dutch government, have stocks of FFP2 face masks.

The Dutch government has the largest stock of FFP2 face masks in the Netherlands. At the beginning of the Covid-19 pandemic, there was a shortage of Personal Protective Equipment (PPE) in the Netherlands. Hospitals could not order PPE from their regular suppliers as the suppliers weren't able to keep up with the sudden increase in demand. Because PPE was necessary to protect healthcare workers from the virus, the Landelijk Consortium Hulpmiddelen (LCH) created stocks of PPE that healthcare institutions could use in the event that their regular suppliers could not provide enough materials. Hospitals are not allowed to order PPE from the LCH when they are able to order from their own suppliers (Van den Hoek & Hansen, 2021). This means that the stocks of the government barely get depleted. Suppliers increased their supply relatively early in 2020. Consequently, hospitals did not have to order from the LCH anymore (Hendrickx & Kreling, 2021). At the time of writing this report, it is reported that the Dutch government has a stock of 43 million FFP2 face masks (NOS, 2021). Hendrickx & Kreling (2021) wrote that on the basis of the current demand, this stock is enough for the next half-century. The stock is expected to increase, as the Dutch government still has contracts with FFP2 face mask manufacturers until 2022.

A major problem with this large stock is that FFP2 face masks have a limited shelf life (Hendrickx & Kreling, 2021). The face masks degrade over time. For example, the ear loops become looser which affects the fit over the face (3M, 2016). This, as well as the possible degradation of the filter layers, means that expired face masks do not meet the certification guidelines anymore and cannot be safely used. The shelf life of FFP2 face masks differs between manufacturers and varies from one to five years (Hendrickx & Kreling, 2021).

The LCH is not allowed to give the masks away for free, as this is seen as a market disturbance by the government. Therefore, part of the stock is being sold to foreign buyers for a lower price than they were bought for (Van den Hoek & Hansen, 2021). According to Van den Hoek & Hansen (2021), some of these bought face masks end up in the Netherlands again when foreign buyers sell them to Dutch customers. The FFP2 face masks that are not sold or donated to charities will likely be disposed of through incineration (Hendrickx & Kreling, 2021).

We assume that the stocks of face masks in hospitals will be used before they reach their expiration date. This means that, at least in the near future, there are no unused FFP2 face masks that end up as waste in hospitals.

Waste

FFP2 face masks are intended for single-use and thus are disposed of after having been used once. Dutch hospitals process their infectious plastic waste, including used FFP2 face masks, according to government guidelines. All infectious plastic waste has to be incinerated (Das et al., 2021). The World Health Organisation determined that this has to happen at temperatures between 900 and 1200 ℃ (Das et al., 2021). Waste from manufacturers, like the 15% fabric waste and 15% rejected face masks, gets incinerated as well. During incineration, plastics are completely broken up and destroyed (Landelijk Meldpunt Afvalstoffen, 2021). This means that all materials containing plastics (fabrics, ear loops and entire face masks) that get incinerated, release no MPs in their end-of-life stage.

3.2.7 Total plastic emissions of FFP2 masks

In the flowchart (fig 3.15) the emissions of MPs from FFP2 facemasks used in Dutch hospitals in 2020 are quantified. See appendix A for the calculations. This flowchart does not show the flows of polyurethane and elastane, as these flows are so small that they are negligible (see Appendix A).

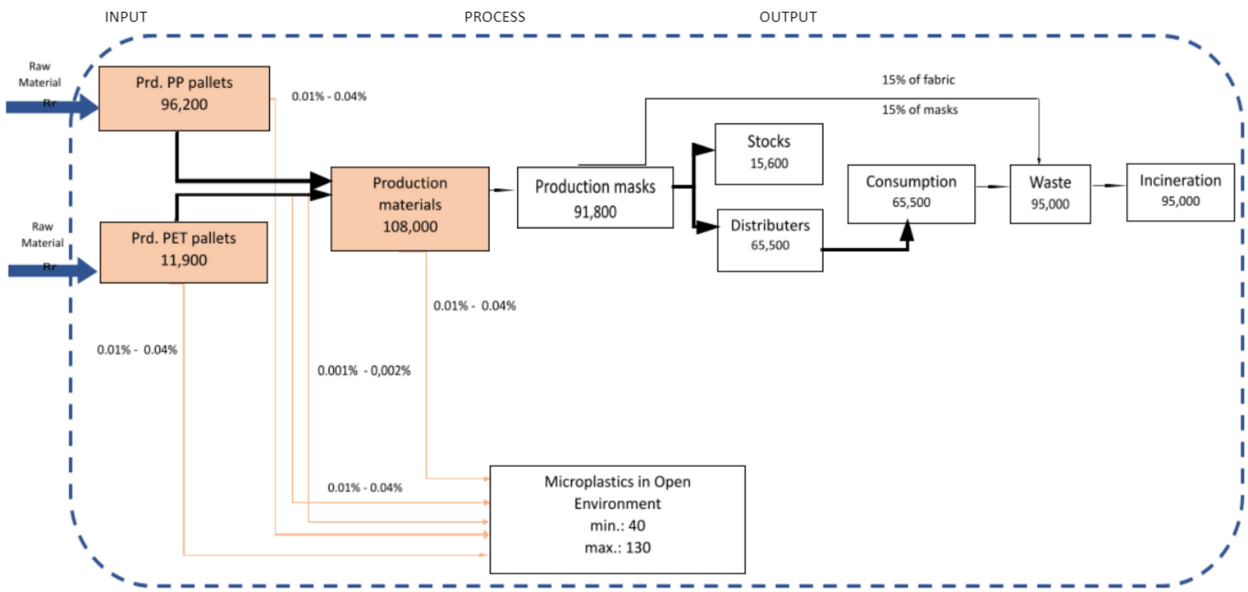

Figure 3.15: minimum and maximum percentages of flows of plastic emissions in kg/year in the life cycle of FFP2 face masks used in Dutch hospitals.

3.2.8 Total plastic emissions

The results on the sources and relative sizes of microplastic emissions during the product chains of type I and FFP2 face masks are summarised in table 3.7.

Table 3.7: The processes in the life-cycle of face masks in which microplastic emissions take place.

Microplastic emissions	Type of MPs released	During the life-cycle of type I masks	During the life-cycle of FFP2 masks	Relative size of emission compared to those of other sources in the product chain
During the handling of plastic pellets in production facilities	Primary	x	x	Medium
During the handling of plastic pellets in intermediary facilities (such as distribution centres and storages)	Primary	x	x	Medium
During the transport of plastic pellets	Primary	x	x	Small
During the handling of plastic	Primary	x	x	Medium

pellets in material manufacturing facilities				
During the use of face masks	Secondary	x	x	So small as to be negligible
During the weathering of facemasks in the environment	Secondary	x		Large

4. Discussion and Conclusions

4.1 Discussion

4.1.1 Changing policies

The COVID-19 pandemic induces rapid decision making and quick adaptation to new measures. With the quantifications of MP emissions, assessments can be made on how changing policies may impact MP pollution from both type I and FFP2 face masks.

On January 14th 2022 the Dutch government made a change in the national face mask policy. The government strongly recommends the use of medical, type II and IIR, face masks and discourages wearing face masks made of cloth (for example cotton) and type I masks. Type II and IIR are seen as more effective masks than type I and cloth masks in preventing Covid-19 infection. The reason for this is that type II and IIR masks prevent inhalation of virus particles but in addition also prevent virus particles from being exhaled into the environment (Rijksoverheid, 2022b). The amount of plastic used in type II and type IIR face masks is the same as in type I masks which means that this change policy has little or no effect on the emissions from pellet loss or from the degradation of a single mask. However, the change in policy guarantees that more people will use disposable face masks, as wearing cloth masks is discouraged. According to our poll, 51.9% of the Dutch population used face masks made of cloth before January 14th (see appendix D). If everyone who wears a cloth mask starts using a medical mask, an increase of pellet loss and face masks in litter can be expected when no reduction measures are taken. Suppose that all people that wore cloth masks (51.9% of people) start using type I masks (or masks with similar plastic content) then an additional amount of 131.6 tons of MPs would enter the environment in a year according to our type I MSA. (see appendix A). Of this 131.6 tons/year, 4 tons comes from pellet loss and 127.6 tons/year comes from loss during usage (see appendix A). In this scenario, the total microplastic emissions from type I face masks used in a year would be 246 tons. An additional change in policy is that the Dutch government now recommends face masks to be worn outside when it is not possible to keep a distance of 1.5 metres (Rijksoverheid, 2022a). It is too early since the policy change to find out if this change has increased face mask litter. In theory, the litter of face masks could increase as more masks are used outside.

In many German states, citizens are required to wear FFP2 face masks in public spaces. In the case that the use of FFP2 face masks will be made mandatory in the Netherlands as well then there will be an increase of microplastic emissions to the environment. The plastic content of an FFP2 mask is higher than that of a type I mask. This means that for one face mask the amount of pellet loss and the number of MPs released from weathering in the environment will be higher. According to our type I MSA an increase of 241.6 tons/year of plastic emissions to the environment can be expected. This would result in a total microplastic release to the environment of 356 tons (see appendix A). On the other hand, FFP2 masks are more expensive than the masks that are now used in the Netherlands. This could lead to behavioural changes like wearing the same mask more often which would result in less production and waste and thus less microplastic emissions.

Sooner or later, all measures relating to face mask use in the Netherlands will cease. When this happens, type I face mask use will quickly decrease. However, the possibility exists that people will continue wearing face masks in public. In countries in Eastern Asia, for example, the use of face masks in public areas to protect viral infections from spreading has been embedded in the culture since long before the Covid-19 pandemic. Masks are used to prevent flu infections and to protect against allergens and air pollution. People in the Netherlands may have experienced these advantages and can choose to keep wearing face masks in the future. It is sure that the microplastic emissions will significantly lower when the demand for face masks becomes lower. Total annual microplastic emissions may become so small as to have masses in kg's or even in grams. When this happens the emissions are so small that mitigation efforts are not needed anymore.

In time, the number of Covid-19 cases in hospitals will decrease. When there are fewer patients with Covid-19 in hospitals, the number of FFP2 face masks used will decrease as well. Eventually, hospitals may use a similar number of FFP2 masks than before the pandemic. It is possible that for a short period of time more FFP2 face masks will be used than before the pandemic, as hospitals will try to use up stocks with a limited shelf-life. This will not result in more MPs emissions as these only occur during production, and the use of masks from stocks does not result in increased production.

4.1.2 Proxies

One of the purposes of this study was to find possible proxies to swiftly identify MPs emissions. A lot of thought was put into this but it turned out to be quite difficult to do. We have identified a couple of possible proxies that could be used in future research.

Thanks to our data collection and survey, we identified hot spots such as bus stops, supermarkets, bike paths and sidewalks. Also, population density, waste management and infection rate seem to be important factors of whether face masks end up in litter and in which numbers. Policy measures regarding the use of face masks change rapidly and also influence the number of face masks that end up in the environment, thus also influencing the number of face masks that can degrade into MPs. Furthermore, these policy changes can also affect MP pollution earlier in the production chain when decreasing or increasing the manufacturing of materials. The culture and institutions in a specific area are also of importance. If the population of a country is more or less inclined to follow policy measures, this will have an impact on the emission of MPs into the environment.

Sand abrasion and weathering are expected to influence the speed of MP release in face masks as friction is an important aspect of the release from MPs in many plastic products (Wang et al., 2021; Sullivan et al., 2021). Therefore, areas where (natural) friction is expected, could function as a proxy to identify critically (micro) plastic polluted areas from face masks. Examples of those possible critical areas where factors like mechanical friction and sand abrasion are high are roads with high traffic intensity and beaches. As a result, when face masks end up on busy streets and beaches, the MP emissions to the environment will likely be faster and larger. Friction can also be present during the production of plastic products. Friction as a proxy could in theory be used to find out which machine in a production process results in the most weathering and thus in the largest creation of MPs.

We find that using a combination of these variables potentially leads to a usable proxy to estimate MPs leaking into the environment. The more of these variables we can combine, the more valid the proxy will be. To find suitable proxies, we suggest that the following five variables need to be taken into account:

- Identification of hot spots and critical MP polluted areas
- Population density and waste management
- Policy measures in place
- Culture and institutions
- The presence of friction

4.1.3 Methods

In this study, we used the SCOR model and Material System Analysis. The adapted SCOR model that was used is useful in finding sources of microplastic release. The Material System Analysis is the best method to quantify the emissions. The combination of these two methods was valuable and we can recommend for these methods to be used in future research into MPs emissions from product chains as well. However, there are some comments to be made about the methods.

A detailed SCOR model can be used to thoroughly map the entire supply chain. Quantification of the processes in every step of the chain could possibly provide a better overview of the areas in the chain most important for MP pollution. However, we find that the data needed for quantification was lacking in this research due to the nature of the study. The advantage of using the SCOR model is that it is a standardised method. This means that comparisons can be made between product chains that have been mapped through the use of this model. In this research, the SCOR model was a good method to use as an aid to describe the processes in the production chains of the face masks. Through this description, we could find sources of microplastic emissions. The SCOR model is however not designed for scientific research. It is primarily used internally in companies or by external bodies whose goal is to improve the supply chain to the benefit of the investigated company. Using this model for environmental research purposes such as done in this study makes actors hesitant to submit the information necessary to assess their actions. Companies were not eager to provide us with data that could harm their public image. For environmental purposes, a large portion of the SCOR model's framework seems to be irrelevant. Furthermore, gathering the relevant data implies that sensitive information of a company must be retrieved. To be able to retrieve such information, one needs to provide the company with potential positive impacts on the company itself. If there is nothing to gain, companies will be reluctant to provide the necessary data. A collaboration between environmental scientists and supply chain managers might be a solution. It might stimulate mutual learning and provide both environmental scientists as production facilities and supply managers with solutions to their problems.

The Material System Analysis was the best method within the family of Material Flow Analysis to research the flows of MPs. There is no standardisation of Material System Analysis so the MSA for type I and FFP2 masks differ in their structure. We have tried to tune the methods as close as possible so they can be compared. The comparison of the MSA's shows both which sources can be present in more products and which sources could differ between products. The input data into the calculations for the MSA were not representative of the entire country. Were we to carry out the polls again, among the same people or even among different people, it is highly unlikely that we would get the same results. This limitation should be taken into account when assessing the type I MSA as the results of the polls form the basis of this MSA. However, we believe that the type I MSA is very valuable in giving an indication of possible microplastic emissions in a scenario of a one year pandemic (365 days) with flexible precautionary measures and with an assumption that the face mask acceptance rate is a 100%. The FFP2 MSA is based on information gathered from hospitals. This information can be regarded as reliable. The assumptions made on face mask use in the FFP2 MSA (three responses for 115 hospitals) are smaller than in the type I MSA (136 responses for around 17 million people). Based on this alone, the FFP2 MSA is slightly more reliable than the type I MSA.

4.1.4 Data availability

The data and information collection efforts were considered very successful. We managed to get useful information and data to answer our research questions. Among these were the data from street litter collectors, water authorities and the data and information that was gathered during the site visits of the face mask factories. The site visits were very valuable as detailed online data on the materials used was not available. The polls on face mask usage by Dutch consumers was very valuable in determining the number of face masks used and the number of face masks lost to the environment. Literature research also resulted in good reliable information about many subjects, such as the production processes of materials and percentages of pellet loss at different stages of the production chain of pre-production pellets.

Direct data and information from face mask- and material manufacturers from abroad, other than websites and youtube video's were not found because our requests were not answered. This wasn't considered a limitation in the end because the data and information we gathered from the Netherlands could be used as a model for the overall production processes (see table 4.1). Gathering data from hospitals also proved to be difficult because during our study the hospitals were preoccupied handling the covid pandemic in their hospitals. However, the gathered data from the three hospitals was reliable enough to get an indication of the microplastic emissions in the product chain of FFP2 face masks.

Table 4.1: Approached parties through telephone, e-mail and polls.

Contacts	Approached	Reacted	Percentage of reactions
Producers of face masks (IIR, type I,II and FFP2)	7	3 Of which 2 site visits	40%
Collectors of street litter	4	4	100%
Water authorities	3	2	67%
Hospitals	11	3	27%
Authorities on waste products	2	1	50%
Face mask distributors	5	1	20%
Poll on usage of masks via LinkedIn		136	
Poll on usage of masks at TAUW (company)		107	

4.1.5 Relevance of the study

4.1.6 Suggestions on microplastic emission mitigation

With the help of the gathered data, we can formulate useful suggestions for mitigation strategies to reduce microplastic emissions.

Over 90% of the melt-blown substances used today derive from PP (Yu et al., 2015). As stated previously, the downside of this product is not only its persistence in nature but also its limited and polluting source (fossil fuels). An alternative is to use biopolymers instead of synthetic polymers. A study conducted by Shafari, Shim & Joijode (2021) found that the use of polylactic acid for melt-blown filter media showed similar filtration efficiencies as PP. They even showed that for the same fibre diameter, polylactic acid has an even higher filtration efficiency. However, technological advances have to occur to make melt-blown filter material with the same fibre diameter as PP filters. It is important to notice the potential of polylactic acid. It is derived from renewable sources, it is biodegradable which removes the contribution of MPs to the environment completely, and there is a potential to produce filters with an even higher filter efficiency and breathability in the future.

As a result of the accumulation of plastics in the environment due to their properties, the use of biodegradable PP in face mask materials such as filters and inner -and outer layers can be considered. Biodegradable PP contains an organic additive. This additive contains hydrophilic parameters. These alter the polymer chain and allow enzymatic action to reduce the structure of the polymers (Miyazaki et al., 2012). This helps to break down the PP into CO_2. However, a study by Samper et al. (2018) found that when PP and biodegradable PP are recycled together, it reduces the quality of the secondary products. This is something to keep in mind whenever one decides to use biodegradable PP in a product. Actions in waste disposal of the said product need to be altered to not interfere with recycling processes.

Integration of environmental objectives in the SCOR model. The supply chain is mapped using the SCOR model. When all businesses involved in the production, handling and processing of the MPs commit to a set of guidelines that prevent MP losses, a significant reduction of MPs entering the environment is possible. These guidelines need to be specified by environmental scientists in collaboration with the industries. Reporting and auditing are key elements to make such an initiative successful (OSPAR, 2018). Another option is that this set of guidelines become a regulation for companies to comply with. This can be in the form of certification for a "zero pellet-loss"- working environment for example.

The correct use and disposal of face masks are subjected to behaviour. In hospitals, this behaviour is controlled and regulated by the internal guide of such enterprises. In daily life, opportunities such as waste bins near hotspots where face masks are mandatory should be provided. However, these opportunities are already established in the Netherlands because of campaigns to reduce litter in general. Informational campaigns regarding accidental loss of face masks can reduce the number of masks found in litter.

Although public waste disposal opportunities in the Netherlands are already fairly well established, an option could be to provide designated face mask disposal bins near exits of areas where face masks are mandatory. Examples are at exits of shopping malls, supermarkets and stations. Creating a type of recognisable mascot advertised in the media can enhance the compliance of the general public to discard of the items properly. Another benefit this has is that face masks are separated from the rest of the waste (see fig 4.1). This creates opportunities for recycling. Plaxtil, TerraCycle and Interall Group are examples of start-ups that collect, sterilise and mould medical face masks into secondary products like garden furniture, other PPE or primary plastic pellets, enhancing the circularity of the face masks. But, medical face masks are difficult to recycle. The machines used are expensive and the number of face masks that can be processed at the same time are low in comparison with the face masks used every day by the general population. Another difficulty is that infectious waste, such as used face masks from hospitals, are by law required to be incinerated. Options to (cost) efficiently and safely recycle face masks into secondary products could be further researched.

Figure 4.1: Example of a recognizable disposal bin for medical face masks near hotspots (TerraCycle)

The discussed measures are suggestions. Additional research is needed to give a well-developed advice about measures. As certain measures such as the separate waste collection of face masks are costly, a cost-benefit analysis should be performed on the possible measures. A small scale pilot project on face mask collecting measures could be part of such an analysis. Waste collection is a key element here. According to Dirk Groot, who collects and inventories waste, face masks were the third most found object in litter in January '22. This is based on the waste collection in 5 municipalities in the Netherlands (Groot, 2022). The inventorisation of litter provides us with information on two important aspects. Firstly, it provides us with the relative weight of the problem compared to other problems. As face masks have quickly risen to the third most found object in litter, we must acknowledge that it is a potential new environmental hazard. However, we need to be aware that this situation is temporary and that the use of face masks will most likely decrease significantly in the near future. Secondly, it can provide us with data on how effective measures are. For example, according to Dirk Groot's waste collection, the number of plastic bottles found in litter is steadily decreasing since the implementation of deposits on plastic bottles (Groot, 2022). Therefore, monitoring face masks in street litter after possible implementation of waste management measures or behavioural education is recommended to measure the effect of the mitigation measures.

4.2 Conclusions

In this study, we aimed to discover where in the product and environmental chain of type I and FFP2 face masks emissions of MPs take place. There are three distinct phases in the production chain of the masks where microplastic release can take place: during the production stage, the usage stage and the end-of-life stage.

For type I masks most microplastic emissions take place during the waste management stage. Waste that is not carefully managed, such as litter, can completely degrade into MPs in the environment. In our researched scenario 111 tons of plastics are released into the environment due to litter of type I masks. During the production stage, the pre-production pellet loss is a significant source of microplastic emissions. Pellet loss accounts for a smaller, but relevant, amount of microplastic emissions in the product chain of type I masks: 3.4 tons in the researched year. The total microplastic loss from type I masks is 114.4 tons of plastics.

The total plastic loss during the product chain of FFP2 face masks is notably lower compared to the emissions of type I masks. The total microplastic loss from FFP2 masks used in Dutch hospitals in 2020 was between 41 and 131 kgs. Unlike in the product chain of type I masks, there was no microplastic loss during the usage stage of FFP2 masks. The total microplastic emissions are solely caused by pellet loss.

In both production chains, there were no microplastic emissions from waste processing. During both product chains, the collected waste of materials and masks gets incinerated. Most type I face masks end up in household waste and in the Netherlands all of this waste is incinerated. FFP2 masks get collected in hospitals as ‘medical waste’ which is required by law to get incinerated as well. Incineration of materials and masks destroys all plastics which means that no microplastic emissions occur as a result of this. This means that the face masks that are properly disposed of do not release MPs in their end-of-life stage. However, FFP2 face masks could potentially release more MPs than type I face masks if they do end up in the environment. The reason for this is that FFP2 face masks contain two more filter layers, which means that the mask contains more plastic in total.

In this research, we aimed to discover proxies that can be used to swiftly identify MPs emissions. We found a combination of variables can be used as a proxy to estimate the mass flow of MPs leaking into the environment. The more of these variables are combined, the more valid the proxy will be. The following five variables can be combined into a proxy:

- Identification of hot spots and critical MP polluted areas
- Population density and waste management
- Policy measures in place
- Culture and institutions
- The presence of friction

Government policies affect face mask usage. This in turn affects microplastic emissions. Policies can lead to an increased usage of face masks or the usage of different types of face masks. Using more face masks leads to more microplastic emissions and using face masks with a higher plastic content will increase microplastic emissions as well. Currently, in the Netherlands it is discouraged to wear cloth face masks. In the event that every person that wears a cloth face mask would start wearing a type I face mask, an additional 131.6 tons of plastics would enter the environment in a year. The total microplastic emissions from type I masks would then be 246 tons/year. If, as is the policy in many German states, only FFP2 masks are allowed to be worn, 356 tons of plastic would enter the environment annually.

Research into microplastic emissions from face masks is a still developing research field. More research can improve quantitative analyses of microplastic emissions.

5. Suggestions for further research

Given certain assumptions on the calculations of the data in this research, the number of users of FFP2 masks in the general public is considerably higher than the number of users inside a hospital. A more in-depth investigation on who wears these types of face masks, when they use them and how often could provide a better overview of whether FFP2 face masks can be considered to contribute significantly to MP pollution. Especially a comparison with other types of face masks is evident, as the difference between both is easily visible. This is not the case between for example Type I masks and IIR masks.

An important limitation in this research is the calculation process of the amount of type I/II medical face masks and FFP2 face masks used by the population in the Netherlands. It is based on two different described scenarios and results from an online survey. A more veracious and reliable MSA should be based on mathematical formulas with representative variables. For example in the study of Chowdhury et al., (2021) where daily face mask usage depends on coastal population percentage, mask acceptance rate by the general population, and the number of face masks used by an individual. If the calculation process is based on a survey, the survey questions and survey population should be constructed and chosen carefully to get valid and reliable results.

MSA is a common approach to model and quantify flows and stocks of plastic materials. Different software products exist for quantification. For example, OMAT, STAN or DPMFA. Using a software program for MFA or MSA improves its reproducibility and usability (Kawecki, et al., 2021). The MSA's in this research were not constructed using specific software programs but were constructed in PowerPoint. Therefore, the reliability of the MSA's in this research is questionable. It is recommended for further research that to construct a reliable and usable MFA or MSA one of the software programs should be used. This use of this specific software could be a useful tool to make scenarios of what the impact of different policy measures regarding the use of face masks could mean for MPs' pollution.

From the results of this research, it became clear that the microplastic emissions during the production stage are small in comparison to emissions during the usage and waste stages. This is a result that is supported in other literature as well (Ryberg et al., 2019). Therefore it can be recommended to only search for significant sources of microplastic emissions in the usage and waste management stages when looking for the largest microplastic emissions in the production chain of a product. However, it is interesting to look at the production stage of a product when a high concentration of MPs is found near a production facility, as it is reasonable to assume that this high concentration is connected to the presence of the production facility.

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Appendix A: Calculations for the FFP2 MSA

Amount of FFP2 face masks used in Dutch hospitals in 2020:

Table A.1 — The amount of FFP2 face masks ordered and used by Dutch hospitals.

	Hospital A	Hospital B	Hospital C	Average	For all Dutch hospitals
Number of FFP2 masks used pre-Covid-19 in a week	540	236	≈ 57	≈ 277	≈ 31,900
Number of FFP2 face masks used during the Covid-19 pandemic in a week	1 week: 6350 Other weeks: 1600	≈ 2143	2000	≈ 1713	≈ 197,000
Total FFP2 face masks used in 2020	Estimation of use: 77,900	Ordered: ≈ 113,600	Ordered: 100.000 Estimation of use: 84,600	Estimation of use: 92,000	Estimation of use: 10,500,000

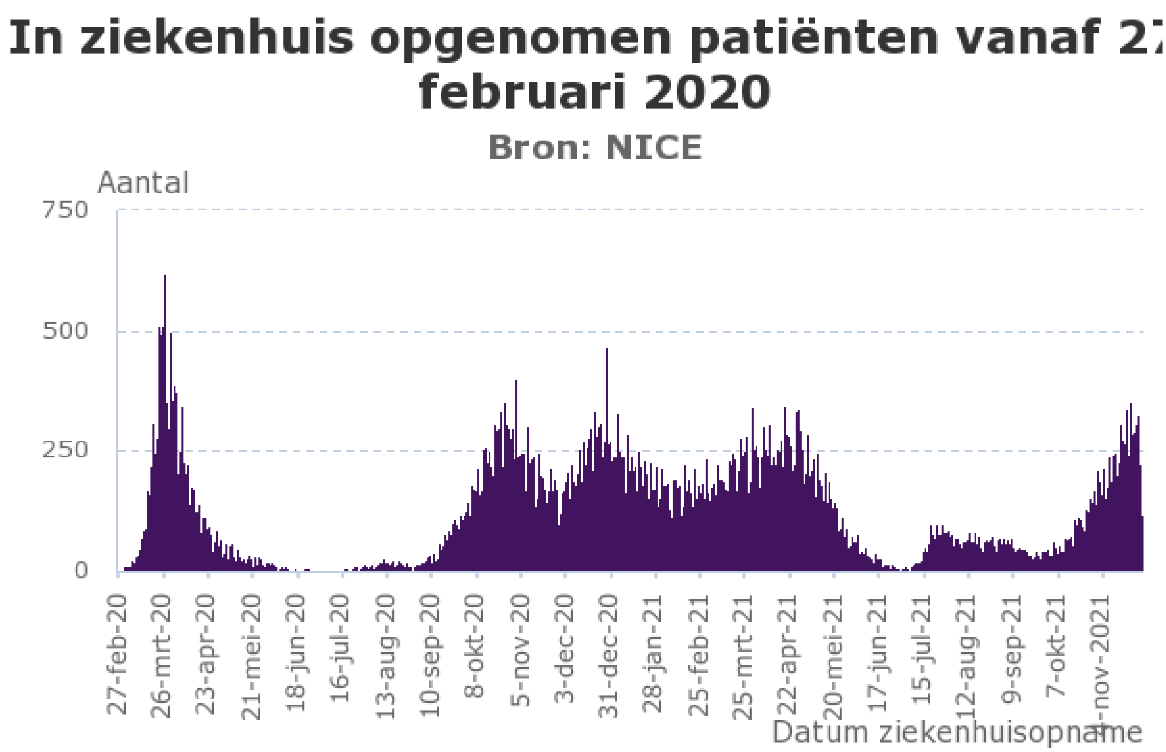

Figure 1.A — To hospital admitted patients with Covid-19 from February 27, 2020 to November 4, 2021 (NICE, 2021).

To calculate the number of masks used in a year we had to multiply the amount that were used in a week by the number of weeks in 2020. 2020 had a leap week, so it contained 53 weeks. We used figure 1.A to estimate the number of pre-Covid and Covid weeks there were in 2020. We chose 11 pre-Covid weeks and 42 Covid weeks. The total FFP2 face masks used in 2020 were calculated by 11 x amount pre-Covid + 42 x Covid = total. For hospital A this was different as there was one outlier week during the year. The calculation for week A was 11x540 + 1x6,350 + 41x1,600 = 77,890 masks.

In 2019 there were 116 hospitals in the Netherlands and in 2021 there are 114 hospitals (Volksgezondheidenzorg, 2021). There is no data available for the number of hospitals in 2020, so we took the average of 2019 and 2021 which is 115 hospitals. Included in this amount are general, academic and children's hospitals.

The total FFP2 face masks used by all Dutch hospitals was calculated from the average values:
11x277 + 42x1,713 = 92,030 masks
92,030 x 115 = 10,583,450 masks

Note: we did not take the low occurrence of covid-19 patients in the summer of 2020 into account for calculation of the amount of used face masks in hospitals. The reason for this is because hospitals did not mention a change in the use of face masks during this period.

Number of FFP2 face masks ordered by Dutch hospitals in 2020:
Based on data from hospital B: 84,627 masks were used out of the 100,000 masks that were ordered in 2020. This means that 84,627/100,000 ≈ 84.6% of the ordered masks were used.

Applied to all hospitals in the Netherlands this means that (10,583,450 / 84.6) x 100 ≈ 12.5 million masks were ordered in 2020

Mass of plastic present in the masks ordered by Dutch hospitals in 2020:

12.5 million masks x 6.24 grams of MPs per mask = 78,000 kg plastic = 78 tons of plastic

Plastic flows in the flow diagrams:
The plastic flows have been calculated from the mass of plastic present in the 12,5 million FFP2 face masks ordered by Dutch hospitals in 2020: 78 tons. Then, with the help of known percentages of plastic loss, the flows of plastics could be calculated.

Some examples:
78.000 tons of plastic were present in the 12.5 million ordered face masks. However, more face masks were produced: there is a loss of 15% of masks due to quality standards. This means that 12.5 million is 85% of the total masks produced, so 78 tons is 85% of plastic material needed in the production of all produced face masks. This leads to: (78.000 x 85) x 100 = 91.764 kg plastic used to produce all produced face masks. This means that the plastic loss due to quality standards for masks is 91.764 - 78.000 = 13.764 kg. This goes towards incineration.
To produce these masks, material was needed. There is a loss of 15% of plastic material for every face mask produced: (91.764 x 85) x 100 = 107.957 kg plastic present in the material that was used to produce all facemasks. The plastic loss flow is 107.957 - 91.764 = 16.193 kg. This goes towards incineration.

To calculate the amount of Polypropylene and PET needed to produce the face masks first the ratio PP/PET had to be determined. 0.7 (plastic content in the earloops of one mask=PET)/6.24 (total plastic content of a mask) x 100% = 11%. The calculated plastic content in this stage of the product chain is 107.978 kg. 107.978 x 0,89 = 96.100 kg PP. 107.978 x 0,11 = 11.878 kg PET. From these values pellet loss during the production of plastic could be calculated. For example for Polypropylene: (96.100 / 99,99) x 100 = 96.109 kg plastic produced. The loss flow from PP pellet loss during production is: 96.109 - 96.100 = 9 kg.

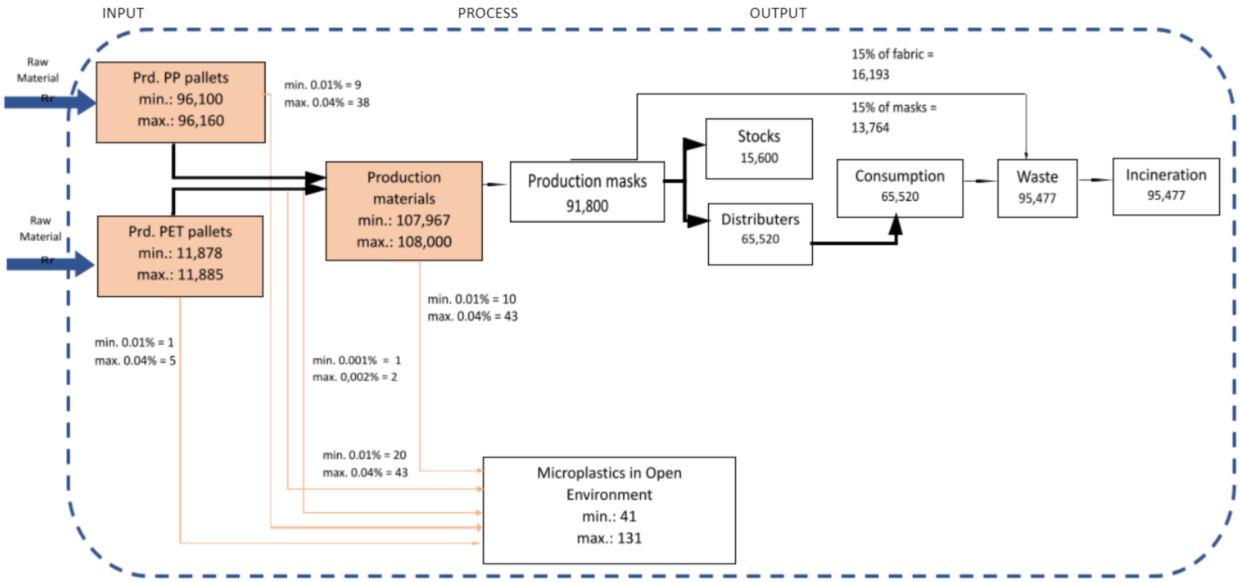

Figure A.2: Exact numbers for the plastic flows in the product chain of FFP2 face masks.

Plastic flows of polyurethane and elastane:

The flows of plastic emissions from the production of polyurethane and elastane are so small that they are negligible. These flows consist of 0 kg both when using 0,01% and 0,04% of pellet loss.
For example: (1544 / 99,96) x 100 = 1544 kg. 1544 - 1544 = 0 kg.

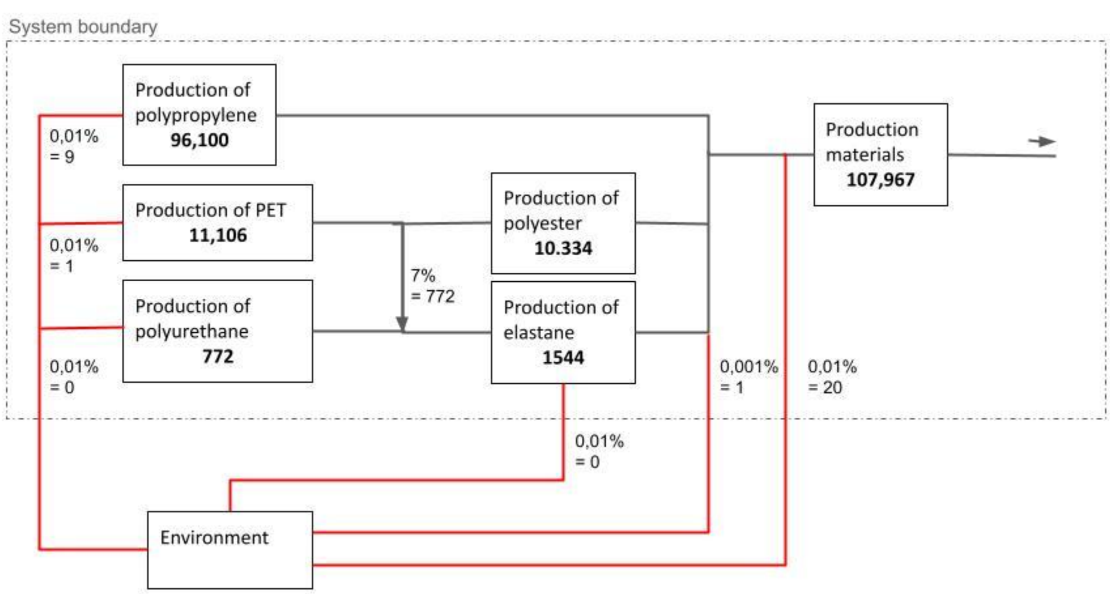

Figure A.3: Plastic flows of plastics used for the production of FFP2 face masks, including polyurethane and elastane.

Mass of MPs entering the environment in a year if everyone that uses cloth masks started using type I masks:

Total plastic emissions from all type I masks in this scenario:
114.4 / 45 x 100 = 254 tons/year
45 + 51.9 = 96.9% of people are wearing a type I mask so:
254 x 0.969 = 246 tons/year

This is an increase of 246 - 114.4 = 131.6 tons/year.

Additional pellet loss:
Assuming that the total microplastic loss consists of the same ratio of pellet loss and loss from usage as in figure 3.13).
3.4 / 114.4 = 0.03
0.03 x 131.6 = 4 tons/year

Additional emissions from usage:
131.6 - 4 = 127.6 tons/year

Mass of MPs entering the environment in a year if 100% of face mask users used FFP2 masks:
FFP2 face masks have a higher plastic content than type I masks. The plastic content of FFP2 masks is 5.3 / 3.7 = 1.4 times higher.
If FFP2 masks are used in the same amount of type I masks (45%) there is a plastic emission of:
114.4 x 1.4 = 160 tons/year.
But in this scenario 100% of people use FFP2 masks. This results in (160 / 45) x 100 = 356 tons of microplastic released into the environment in a year.

This is an increase of 356 - 114.4 = 241.6 tons of plastic/year.

Appendix B: Explanation of terms in SCOR model

Performance
A performance attribute is a group of metrics used to express a strategy. The performance attributes contain five elements namely:

- **Reliability**: Reliability focuses on the predictability of the outcome of a process
- **Responsiveness:** The Responsiveness attribute describes the speed at which tasks are performed
- **Agility:** The Agility attribute describes the ability to respond to external influences and the ability to change
- **Costs:** The Cost attribute describes the cost of operating the process. It includes labour costs, material costs, and transportation costs
- **Assets:** Asset management strategies in a supply chain include inventory reduction and
- in-sourcing vs. outsourcing.

These attributes are measured by metrics. These metrics range from level 1 metrics to level 3 metrics.

Processes
All processes in the supply chain are described by the terms Plan, Source, make, deliver and return at level 1. These terms have the following meaning:

- **Plan**: The Plan processes describe the planning activities associated with operating a supply chain. For example, the customer requirements for a certain face mask.
- **Source**: The Source processes describe the ordering (or scheduling) and receipt of goods and services. For example, a purchase order of face masks during a pandemic.
- **Make**: The Make processes describe the activities associated with the conversion of materials or creation of the content for services. For example, the plastics needed to produce face masks.
- **Deliver**: The Deliver processes describe the activities associated with the creation. maintenance, and fulfilment of customer orders. For example the delivery of face masks to a customer.
- **Return**: The Return processes describe the activities associated with the reverse flow of goods back from the customer. For example, returning a delivery of the wrong type of face masks.

At level 2, these processes are described in more detail in sub-processes. An example of a level 2 process is producing face masks based on a customer order (make to order). Examples of level 3 processes are producing and testing the face masks or packaging. describe the steps to execute level 2 processes.

Practises
The SCOR model has four categories of practises that exist within any organisation, namely leading or emerging practises, best practises, common practises and poor practises. In the SCOR model it is the aim to transform all practises to best practises. These best practises can not only contribute to supply chain optimization but also to environmental improvement (greenSCOR). A metric to measure a greenSCOR best practice is for example the solid waste generated in face mask production.

People
The People section in the SCOR model aims to match team skills to organisation strategy. Elements that are described are skills, experience, attitudes, training and competency.

Appendix C: Examples of SCOR model applied to a type IIR and FFP2 face mask manufacturer

In order to get insight into the product chain we performed an analysis with the SCOR-model on type IIR face mask manufacturer that we visited on November 3rd 2021. The same we did for a FFP2 manufacturer that we visited on November 26th. Detail level 2 of the SCOR model is used for performance, processes and practises. On some process elements level 3 is used because these are considered important in relationship with the use of plastic and plastic emissions. The cost and people elements aren't described in our research as it is not considered relevant for our research objective. Table C.1 shows the aspects that we analysed in the SCOR-model.

Table C.1 — Analysed SCOR model aspects for both company A and B highlighted in green

	Plan	**Source**	**Make**	**Deliver**	**Return**
Performances	Reliability	Responsiveness	Agility	Costs	Assets
Processes (Level 2)	Make to stock	Make to order	Engineer to order		
Practices	Best practices	Leading practices	Common practices	Bad practices	
People	Skill	Experience	Aptitudes	Training	Competency

Table C.2 — SCOR model level 2 processes based on information from Type IIR (A) and FFP2 (B) company

	Company A	**Company B**
sP1 Plan Supply Chain	Polypropylene producers -> Melt-blown polypropylene filter manufacturers -> FFP2 face mask producers -> LCH -> Retail shops & pharmacies -> General public -> Waste & Litter	Polypropylene producers -> Melt-blown polypropylene filter manufacturers -> FFP2 face mask producers -> LCH -> Hospitals -> Waste incineration
sP2 Plan Source	Melt-blown polypropylene filter manufacturers from China. They also provide the inner - and outer layer materials and elastic bands for the ear loops. The aluminium nose clip is ordered elsewhere.	Melt-blown polypropylene filter manufacturers from the Netherlands and Germany. They also provide the inner - and outer layer materials and elastic bands for the ear loops. The aluminium noseclip is ordered elsewhere.
sP3 Plan Make	The Type IIR face mask producer. Done in the Netherlands by a number of companies. All of these companies started because of the high demand of face masks due to the pandemic. Most of these companies have experience in textiles but not in filter applications. Company A, however, started from scratch with a few professionals working as a social enterprise hiring only refugees.	The FFP2 face mask producer. Done in the Netherlands by a number of companies. None of these are only producing FFP2 face masks. Most of these already have experience in filtering applications and took on the challenge to produce these since COVID-19 created an increased demand for the products.
sP4 Plan Deliver	Delivery of finished products goes from company A straight to the warehouse of LCH or to other costumers like dentists. The goal of the producer is to fulfil the demand of the customer in time.	Delivery of finished products goes from warehouse of company B to warehouse of LCH. This because demand can rise faster than production can produce. The goal of both the customer as the producer is that every type of demand of hospitals

		can be filled in immediately, without overstocking as masks have an expiration date.
sS1 Source Stocked Product	The filter materials, inner - and outer layers, nose clips and elastic bands are all stock materials. There is a choice between width and length of roles, but these are all standardised. Custom made roles could potentially reduce the number of waste created during the production of face masks.	
sM2 Make-to-Order	Company A & B have stocked some face masks for times when demand rises suddenly. However, they produce face masks by demand. When an order comes in this will be made. If orders stop coming in, production stops as well.	
sD1 Deliver Stocked Product	The face masks of company A are stocked in the warehouse of the largest client (LCH). There they might remain. LCH stocks the products in large quantities. The reason for this is that when the demand rises such as in times of high COVID-19 incidence, there is a buffer.	The face masks are stocked in the warehouse of company B first, after which they go to the warehouse of LCH. There they might remain. The client of company B stocks the products in large quantities. When the demand rises such as in times of high COVID-19 incidence, they have a buffer and can replenish the needs of hospitals.
sR	No defective face masks have been returned. No number of defective face masks/box has been provided by the customers to the producer.	No defective face masks have been returned. No number of defective face masks/box has been provided by the customers to the producer. The producer is considering asking for this information of the clients.

Table C.3 — Reliability performance based on information from Type IIR (A) and FFP2 (B) company

Level 2 metrics	**Company A**	**Company B**
RL2.1 % of orders delivered in full	100%	100%
RL 2.2 Delivery Performance to customer commit date	Their first and main order was from LCH. They ordered 48 million face masks. This was delivered a month after the commit date. Due to the sort of enterprise, we see this as an enormous accomplishment.	Never later than a month after the commit date. Face masks are picked up by transportation arranged by the client (LCH). (*Commit date: Depends on operational circumstances. As design of the product is always being assessed and improved, machines have to be adapted regularly. This also means that the lines might not work on maximum capacity constantly.)*
RL 2.3 Documentation accuracy	Certification proved to be an issue and a long process. Documentation of internal items such as payments and shipments were not provided.	The company's main products are filtration systems. Certification of filters and products is taken seriously. Documentation of internal items such as payments and shipments were not provided.
RL 2.4 Perfect condition	Face masks are cherry picked every hour for testing on water resistance, airflow and ear loop strength. During the production process the operator also checks the quality visually, but not every mask. Every day the number of discarded masks was logged.	Each face mask produced is screened visually. Non perfection will be fixed or discarded. On top of that, every hour samples are taken to test the filtration and durability of the masks.

Table C.4 — Responsiveness performance based on information from Type IIR (A) and FFP2 (B) company

Level 2 metrics	**Company A**	**Company B**
RS 2.1 Source cycle time	The filters, ear loops, inner -and outer layers are all produced in China. These cannot be delivered fast. Source materials were therefore stocked in their warehouse in the amount necessary to not run out of materials when face masks have to be produced at maximum capacity (no quantification provided).	The filters, ear loops, inner -and outer layers are all produced in either Germany or the Netherlands. These can be delivered fast (no quantification provided). Source material is stocked in their warehouse in the amount necessary to not run out of materials when face masks have to be produced at maximum capacity (no quantification provided).
RS 2.2 Make cycle time	225,000 face masks can be produced daily. However, they try to assure quality by setting the production machines to a lower speed. As the order of 48 million masks was to be delivered on a weekly base, an optimum speed could be obtained.	30,000 of their newest type of face masks can be produced daily. They are in the process of upscaling this quantity by adapting old production lines to the new specifications.
RS 2.3 Deliver cycle time	Delivery handled from Company B and LCH is handled by LCH. They also have a webshop where everyone can buy their face masks. This delivery is done by themselves with a van if quantities are large and nearby such as is the case when for example dental practises place orders. Small orders from individuals in distant locations are sent through delivery companies.	Delivery handled by Company B is that between their production location and their own warehouse. This is done by an external transporter of their choice. As LCH is their only client, delivery from the producer's warehouse to the LCH warehouse is done by the client (LCH). *(No truck runs empty. When finished products need to be delivered from the production site to the warehouse, the truck brings source materials for further production.)*
RS 2.4 Delivery retail cycle time	No data on late arrivals has been provided.	Applicable to the distribution of FFP2 face masks from the LCH warehouse to the hospitals. Hospitals did not have any issues with late arrivals of FFP2 face masks.
RS 2.5 Return cycle time	As of yet, no face masks have returned to the producer.	

Table C.5 — Agility performance based on information from Type IIR (A) and FFP2 (B) company

Level 2 metrics	**Company A**	**Company B**
AG 2.1 Upside Adaptability (Source)	PP and PET pellets are easy and cheap to produce in large quantities. Producers of PP can also switch over quite rapidly to the production of PP with different specifications. (% sustainable increase not provided) *(The problem in changes in the production process involve spillage or loss of materials when the change is done. There is a significant number of low-grade PP produced in the process of optimising to the new specifications of the substance.)*	

AG 2.2 Upside Adaptability (Make)	There are different sizes of filter material rolls. These are standardised in length and width. Adjusting the dimensions of the inner - and outer layer is more straightforward. Upscaling does not necessarily mean that more labour is required immediately. The speed of the machinery can be adjusted. *(The process of compressing the layers with the filter layers has a downside. The inner - and outer layer have to be wider than the filter layers to be compressed smoothly. Therefore, even if adjustments of the inner - and outer layer are easily done, it is not of much use as this is not a possibility with the filter material. Due to the design of FFP2 face masks (cutting is necessary), around 15% of the source materials end up being waste.)*	
AG 2.3 Upside Adaptability (Deliver)	Materials are stocked so that there is sufficient availability to work according to the weekly demand of LCH. Stock of sufficient materials is important as these come from China and cannot be delivered immediately.	Materials are stocked so that there is sufficient availability to work at full capacity for one month. Delivery as of yet can be done in one week (No further quantification provided).
AG 2.4 Upside Return Adaptability (Source)	Materials are inspected upon arrival and are sent back immediately when it does not meet expectations. This happens from time to time. Resending orders does not take any longer than the initial order (No quantification provided).	
AG 2.5 Upside Return Adaptability (Deliver)	Collection of damaged goods and resending takes some time (no quantification provided).	
AG 2.6 Downside Adaptability (Source)	PP pellets are easy and cheap to make in large quantities. They can downsize their production. A downsize of 20% does not have consequences for their employees' positions. The pellets are needed for the production of an abundance of materials, and the demand for the pellets is still expected to rise significantly.	
AG 2.7 Downside Adaptability (Make)	Machinery can be slowed down. Chemical composition of pellets can be adjusted to the need of the client.	

Appendix D: Survey on face mask behaviour of the general public

A questionnaire was sent through social media to random people regarding their behaviours when using face masks. 131 people filled the questionnaire. The following questions were posed:

1. Which age category are you in?
2. When did you first wear a face mask?
3. What type of face mask do you wear?
4. How many times do you wear the same disposable face mask?
5. How many face masks did you wear on average on a weekly base when face masks were mandatory in public transport and public spaces?
6. How many face masks did you wear on average on a weekly base when face masks were mandatory only in public transportation?
7. How do you discard the face mask?
8. Have you ever lost a face mask on the street?
9. Do you ever recognise face masks in litter? If so, where do you see them?

The following answers provided to be useful for our study:

What type of face mask do you wear?

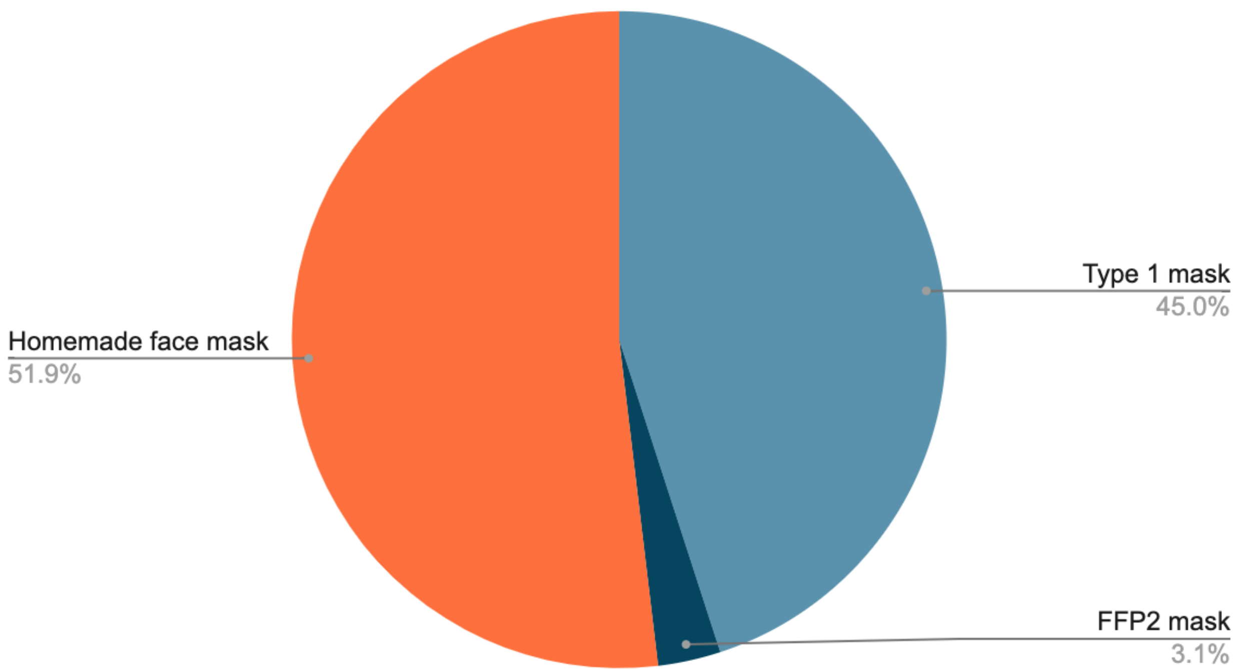

Figure D.1 — Answer to question 3 in the survey.

Have you ever lost a face mask on the street?

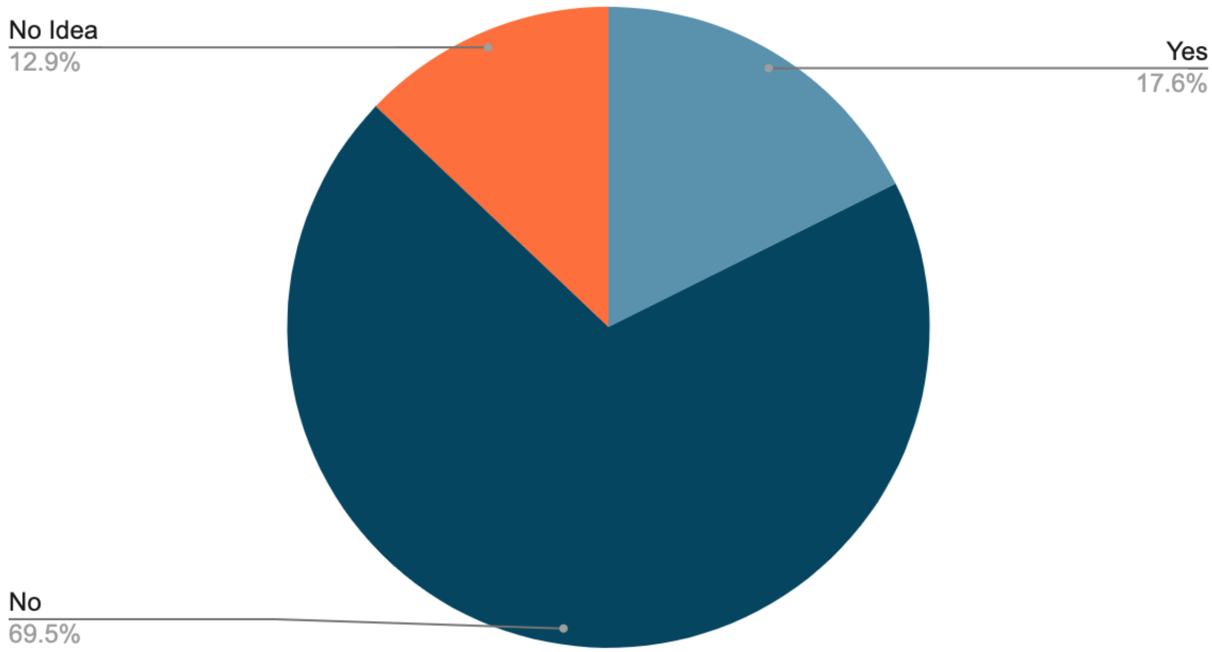

Figure D.2 — Answer to question 8 in the survey.

How many times do you wear the same disposable face mask?

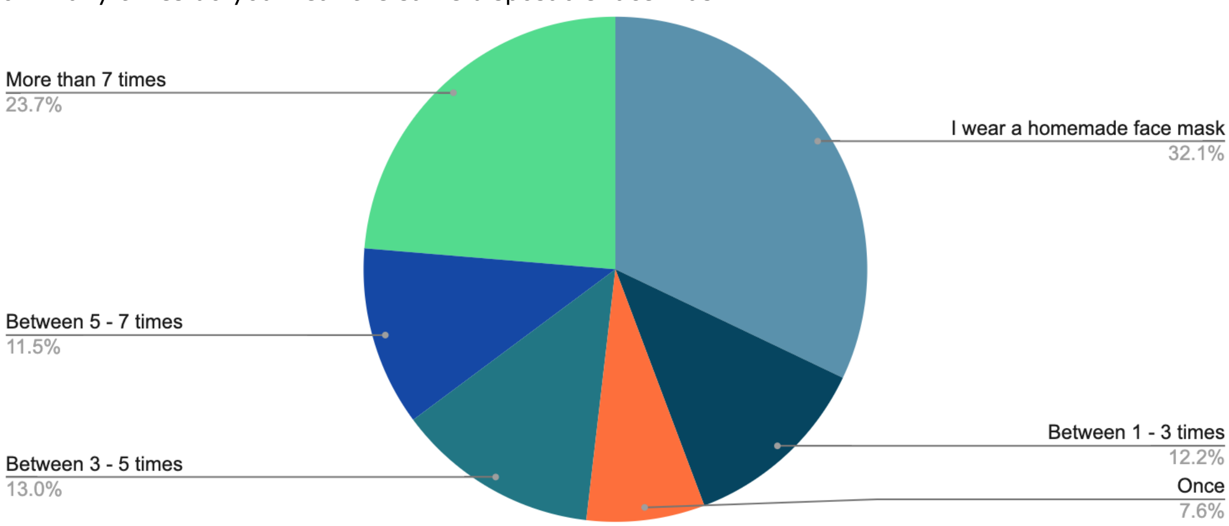

Figure D.3 — Answer to question 4 in the survey

Of the 131 respondents, 118 answered the question of whether they find face masks in the environment and where they see them. These answers were coded into several categories. We then used codes (keywords) to derive how many times face masks were found in a certain location. The answers are provided in figure D.4.

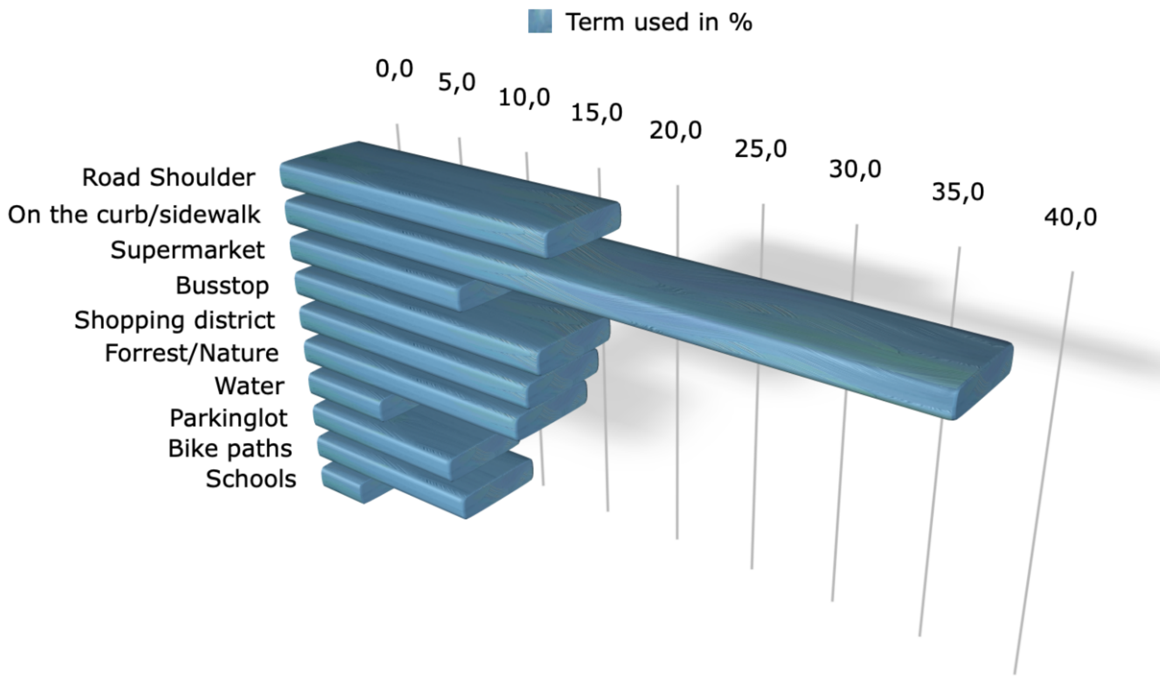

Figure D.4 — Number of times in percentages that these keywords came up in the respondents' answers.

Of the 118 respondents, ≅30% saw littered face masks on the sidewalk. Unfortunately, the number of face masks spotted by the respondents (between 15%-18%) in shopping districts, bus stops and nature are quite similar. However, the interpretation of these results can go different ways. As there are less people in forests than in shopping districts, do the shoppers litter less or do people in forest tend to litter more? Availability of disposal opportunities and better waste management in urban areas than in forests, among others, are factors to take into consideration when interpreting these results.

Appendix E: Literature research on SCOR-model applications

The SCOR-model is mainly used by companies to map and analyse the performance of the logistics chain and related processes in the organisation. It is mostly used by manufacturing companies for which it was initially developed, though it has also been used by other companies. These results are usually not published by companies and/or not available online. The SCOR-model isn't a tool that is usually used in scientific research. Therefore, finding scientific information sources about SCOR-model applications are scarce. However, we executed a traditional literature research making use of databases like Sciencedirect and Google Scholar. Among the scarce publications, there were no studies about the SCOR-model in relation to plastic items or material. Though, several publications were found that pinpointed the success, advantages and disadvantages of the SCOR model. In some cases, an application of the SCOR model on a certain product was described.

Li (2011) concluded that Plan and Source decisions are more important to external-facing supply chain quality performance, while Make decisions are significantly correlated to internal-facing firm level performance (Li, Su, & Chen, 2011). Earlier research done by Lockamy III (2004) concludes that for all processes (plan, source, make, deliver) the planning processes are important, while collaboration is important for plan, source and make and teaming is important for plan and source.

Persson (2010) describes one case study of the application of the SCOR model. This study was done to test a new template of the SCOR model. Alfa Laval was a global provider of specialised equipment, systems and services, dedicated to heat, cool, separate and transport products such as oil, water, chemicals, beverages, foodstuffs, starch and pharmaceuticals. The study revealed that supply chains or networks are complex and often contain special features that are difficult to model with a simulation based on SCOR. Also concluded was that the SCOR model is highly standardised and difficult to use in all instances (Persson, 2010).

Lima-Junior (2019) also mentions a disadvantage of the SCOR-model, namely the difficulty of adjusting them to the environment of use, since their implementation and updating require manual parameterization of many fuzzy decision rules. However, the SCOR model can also help to identify areas that have performance problems and may need improvements (Lima Junior, 2019).

Sellitto (2015) conducted a study of an application of the SCOR model in the footwear industry. The study focused on SCOR performances and processes. Practises and people were not included. The study focused on one footwear manufacturer, four suppliers, three distribution channels and a return channel. The study concluded that delivery(process) and flexibility(performance) for this particular supply chain could be improved (Sellitto, Pereira, & Borchardt, 2015).

Another example of an application of the SCOR model is a study by Huang (2013). In this study the impact of additive manufacturing (3D printing) in the aircraft spare parts supply chain is analysed. The result shows that the use of AM will bring various opportunities for reducing the required safety inventory of aircraft spare parts in the supply chain (Huang, Mokasdar, Zhou, & Hou, 2013).

All in all, we conclude that the SCOR-model has advantages and disadvantages. In certain cases, it seems successful in improving supply chain performance. As it is a standardised method, supply chains can be well compared with each other. On the other hand, the model seems too complicated for less complex supply chains while on the other hand complex supply chains are too special to be analysed with a standardized model like SCOR.

InCompany Milieuadvies

faculteit Management, Science & Technology,
Vakgroep Science
Open Universiteit
Postbus 2960
6401 DL Heerlen, NL
tel. +31 45 576 2877
secretariaat.mst@ou.nl
www.ou.nl/nw
www.Incompany-milieuadvies.nl

Open Universiteit
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