

SMED Report No 7 2023



# Microplastic Emissions from Paint

Sara Brännström, Hanna Rosengren, Anna-Lisa Wrangle, Mikael  
Olshammar

IVL

Agreement: NV-02456-23

**Commissioned by the Swedish Environmental Protection Agency**

Publisher: Swedish Meteorological and Hydrological Institute

Address: SE-601 76 Norrköping, Sweden

Start year: 2006

ISSN: 1653-8102

*Swedish Environmental Emissions Data(SMED) is a collaboration between IVL Swedish Environmental Research Institute, Statistics Sweden (SCB), Swedish University of Agricultural Sciences (SLU), and the Swedish Meteorological and Hydrological Institute (SMHI). The collaboration was established in 2001 with the long-term aim of gathering and developing emission statistics competence in Sweden. SMED, on behalf of the Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management, is heavily involved in work related to Sweden's international reporting obligations regarding emissions within six subject areas (air, water, waste, hazardous substances, noise, and measures). Environmental statistics are also produced for national and regional needs, and SMED compiles data for both milestone targets and environmental quality objectives within these needs. SMED also develops new methods and produces statistics for follow-up of Sweden's National Waste Plan and Waste Prevention Program. For more information, visit the SMED website at [www.smed.se](http://www.smed.se) (in Swedish).*



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# Summary

Swedish Environmental Emissions Data (SMED) is a collaboration between IVL Swedish Environmental Research Institute, SCB Statistics Sweden, the Swedish University of Agricultural Sciences (SLU), and the Swedish Meteorological and Hydrological Institute (SMHI).

Recent attention has been focused on the potential environmental and health impacts of microplastics, but there is still significant knowledge missing regarding these impacts. The Swedish Environmental Protection Agency has is responsible for the national plastics coordination, in which one aim is to develop new knowledge in relation to important sources of microplastic emissions. Within the scope of this work, SMED has been assigned to review the role of paints as a source of microplastics and suggest feasible indicators to monitor annual release from paints.

This report aims to compile existing knowledge of various paint and coating systems and their contribution to microplastic emissions. Sectors responsible for the highest emissions have been identified to facilitate prioritization of actions to lower microplastic emissions from paints. Additionally, this report proposes a key indicator for tracking annual national levels of microplastic emissions from paints.

The report concludes that the sectors with the greatest risk for microplastic emissions from paint include architecture, antifouling and hull coatings, coatings used in general industry, and the automotive industry. In Sweden, data on the volume of architectural paints and antifouling/marine coatings placed on the market can be readily obtained from the Swedish product registry. However, information regarding paint usage in general industry and the automotive sector is limited because coatings are often applied overseas prior to import into Sweden and many of the products coated in Sweden are exported abroad.

This project has developed a simplified method to calculate annual microplastic emissions from paint in Sweden including emissions from architectural and marine sectors. Emission factors for different parts of a paint's lifecycle were included and a range of solid contents based on a set of commercially available paints were used to provide a worst case, best case, and average case. By using this method, release of microplastics from architectural paint was estimated at 209 to 3 700 tons per year and release from antifouling and hull coatings at 30 to 308 tons per year in Sweden.

Comparing these numbers to estimated quantities of microplastic emissions from other sources, coatings are a substantial source of microplastics.

Wear from road traffic is regarded as the largest source of microplastics in Sweden, accounting for about 7 674 tonnes per year. It has been estimated that the amount of synthetic fibres released from textiles is between 8 to 956 tons annually and that microplastic emissions from industrial plastic pellet production is between 12 to 235 tons annually (Magnusson et al., 2016).

Since coatings typically need to meet various technical requirements to protect the underlying substrate from corrosion and wear, efforts to reduce microplastic releases from paint and coatings might incur higher costs and obstacles than efforts to address other microplastic sources such as littering.

For future monitoring of microplastic emission from paint in Sweden, the project recommends the amounts of architectural and boat paints including antifouling coatings placed on the Swedish market annually (expressed in kg of dry weight) as indicators.

Keywords: microplastics, paint, coating, indicator

# Sammanfattning

SMED utgör en förkortning för Svenska MiljöEmissionsData, som är ett samarbete mellan IVL, SCB, SLU och SMHI.

De potentiella miljö- och hälsoeffekterna av mikroplaster har den senaste tiden uppmärksammats, men det finns fortfarande betydande kunskapsluckor. Naturvårdsverket ansvarar för den nationella plastsamordningen inom vilket det ingår att öka kunskap. Detta kan t.ex. inkludera att identifiera viktiga källor till utsläpp av mikroplast och att arbeta för att minska utsläppen av mikroplast från dessa källor. SMED har inom ramen för detta arbete fått i uppdrag av Naturvårdsverket att utreda färg som källa till mikroplast och föreslå indikatorer för att följa upp årliga utsläppsmängder.

Denna rapport syftar till att sammanställa befintlig kunskap om olika färg- och ytbehandlingssystem och deras bidrag till mikroplastutsläpp. Sektorer som ansvarar för de största utsläppen har identifierats för att möjliggöra prioritering av åtgärder för att minska mikroplastutsläppen från färger. Dessutom föreslår rapporten en indikator för att följa upp de årliga nationella utsläppen av mikroplastutsläpp från färger.

SMED drar slutsatsen att de användningsområden där det råder störst risk för utsläpp av mikroplast från färg inkluderar: husfärg, båtfärg inklusive antifouling (påväxthindrande system) för båtar, ytbehandlingar inom industrin och speciellt fordonstillverkning. I Sverige kan uppgifter om volym husfärg och båtfärg inklusive antifouling som sätts på marknaden erhållas från det svenska produktregistret. Information om färganvändning inom industrin och fordonssektorn är dock begränsad på grund av att en betydande mängd av dessa ytbehandlingar sker utomlands och många av de produkter som behandlas i Sverige exporteras utomlands.

Projektet utvecklade en förenklad metod för att beräkna årliga utsläpp av mikroplast från färg i Sverige inom byggnads- och den marina sektorn. Emissionsfaktorer för olika delar av färgens livscykel inkluderades och ett spann för det fasta innehållet i färgen togs fram baserade på en sammanställning av kommersiellt tillgängliga färger, vilka användes för att ge ett värsta fall, bästa fall samt ett genomsnitt. Genom att använda denna metod uppskattades utsläppen av mikroplast från husfärg till 209 – 3 700 ton/år och från båtfärg inklusive antifouling till 30-308 ton/år i Sverige.

Genom att sätta dessa siffror i relation till uppskattade mängder mikroplastutsläpp från annan verksamhet framgår att färg är en betydande källa till mikroplast i Sverige.



Slitage från vägtrafiken anses vara den största källan till mikroplastutsläpp i Sverige med cirka 7 674 (ton/år) och man har uppskattat att utsläpp av syntetfibrer från textilier är mellan 8 – 956 ton per år och utsläpp från industriproduktion av plastpellets uppskattades till mellan 12 – 235 ton i samma rapport (Magnusson et al., 2016).

Med tanke på att färgsystem vanligtvis måste uppfylla olika tekniska krav för att skydda det underliggande underlaget från korrosion och slitage och det ofta saknas bra alternativ, kan åtgärder för att minska mikroplastutsläpp från färg medföra högre kostnader och större tekniska utmaningar jämfört med att minska mikroplastspridningen från andra källor såsom genom minskad nedskräpning av makroplast.

För att följa upp mikroplastspridning från färg i Sverige rekommenderade projektet indikatorer för uppföljning bestående av mängden husfärg och båtfärg inklusive antifouling som släpps ut på den svenska marknaden årligen uttryckt i kg torrvt.

Nyckelord: mikroplast färg lack indikator

# Background

## Swedish national plastics coordination

Since the beginning of 2021, the Swedish Environmental Protection Agency (Swedish EPA) has been assigned by the government to be the national plastics coordinator. This mission includes pushing for sustainable plastic use, as well as developing and disseminating important knowledge about plastics and microplastics.

In 2020, the Swedish EPA produced a status assessment, in which various obstacles to achieving sustainable plastic use were analysed. Among these, *limited knowledge of the sources and transport routes of microplastics* was highlighted as an obstacle, as the report further stated that this limited knowledge *makes it difficult to assess risks, as well as to set requirements for/control against/inform about reducing leakage* (Swedish EPA, 2022a).

Subsequently in 2021, the Swedish EPA developed a roadmap towards sustainable plastic use (Swedish EPA, 2021). The road map identified *"design for resource-smart production and use, including increased wear resistance"*, as well as *"solutions for reduced leakage, design, knowledge dissemination and development"* as priority areas for development for moving towards sustainable plastic use. Sustainable plastic use means that plastic is used in the right place, in resource- and climate-efficient ways, and within non-toxic and circular flows with negligible leakage. To achieve this, efforts need to occur in four impact areas; *raw materials and production with minimal environmental impact, smart use of resources, reduced leakage of plastic into nature, and greatly increased and high-quality material recycling*.

## Paint as a source of microplastics and plastics in circular flows

Paint (including outdoor and anti-fouling paints) has been previously identified as one of the most important sources of microplastics (Swedish EPA, 2022b), (Magnusson et al., 2016). However, there is a lack of knowledge in this area, which is why the Swedish EPA, via this study, wants to acquire more in-depth knowledge in this area and get proposals for a detailed implementation plan of an indicator for continued and future follow-up on microplastic dispersion from paint.

The government commission *Rätt plast på rätt plats (The right plastic in the right place)* (Swedish EPA, 2022c) is about promoting the transformation of

plastic to a circular economy to achieve Sweden's goal in becoming the world's first fossil-free welfare state. Within this work, the Swedish Environmental Protection Agency shall analyse and map which types of plastics are suitable for different types of uses in order to achieve circular flows and reduce the climate impact from plastics. In the interim report on mapping plastic flows as part of the government commission *Rätt plast på rätt plats* (Swedish EPA, 2022a), one of the conclusions was that there are several gaps in knowledge about the use of plastic.

Paint as a possible source of environmental microplastics has recently received attention in the EU through an initiative to limit unintentionally formed microplastics in the environment (European Commission, 2022a). Part of the commission's work is to carry out studies and collect information about microplastics. Initially, these studies only included pellets, synthetic textile fibres, and tire wear particles, but have now been extended to also include paints, washing and dishwasher tablets, and geotextiles.

There is currently a lack of knowledge about paint and coatings as a source of microplastics, and in order to limit unintentionally formed microplastics, the Swedish EPA must increase its knowledge within this area.

## Indicators

The Swedish roadmap towards sustainable plastic use specifies which indicators will be used for monitoring each impact area (Swedish EPA, 2021). For the impact area "reduce leakage of plastic into nature", the following indicators were specified for monitoring progress within the impact area:

- Littering of objects containing plastics (weight/year, divided by product category).
- Estimated total leakage of microplastics in Sweden (weight/year, divided by source and transport route).

SMED has in a previous assignment (Unsbo et al., 2022) suggested how indicators for microplastics can be followed up, i.e. how to estimate total leakage of MP in Sweden (weight/year, per source/transport route).

## Purpose and goal

This project aim was to develop more knowledge about the spread of microplastics from different types of paint in Sweden to provide an improved knowledge base for national remedial work.

Building on this, the purpose of the next step was to make a data compilation and clearly define how one or more indicators for microplastics from paint should be used in Sweden.

## Knowledge compilation

### General knowledge

#### The definition of microplastics

According to the Swedish EPA's definition of microplastics, dried paint particles between 1 nm and 5 mm in diameter, independent of shape are classified as microplastics (Swedish EPA, 2022b). Water-soluble polymers are not considered microplastics according to this definition and although these can also be problematic, particularly in situations where they are dissolved but do not break down, they are outside the scope of this report. As discussed in a previous project (Unsbo et al., 2022), when one estimates microplastic release from paint, issues arise when one must consider which ingredients should be considered microplastics. Estimations have been based on flux calculations, in which the quantity of microplastics is often converted to mass of polymers (Turner, 2021). However, plastics are not solely comprised of polymers. Many plastics also contain additives that enhance the material functions and properties. When it comes to paints, the concentration of components can vary a lot depending on the application and the type of paint used. (Costa et al., 2023). On average 37% of paint is made up of plastic polymers (Paruta et al., 2022). The rest of the paint consists of solvent, which evaporates before or during the curing process, and additives. When calculating the emission of microplastics, all solid content that stays in the paint after curing should be considered for polymer-containing coatings. This has also been discussed by (Gradient Corporation, 2022; Turner, 2021). There is also a large risk that additives within microplastics that end up in the environment are leached. This risk is even greater the smaller the particles are due to larger surface area (Costa et al., 2023).

#### Areas of use and functions for plastic-containing paints and varnishes

Coatings are used for a wide variety of applications in several sectors. Coatings are designed with different properties to serve a wide range of functions. The composition, such as polymer content and additives, as well as curing mechanism varies greatly. To understand what kinds of coatings can lead to microplastic emissions, this chapter will cover information about how a coating is made. In addition, different applications for paints and

coatings, as well as the areas which have the highest risks of releasing microplastics into the environment will be discussed.

### **Paints versus coatings**

The terms, paints and coatings, often have the same meaning, but the term coating is typically used in industrial settings. In general, a paint is always liquid and is used to add colour to a surface. Coatings are commonly sold in liquid form, but they can also be in a range of other forms such as solids or aerosols. They are typically used to add a specific function (for example corrosion protection, anti-fouling) to a surface. A coating may also contain pigments but not always. Varnish is a type of coating that acts in a similar way to a paint, but it typically does not contain any pigment. Instead, it is mostly used to add gloss to a surface, and it is a common method to treat wood. Although this report will cover both coatings, paints and varnishes, we will mostly refer to the term “coating” as a generalization. Note that a paint is a type of coating but all coatings are not paint (Renovia, 2019).

### **The composition of a paint**

A paint is usually made up of the following components: binders, solvents, pigments, fillers, anti-fouling agents, anti-corrosion agents, UV stabilizers, and other additives depending on the final application. In this section we primarily present common binders since these are often polymers, which are the components typically associated with plastics (all plastics are made from polymers, but not all polymers are plastics). This section will also cover some information about solvents and briefly describe anti-fouling additives and pigments since these are other important commonly used ingredients that are also mentioned later in this report. Many more additives exist as they are useful to fine tune the properties of coatings; however, we will not focus on them in this project.

### **Binders**

A coating binder is the main part of most paint systems that reacts to form a protective surface. The binder is often composed of oligomers or polymers and monomers that react after the paint is applied to a surface. Monomers are molecules which have the possibility to react and form longer structures, I.e. polymers. For example, if you polymerize a monomer of acrylic acid you end up with poly(acrylic acid), which is a long structure with acrylic acid as a repeating unit (see Figure 1).

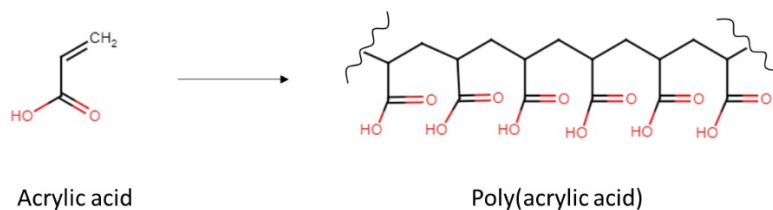


Figure 1. Polymerization of the monomer acrylic acid to poly (acrylic acid).

Some common binders for coatings are based on polyesters, polyacrylates/acrylates, alkyds, epoxides, and polyurethanes. The components in the binder react and form a polymeric network (see Figure 2), which locks the paint and all the other additives such as pigments in place, in a process called curing. Depending on the reactive groups of the binder components, curing can be done in different ways. Some examples include heating, UV curing, mixing different types of reagents, and air-drying where oxygen reacts with some of the chemical groups and forms crosslinks.

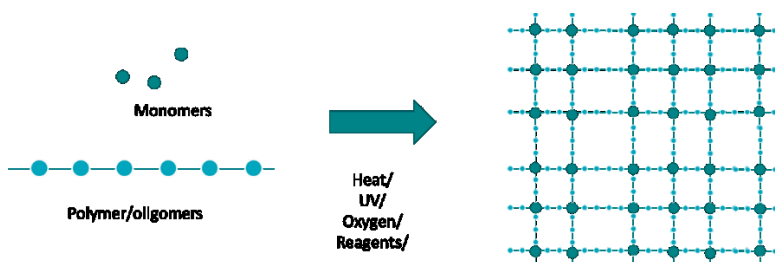


Figure 2. Schematic overview of polymers and monomers reacting to form a polymeric network through curing.

## Polyester

Polyesters are made by reacting di-alcohols and di-acids or multifunctional diol-diacids in condensation polymerization. During polymerization, ester bonds are formed and water is formed as a by-product. The process can be relatively non-toxic. A polyester can in theory de-polymerize in water or methanol but generally a large polyester will not break down in normal conditions found in nature. Increased temperature, additions of catalysts, or industrial composting where the conditions are controlled are some examples of how polyesters can be broken down. However, when polyesters are used in the binder of a coating the polymer becomes more difficult to depolymerize because they are crosslinked with bonds that are typically not hydrolysable. Once the polyester is cured, a different type of reaction with other types of chemical functional groups is carried out. For example, it is common to have unsaturated polyesters that contain double bonds which can undergo radical polymerization, which is often induced by heat or UV

light. Polyesters can also be crosslinked with other reagents that react with the alcohol or carboxylic end-groups.

The monomers that are used to form polyesters are often non or minimally toxic since they often occur naturally or have similar structures to acids and alcohols which are found in nature (Poth, 2020).

### **Alkyds**

Alkyds are in some ways related to polyesters. To make an alkyd you react polyesters with unsaturated fatty acids. The unsaturated bonds in the fatty acids form crosslinks when exposed to oxygen in the air. The curing time can be modified by adding antioxidants which delay the process. Examples of fatty acids that are added to make alkyds include linseed oil, soybean oil, sunflower oil, castor oil, and tung oil. Alkyd coatings are commonly used to coat wood for outdoor applications (Abraham and Höfer, 2012; Bentley and Turner, 1997; Poth, 2020).

### **Acrylic**

Acrylic based binders react by radical polymerization and the repeating unit contains carbon-carbon bonds. The reaction is irreversible unlike the synthesis of polyesters and the reaction can be very fast. There are also latex-formulated coatings containing polyacrylates that do not crosslink but just harden as the solvent evaporates. Acrylic paints are very durable and not sensitive to hydrolysis. Solvent-borne acrylic resins dry quickly and have good adhesion and are therefore commonly used in the automotive, appliance, and coil industries. Because of their inertness and high ability to retain colour even when exposed in outdoor conditions they are often used in architectural or decorative finishes (Weiss, 1997).

Because acrylic binders are often water-soluble before curing it is possible to make the coating water-borne. Using water-borne coatings has gained more interest over the years as it is a more environmentally friendly option to solvent-based coatings. Unfortunately, there are some limitations, particularly regarding adhesion and drying times, which makes it more challenging to use in some industrial applications. Today, acrylic coatings account for approximately 25% of all coatings globally (“Sharing insights elevates their impact,” 2023).

### **Epoxy**

Epoxy Coatings have a high chemical resistance, high thermal stability, good adhesion, and high toughness. In some cases, they also offer chemical and corrosion resistance. However, they do tend to yellow over time, which is not ideal for decorative paints. Epoxy coatings are therefore more

commonly used in applications such as pipelines, exteriors/interiors of ships, and traffic markings. The service life of traffic markings is 2-3 years. Epoxy coatings have also been used for marine applications. They are also used in automotive clear coatings, some architectural paints, and general industrial coatings, for which high durability and stain resistance are important. The expected service life in salt-water is six years and in a marine atmosphere is eight years (Bleile and Rodgers, 2001).

### **Amino resins**

Amino resins are produced by reacting formaldehyde and urea or formaldehyde and melamine, which is then used as the crosslinking agent. The agent reacts with alcohol groups from for example polyesters, epoxides, and acrylics. The urea-formaldehyde based resins are often used in coatings for general purpose industrial, paper, wood, and automotive finishes. Curing is commonly done by heat (Weiss, 1997).

### **Polyurethane**

Polyurethane resins are often made from isocyanates and efficiently crosslinks the binder by reacting with alcohols or amine groups. Due to the wide range of available isocyanate monomers or oligomers, the properties of the paint can be tailored to fit specific properties both related to the drying time, film forming ability, curing time, and final properties of the cured paint. The reaction is very fast and efficient but there are large health concerns related to isocyanates e.g., they are often classified as respiratory or skin sensitizers and sometimes as toxic. Isocyanates are commonly used in paints for automotive repair coatings (OSHWiki, 2017).

### **Solvents**

Solvents are used to help reach a good film-forming property and make it easy to apply the paint to a surface evenly. After application the solvent usually evaporates so when calculating the mass of the final coating, the solvent should be excluded. However, there are cases where so-called reactive solvents are used. In these systems, a monomer that has a low molecular weight and is in liquid form functions both as a solvent while also reacting with the binder during curing and forms the crosslinked network that holds everything together. Thus, a reactive solvent should be included when calculating the final amount of cured paint. Common solvents that do evaporate before curing are; xylene, toluene, ethylbenzene, aromatic and aliphatic naphthalene, acetone and ethyl acetate and different hydrocarbons such as heptane and hexanes. Some paint systems also use water as solvents, and these are often considered to be more environmentally friendly than



those based on organic solvents. Examples of reactive solvents are styrene and acrylates (Cousinet et al., 2015; Popov, 2015; Zhang et al., 2017).

### ***Antifouling agents***

To prevent growth on the hulls of boats and other marine surfaces, antifouling agents have often been added to marine paints. Historically Chrome (VI) has been used a lot, but this substance was banned in 2016 (ECHA, 2023). Tributyltin (TBT) and other tin-organic compounds have been banned for use in the EU since 1989 (Båtmiljö.se, 2023). TBT is hazardous to a wide range of marine organisms. On small boats it has been prohibited since the mid-1980s but can still be present on some larger vessels. Lead oxides have previously also been used in antifouling coatings but are now prohibited because they exhibit a wide range of negative health impacts alongside ecotoxicity (“FAQ - Questions and Answers about Lead Paint and Lead Paint Laws,” 2017).

Implementations of harsher restrictions around toxic chemicals have driven the development of alternative systems for antifouling coatings. More recently, options and techniques such as silicone-based coatings that create a non-stick surface without being toxic to the aquatic environment have emerged. There are also companies that provide drive in boat washes, but for this it is recommended that boats have a hard coating so that the coating is not rubbed off in the wash (Belzunce et al., 2004; SwAM, 2012).

### ***Rosin***

Rosin consists of a complex mixture of naturally occurring organic acids with high molecular weight and other related neutral compounds. The major component in the mixture is rosin acids. The rest is a mixture of high molecular weight esters, alcohols and other compounds that have structures similar to rosin acids. The exact composition varies and depends on the extent of refinement, but often contains about 90 % acidic material.

While rosin is a natural compound, it should be noted that this does not necessarily mean that it will always be broken down in nature. The acid groups in rosin can be used in esterification, a process common when using rosin in alkyd binders. Depending on how much rosin is modified synthetically, it may still form microplastics if the coating breaks down into smaller flakes. Rosin can also be used in other polymers, for example polyurethane or epoxide systems as part of the binder if it is synthetically modified (Maiti et al., 1989).

Rosin and its derivatives are important in anti-fouling paints. They can be used to carry the antifouling agent or be the antifouling agent itself. In the

latter case, this is often modified versions of rosin such as triphenyltin rosinate and rosin-chlorinated rubber mixtures (Maiti et al., 1989). Rosin is also used in some foul-release coatings where the function comes from the coating dissolving slowly. Since dissolved polymer is not considered microplastics, these kinds of coatings do not lead to microplastics emissions (Lejars et al., 2012; Zhou et al., 2021).

### ***Pigments***

Paints usually contain some form of pigment depending on the desirable end use finish. Pigments can be organic and inorganic and the content of pigments can be relatively high in paints, in some cases up to 55 % of the whole content (Ansdell, 1999). Some examples are carbon black, titanium dioxide and iron oxides. In coatings designed to be clear, pigments are not added; however, clear coats still contain polymeric binder and should therefore also be considered when following the microplastic release from coatings (Popov, 2015).

### ***Other Additives***

Additives can belong to a wide range of different categories and are added for different reasons. Some example reasons are to improve mold resistance, shelf life, and film forming properties (Paiano et al., 2021).

## **Production of paint and other parts of the life cycle**

### **The lifecycle of paint**

#### *Paint production*

Paint is made by mixing components (binder, solvents, pigments, additives) in several different steps under several different conditions. The finished paint product will then be packaged and shipped to the customers, whose application methods can vary. Waste generated from the production process is typically associated with cleaning residual paint from different containers<sup>1</sup>.

#### *Application*

Coil coatings are an example of coatings used in numerous industrial applications. Coil coats are continuously coated on metals, in a highly automated industrial process, in which the material is rolled up into a coil after the coating has cured. These coated flexible metals are often used in different architectural parts. Their life span can be between 10-30 years

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<sup>1</sup> Personal communication with Emma Larsson, Beckers Industrial Coatings AB 2023-06-16.

depending on the degree of maintenance and other variables. In some industries, such as in automotive applications, coatings are often applied by spraying.

Industrially, metal surfaces can also be e-coated, a process which uses electrical current and coatings which can be charged. Other methods include dip coating, spray coating, and brush or rolling coating. The processes are often automated, providing an efficient method for coating the substrate with minimal material losses and the processes are performed indoors, allowing a controlled environment (Paiano et al., 2021).

For wood, different types of spray coating, curtain coating, dip coating and roller coating is used for application. Roller coatings are limited in general to flat surfaces. Other methods such as spray and dip coating are good methods for even application on different shapes (Tikkurila, 2023).

In a Dutch report about paint and microplastics, M. Faber et al. (2021) mention that new automatic spray painters are being developed, which prevent overspray even in strong breezes (Faber et al., 2021).

Larger companies often have good systems for collecting hazardous waste, e.g. solvent or paint residues, and waste management companies are normally used for incineration of the collected hazardous waste. However, for consumer paints there is a larger risk that residues from brushes and rollers are washed improperly and end up in the sewage system. While this could lead to release of hazardous substances into the environment, the paint would disperse and most likely not be cured. Dispersed or dissolved polymers should not be considered microplastics. However, paint containing intentionally added microplastics, for example fillers coated with polymers, should be considered a primary source for microplastics if the particle size is between 1 nm and 5 mm.<sup>2</sup> Other than intentionally added microplastics, paint and coatings should not be considered plastic in their wet state. During or before the curing process, the solvents evaporate, and the remaining components will react and form a solid surface. All that remains in the final cured coating should be considered part of a plastic material that could become microplastics if broken down into smaller pieces. As an example, see Figure 3, which depicts paint flakes that have been left after maintenance of a leisure boat. These flakes are made up of everything from polymers, pigments, and fillers, to even more, which should all be included when measuring the amount of microplastics.

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<sup>2</sup> [https://single-market-economy.ec.europa.eu/news/reach-committee-votes-restrict-intentional-microplastics-2023-04-27\\_en](https://single-market-economy.ec.europa.eu/news/reach-committee-votes-restrict-intentional-microplastics-2023-04-27_en), accessed 2023-09-20.



*Figure 3. Residue from paint that has been scraped off a leisure boat during maintenance.*

### *Use phase and end-of-life*

Once the paint is cured and used in the final product, factors such as wear and tear and service life of the specific product (i.e., building, boat, car etc.), as well as general standards for maintenance will determine how often repainting is needed. Paint is used in a wide range of applications, in which its lifespan can greatly vary. For example, coatings in architectural applications are designed to last anywhere from a few years up to 60 years. Some coatings are designed so they do not need to be reapplied while others might need maintenance several times during a building's lifetime (American Coatings Association, 2013; Paiano et al., 2021; PCI, 2021). Cars are often only repainted in cases where there has been external damage. If the car has no major accidents, only small scratches may require touch-ups, which will consume only small volumes of coating. The average lifespan of a passenger car in Sweden is between 15 and 20 years (Konsumentverket, 2023).

## **Microplastic emissions from paint**

Microplastic particles can be emitted at several stages in the value chain. From production, distribution, application, wear and tear, maintenance, and waste management. In this section different sectors, applications, and the estimated paint losses from these value chain components will be discussed.

Environment Action (EA) published a report in 2022 on plastic leakage from paint into the environment (Paruta et al., 2022). Most paints contain some form of plastic polymer after curing. These cured paints do not cause problems when they are coating their intended surface, in fact they are very useful because their properties can be tailored to suit different applications and protect the surface they cover. The problem arises when fragments of the paint end up in the wrong place. Wear and tear or improper handling of waste during maintenance and demolitions are some of the largest contributing factors resulting in microplastic release from paints. The risk and amount of microplastics that end up in the environment from maintenance and end of life materials with paint or coatings depends on the routines, methods, and knowledge of the person working with it.

According to the report published by EA, the largest volumes of plastic in paint are in paints used by the following sectors: architecture (55 %), general industry (15 %), automotive (10 %), marine (7 %), industrial wood (6 %) and road markings (1%). In Figure 4 these categories and the percentage of plastics in their paints have been plotted for comparison. The orange part of the bars corresponds to the share of the paint that is leaked to the environment according to EA's report. The graph shows that while the automotive sector in total uses more paint containing plastic, the paint used by the marine sector is estimated to have more leakage into the environment. It should be noted that the report by EA focuses only on polymer content. As mentioned in this report, we reason that the whole dry content of the paint should be included (including pigments, fillers etc.). Nevertheless, this still gives a good indication of which sectors to focus on.

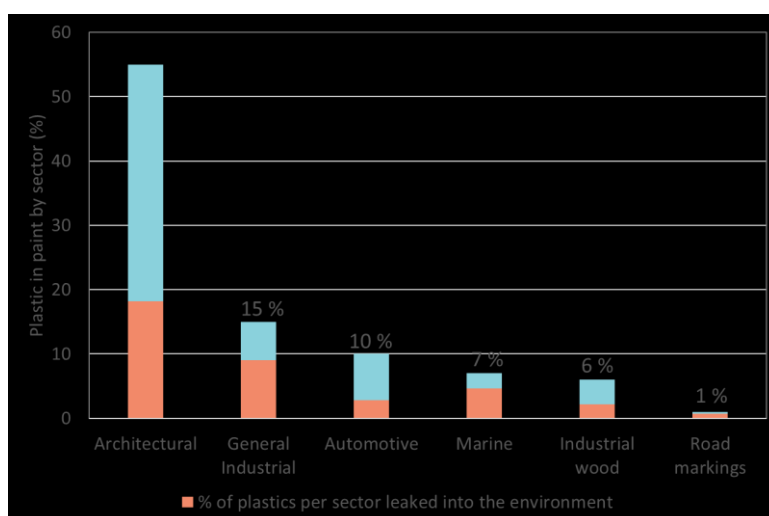


Figure 4. Yearly input of plastic in paint by sector, data is from 2019 (Paruta et al., 2022).

The data suggests that paint applications in the above mentioned sectors have the biggest release of microplastics into the environment. Therefore this report will focus on paints and coating applications in the following areas: architecture, general industry, automotive industry, and marine industry. In this report we include industrial wood applications in general industry. Road markings will not be covered in this report because it will be part of another project related to the road network, which is studied by the Swedish National Road and Transport Research Institute (VTI).

Paints that do not contain synthetic polymers or synthetic binders will not be covered in detail in this report since they do not lead to microplastics. However, some alternative paints and protective systems that are polymer-free will be briefly discussed.

The different categories of coating applications covered in this report have been divided according to Figure 5. Architecture covers coating applications both on the outside and inside of a building (i.e. roof, facade, window frames, doors, walls and many more) and that are used on many different materials (wood, metal and concrete and plaster). Marine includes coating applications used on boat hulls, other parts of boats and ships, and other constructions used in marine environments. General industry is a very broad category that covers almost anything that is painted in an industrial setting and automotive covers coating applications used for cars and other personal vehicles.

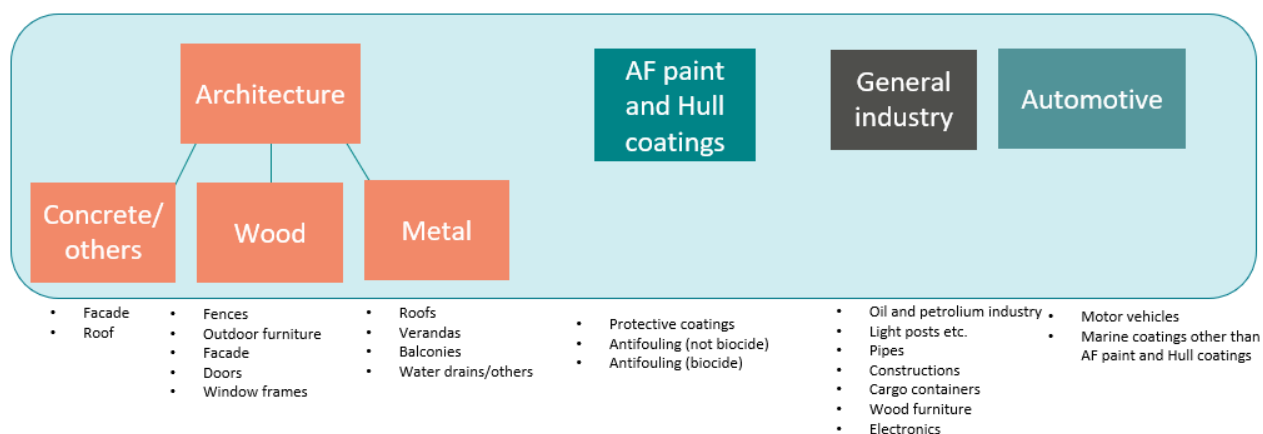


Figure 5. Different categories of coating applications covered in this report and some examples of their end use applications.

Several estimations on microplastic emissions from paint have already been made. The calculations for these estimations are often based on global emission factors provided by the OECD 2009 report.

While some use the OECD 2009 emission factors, others have adjusted the values based on local differences (Sundt et al., 2014). Paruta *et al.* also stated that data from wear and tear emissions is lacking and therefore developed their own method to calculate and determine emission factors for this stage (Paruta et al., 2022). However, these are based on a lot of assumptions and therefore cannot be used as indicators for the Swedish market. The variation in emission factors and microplastic content in different studies are presented in Table 1.

Table 1 Summary of different studies where microplastic emissions from paint has been estimated. Geographical area, painted object, emission factor and the definition of microplastic content are shown.

Reference	Geography	Calculated emissions from	Source of Emission factor	Microplastic definition	Calculation
<b>Plastic Paints the environment, EA 2022</b>	Global	Wear and tear – exterior concrete	Calculated/estimated 7.5%	Polymer content 37%	Based on own calculated models
		Wear and tear – exterior wood	Calculated/estimated 7.5%	Polymer content 37%	Based on own calculated models
		Wear and tear - interior	Calculated/estimated 1.5%	Polymer content 37%	Based on own calculated models

<b>MEPEX Sundt, Schulze &amp; Syversen, 2014</b>	Norway	Paint loss from professional use on large vessels	Adjusted OECD 2009 EF, to the situation in Norway 11%	Polymer binder content in marine paint 25%	Adjusted EF due to the poor wastewater treatment at shipyards in Norway.
		Protective coatings Loss during maintenance to soil and water	OECD 2009 6.4% EF for loss during maintenance of ships	Polymer binder content in marine paint 25%	Assume the same EF as for loss during maintenance on ships.
<b>IVL Magnusson et al. 2016</b>	Sweden	Protective coatings Loss during maintenance to water and soil	OECD 2009 EF for loss during maintenance of ships 6.4%	Polymer binder content 40%	
<b>Finnie, 2006</b>		Antifouling coating Loss from Wear and Tear	CEPE and some assumptions. 34%	Study on release of biocides, not plastics	CEPE considers all biocide in the antifouling paint to be released during the coating's lifetime. But emissions assumed is 34 % loss rate
<b>The Danish EPA Lassen et al. 2015</b>	Denmark	Architectural exterior paint Maintenance (incl. spill during application) and Weathering	2-6%	Solid content	

Total emissions of microplastics in Sweden have earlier been estimated to be 93 tons per year from protective coatings and 35-158 tons per year from decorative coatings (Magnusson et al., 2016). Calculations were calculated according to the following:

1. The volume of paint used per capita in EU was estimated from the total volume of paint put on the EU market and the total number of EU habitants in 2001.
2. The assumption that the proportion of paint used per capita in Sweden is the same as in EU.
3. The total volume of paint put on the Swedish market was then calculated based on values from 2 and the number of habitants in Sweden.
4. For protective coatings they apply the emission factors (EF) provided by OECD 2009 for losses during maintenance and abrasive



blasting of ships. They refer to another report (Sundt et al., 2014), in which authors argue that this factor can also be used for protective coatings.

5. For decorative coatings they apply an EF interval of 1,5% - 5%. The lower value originates from OECD 2009 and the upper value originates from a Norwegian report (Sundt et al., 2014), in which the authors have adjusted the OECD EF to also account for cleaning of surfaces and improper waste management in Norway.
6. The microplastic emissions are then calculated as the polymer content of paints (assumed an average value of 40%).

In this report we argue that all paint flakes rather than solely polymer content should be regarded as microplastics. To estimate the microplastic release from paint in Sweden we used two different calculation methods. In the first method, different EF were used to represent release at different stages of the paint's lifecycle. Most references for the EF based their calculations on the polymer content of the paints, but in this report the whole dry content was used. The dry content was estimated from technical data sheets for 10 different paints in architecture and 10 different paints in marine coatings, and used an average, a minimum, and a maximum value, to calculate a worst case and best-case scenario (see Table 2 for results). However, because of the big assumptions and uncertainties underlying this calculation, another simplified method was also used for comparison. In the simplified method, the total paint volume was calculated using the EF provided by Lassen *et al*, assuming that the release of microplastics in paint would be similar in Sweden and Denmark (Lassen et al., 2015). In this method only one EF is used for the whole life cycle of the paint (results are presented in Table 3). Both methods used data on annual paint volumes reported on the Swedish Chemicals Agency.

Because of the wide range of uncertainty and rough estimates when deciding on the emission factors, we have tried different methods to estimate microplastic release from paint in Sweden. In one case, the microplastic emissions have been estimated using a calculation with different emission factors for the different stages of the paint's lifecycle. Emission factors used for these estimates were based on those from different sources that could be found and calculated using the paint's dry content. In previous reports basing the calculations on the polymer content seems to be the most common approach, but we argue that the whole paint flake would be considered plastic, not just the polymer content. The following equation was used, and the results can be found in Table 2:

$$V_r = V_{tot} * wt\%_{volume\ solids} * (EF_{w\&t} + EF_m + EF_{EoL})$$

$V_r$  = Total volume of cured paint released per year

$V_{tot}$  = Total paint volume from KEMI

$wt\%_{volume\ solids}$  = Fraction of dry content in paint, i. e. VOC and water is excluded

$EF_{w\&t}$  = Emission factor for Wear and Tear

$EF_m$  = Emission factor for Maintenance

$EF_{EoL}$  = Emission factor for End of Life

Table 2. Estimated release of microplastics from paints in Sweden [ton/year].

Category	Volume wet paint (tons) placed on Swedish market 2021 <sup>a</sup>	Volume solids <sup>b</sup>	Emission factor			Total release (ton/year) <sup>f</sup>
			Wear and tear <sup>c</sup>	Maintenance <sup>d</sup>	EoL <sup>e</sup>	
<b>AF paint and hull coatings (low)</b>	780.8	47	1.0	6.4	1.0	30.8
<b>AF paint and hull coatings (average)</b>	780.8	59.8	1.75	20.2	5.5	128.2
<b>AF paint and hull coatings (high)</b>	780.8	85	2.5	34	10	308.6
<b>Architecture (low)</b>	21 023	28.5	1.5	1.0	1.0	209.7
<b>Architecture (average)</b>	21 023	47.7	4.5	3.7	5.5	1 373.1
<b>Architecture (high)</b>	21 023	74	7.5	6.4	10	3 718.2

<sup>a)</sup> Volume as reported to the Swedish product register at the Swedish Chemicals Agency.

<sup>b)</sup> Volume solids estimated based on 10 different paints technical datasheets for architectural paints and 10 marine coatings with the lowest, highest and average value.

<sup>c)</sup> Release factor for wear and tear (architectural coatings) is estimated from EA's report plastic paints the environment 2022. 7.5 % is for outdoors and 1.5 % for indoor coatings. Lassen et al (2015) assumes a loss for marine paints during the paints life to be between 10-50 %. Because self-polishing paints are continuously hydrolyzed and dissolved over time, and according to conversations with Jotun 95% of antifouling paints placed on the market is soft self-polishing paint, 10-50% seems like an over-estimation. It is more likely that it would be 50% of the non-self-polishing paints, which would give a release factor of 2.5% on average for all paints. With their lower limit set to 10 % but applied to only 95% of the paint we get 0.5% release factor, however here we have rounded it up to 1%.

<sup>d)</sup> Release factor for maintenance is most likely high for marine coatings but for architecture in Sweden there are requirements that the paint should be removed with wet blasting and the waste should be collected. OECD claims up to 6.4% can be set as a release factor for architecture, we chose this as worst case. For best case we chose 1 % since probably not exactly all particles will be collected. For marine coatings according to Finnie 2006 the release is between 6.4 % and 34 %.

<sup>e)</sup> End of life probably does not emit as much microplastics as the other categories but EA assumed a n emission factor as 10% during waste for architecture. In lack of data for this for marine coatings, we will also assume 10 % as worst case in this category.

It should be noted that these calculations are very simplified and do not consider many of the different maintenance steps etc. that are likely to occur, but rather only consider the emission factors during the different steps in the paint's lifecycle. The emission factors are also based on what we found in the literature, but a lot of data used for these emission factors is insufficient or based on theoretical estimates and there is no exact data for Sweden. Because of this the calculations have been made as intervals of different emission factors that were found (high vs low).

The Swedish product register have data on annual quantities of paint for different applications and this can be used to calculate an estimation of microplastic emissions from coatings in Sweden. However, many industrial applications are coated abroad and arrive in Sweden already coated. Some are also coated in Sweden and exported. Similarly in the automotive industry, many vehicles are coated prior to being imported to Sweden. Because of this, even if there is data on annual quantities of these paints in Sweden, it is not a good representation of how much actually ends up in the country that could be released as microplastics. Therefore, we have chosen to exclude general industry and the automotive industry when doing estimated calculations of microplastic emissions from coatings in Sweden. Paint for marine and architectural coatings are more commonly painted in the country compared to the other mentioned applications. Therefore, we have only done calculations for these categories. Considering that the general industry is considered one of the largest paint sectors where the paint gets released into the environment, it is problematic that it is not possible to get estimated numbers for this sector. A suggestion is therefore to assume that the release of microplastics from paints in this category would be in quantity somewhere in between the amounts released by architectural and marine paints.

These estimates have given an approximation of the annual release of microplastics from paint in Sweden at between 30 – 308 tons/year for marine coatings and 209 – 3 718 tons/ year for architectural coatings. Compared to the numbers given by Magnusson *et al.* (2016) (93 and 35-158 tons per year, respectively) our approximations are much higher, but still on a similar order of magnitude. Partially, this is to be expected since the whole dry content of the paints have been included in our calculations rather than just polymer content. Furthermore, while Magnusson *et al.*, estimated the volume of paint put on the Swedish market from the volume of paint put on the EU market, our calculation uses input values provided from the Swedish

Product Register. Uncertainties related to data from the Swedish Product Register are discussed under the section *Proposal for indicators for the dispersion of microplastics to the environment from paint*. Magnusson et al. also estimated annual releases of microplastics from materials other than paint. For example, release of synthetic fibers from textiles was estimated to be between 8 – 956 tons annually. Emissions from industrial production of plastic pellets were estimated to be between 12 – 235 tons in the same report. When looking at the total release of microplastics from paint we have to also consider that the number will be higher since we have not been able to estimate any emissions from general industry or the automotive sector. However, the estimated releases from paint are of similar orders of magnitude to the estimated releases from textiles and plastic pellet production, making it one of the largest sources of microplastic emission in Sweden. Thus, working to minimize release of microplastics from paint is highly relevant.

In the sector of general industry, spray painting is the dominating application technique. In the literature it is estimated that about 30 % of paint is lost during spray painting (Sundt et al., 2014). Of course, the amount of overspray and resulting spread to the environment is very dependent on the conditions during the application such as temperature, wind, location (indoors or outdoors), and how well the area has been shielded off, so exactly how much is lost to the environment is unknown. Spray application performed indoors in industrial settings in Sweden is generally handled well and release to the environment is low. However, when application is performed before products are imported to Sweden, it is not possible to estimate how much is released during application. Wet paint is usually spread through the air as fine drops that eventually end up in the environment as dried cured paint, giving rise to microplastic particles (Sundt et al., 2014). However, when application is performed before products are imported to Sweden, it is not possible to estimate how much is released.

Unlike the calculations for paint microplastic emissions used in Paruta *et al.*, Lassen *et al.* used only one emission factor for the whole life cycle of the paint for their calculations. For architectural paint it was assumed that 1-4 % of all the paint put on the Danish market would be released during the paint's lifetime. For marine coatings this estimate was instead 1-20 %. Using only one emission factor is simpler and since all release factors of microplastics from paints are based on several assumptions and estimates this could be a good methodology for estimating paint microplastic emissions that is easier to use. Here we have applied the same release factors as Lassen *et al.* to the volume of paint placed on the Swedish market.

In table 3 the calculated microplastic emission in Sweden have been compared to the estimated microplastics release on the Danish market presented by Lassen *et al.* Applying the same releases factors to the data from the Swedish product register gives quite similar numbers to the emissions estimated for Denmark by Lassen *et al.*

Table 3. Estimated release of microplastics from architecture and marine coatings based on emission factors from Lassen *et al.*

Category	Annual volume (tons) <sup>(a)</sup>	Release factor (%) <sup>(b)</sup>	Release in Sweden per year (tons)	Release in Denmark (tons) <sup>(c)</sup>
<b>Architecture</b>	21023	1	210	190
		4	840	570
<b>Marine</b>	780	2	15.6	16
		20	156	150

<sup>a)</sup> Paint on the Swedish market according to the Swedish product register.

<sup>b)</sup> Release factor used by Lassen *et al.*

<sup>c)</sup> Release estimated by Lassen *et al.* in Denmark. Average paint consumption was set to 9500 ton/year based on the interval stated as 7000-12000 tons/year.

## Architecture

Architectural paint is used on the exterior and interior of buildings. Applications include coatings on roofs, walls, and decking. Exterior coatings are used to provide aesthetic characteristics as well as protection to the underlying surface.

On a global scale, the architectural paint sector is recognized as one of the larger contributors to microplastics release from paint, accounting for 48% of global paint-related plastic pollution (Paruta *et al.*, 2022; Swedish EPA, 2022b). According to Paruta *et al.* (2022), most paints remain on the building until the end-of-life (EOL). Around 15% will be lost to the environment from wear and tear and 10% will be lost through repainting. Leakage rates were estimated to be 23% for interior paint, 71% for exterior wood, and 46% for exterior concrete. However, while the study investigates the global situation, the contribution of microplastics from exterior paint during weathering may be different in Sweden (Paruta *et al.*, 2022). Knowing exactly how the paint will degrade and be released as microplastics is very complex and therefore difficult to estimate. The degradation is dependent on many different variables. Some of the main parameters that affect degradation rate include UV irradiation, painted

surface texture, paint quality, building orientation, distance from sea (atmospheric levels of salt), wind, and rain (Gaylarde et al., 2020). There is however a general lack of knowledge about the emissions from architectural paint. Estimations in the literature have often been based on theoretical calculations and estimates and have not necessarily been following model studies such as accelerated testing. A problem is that there is no standardization or harmonized way to do the theoretical estimates of microplastic emissions from paint so it may be difficult to compare the results between different reports and studies.

Although more detailed modelling approaches have been proposed by Paruta *et al.* (2021), these cannot be proposed as suitable indicators for architectural paint at this stage. As mentioned, several assumptions have been made and the used values to estimate the exposure factors (based on the literature) may not be representative for Sweden. Using the models for an indicator would require more data such as quantities of how much paint is sold to different sectors with more details, how much unused paint is handed in to recycling stations as hazardous waste, how often maintenance is performed, measurements on how much paint is released during different parts of its lifecycle, and many other parameters relevant for Swedish conditions.

### **Interior paint**

Indoor paint is mostly used for aesthetic reasons. Since the indoor environment does not vary so much temperature, moisture, and corrosion protection are not significant concerns, and the paint therefor does not have to achieve as difficult technical requirements as many outdoor paints. Since the ventilation indoors is often limited and we spend a lot of our time indoors, a large focus on indoor paint development has been in decreasing potential health risks. For example, some key aspects that are considered include minimizing toxic chemicals, using less volatile organic compounds, and having more water-borne systems. Waterborne acrylic paints are commonly used for indoor wall paint.

Studies have indicated a higher microplastic leakage from exterior paint compared to interior paint (M. Faber et al., 2021; Paruta et al., 2022). The primary leakage from indoor paints is associated with the washing of paint from brushes and rollers, rather than at the end of their service life. As mentioned, intentionally added microplastics can be released during these steps, but the volumes are considered low since the whole paint is not considered a plastic in the wet state. Furthermore, intentionally added microplastics will be restricted according to REACH legislation and it can

be expected that the risk of release from wet paint will therefore further decrease.

To some extent indoor paint might lead to microplastic emissions during demolitions where dust and particles may lead to direct environmental emissions. However, in this report it is postulated that the volume of released microplastics is larger for outdoor applications, as both removal work and wear and tear often lead to direct losses to the environment (M. Faber et al., 2021; Paruta et al., 2022). There is also less wear to indoor paint since it is subjected to more constant temperatures, less UV exposure, and other less harsh conditions than outdoor paints. Harsher outdoor conditions can cause cracks ultimately leading to paint flaking off outdoors. Many materials, such as metals, wood, and concrete can to some extent expand and contract at different temperatures. This also requires the paint used to be somewhat flexible to prevent cracks from forming.

In Sweden, wood is often turned into smaller wood chips in an outdoor facility to make it more manageable before being incinerated. The process often generates a lot of dust. If the wood is coated, microplastics could be generated and released during this process. Similarly, concrete is often grinded down to smaller pieces outdoors, during which process some of the paint from the concrete if coated might lead to release of microplastics (see Figure 6); however, there is no data available on the microplastic quantities released<sup>34</sup>.



<sup>3</sup> Personal communication with Maria Ahlm, Jan-Olov Sundqvist, Alexandra Almasi, IVL Swedish Environmental Institute, June 2023

<sup>4</sup> Personal communication with Jon Nilsson-Djerf på Avfall Sverige 2023-06-13.



*Figure 6. Demolitions of a building. The concrete is grinded down into smaller pieces, during which process some of the paint may form microplastics or particles that spread to the surrounding environment.*

Varnished or painted floors will be worn down. These particles will be collected by vacuum cleaning or wet cleaning where some portion may be flushed away into the sewer (Lassen et al., 2015).

### **Exterior concrete**

While in some cases concrete can be kept without a surface coating, it may be advantageous to add a finish that prevents moisture and dirt from penetrating the material that is to some extent porous. Moisture can cause damage if frost is formed (Alcro, 2023). Outdoor concrete paints are therefore often epoxy- or acrylic-based as this can give good protection and seal the surface so moisture does not penetrate (EPODEX, 2023; ResinCoat, 2023).

### **Exterior wood**

Because wood shrinks and expands a lot due to temperature and moisture changes outdoors, a flexible coating is required to prevent film-cracking. Good coating options include alkyd-based coatings where the fatty acids provide a bit more flexibility. Acrylate coatings are also commonly used for outdoor wood applications (de Meijer, 2001; M. Faber et al., 2021).

Paints are most common in siding, windows, and doors, while dyes and sealers are more commonly used on decks, cabinets, furniture, and flooring. Oil-based preservatives are utilized for many industrial applications such as



railroads and utility poles. Water-borne surface treatments are more commonly used indoors. (Teaca et al., 2019)

Service life is difficult to predict since coatings are very complex formulations and their interaction with wood, which is a biological material, can vary greatly due to climate and other conditions. On average the service life of exterior wood coatings is between 1-3 years. (Nejad et al., 2017)

### **Exterior metals**

Exterior metal coatings play an important role in preventing metal corrosion, which could have detrimental effects to a construction. There are alternatives to traditional polymer-based coatings such as galvanizing steel, different kinds of alloy combinations that create metal-oxide films, and other types of metal mixtures as coatings. (SSAB, 2023)

The coatings can be applied in different ways. Coating application examples for metals for exterior use include hot-dip galvanizing, thermally spraying coating, and coil coating. Polymer-based coatings for outdoor metal applications can have a binder consisting of polyurethane, alkyd, acrylic, epoxy, oxirane esters, or chlorinated rubber. It is also possible to have a paint that is zinc-rich, which gives extra good corrosion protection. This works in a similar way to galvanizing steel, but the difference is that the zinc is distributed in the coating, and you also have a binder. Depending on which mechanical properties you want from the coating, different kinds of polymeric binder can be chosen but they are often epoxy, alkyl silicate, or some kind of resin that is physically drying. (Tikkurila, 2023)

### **Microplastic emission**

Paruta *et al.* estimate that 33 % of paints in the architectural sector will eventually end up in the environment (Paruta et al., 2022). The majority of microplastic emissions from architectural paint is generated from wear and tear and poor waste management at end of life; for example during renovations or demolitions. It is also assumed that most emissions end up in soil rather than the marine environment.

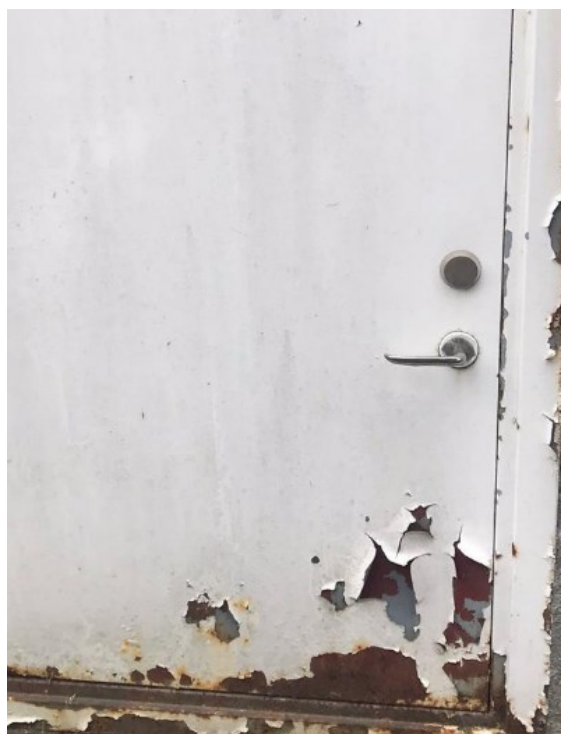
Material losses are estimated to be between 4.8 – 7.9 % from unused paint, and the loss rate from spray painting has been estimated to be somewhere between 19 – 35 %. During brush application, it is estimated that 1.6 % of the paint is lost. However, as mentioned previously, only intentionally added microplastics should be considered as a possible release of microplastics at the stage when the paint is still wet, meaning that the majority of the paint and pre-polymer content should be excluded when estimating potential microplastic release at this stage. Furthermore, these

estimates are mainly based on over spraying, and estimate the amount of paint that does not end up on the intended surface, but the majority of this paint is still collected and not necessarily spread to the environment (Hann et al., 2018), (International Labour Office, 2012), (OECD, 2009), (International Labour Office, 2012).

Substance flow analyses in Denmark assume that about 3-4% of paint that is applied outdoors is lost to the environment during maintenance (re-painting), about 25 % is lost to sewage from paved areas due to abrasion during the lifetime of the paint, and the rest ends up in soil (Lassen et al., 2015).

Lassen *et al.* assumed that the consumption of paint from outdoor applications on buildings is 7,000-12,000 t/year (dry weight) and an emission factor of 2-6% was applied for the whole paint lifecycle. Out of this, it was assumed that 10-30% of the release is discharged to the sewage system and 2-10% is released to surface water. 15-25% of the quantity that reaches the sewage system was assumed to ultimately reach the aquatic environment because the particles are so small. (Lassen et al. 2003).

Release from wear and tear is not considered a big volume for indoor paint applications. However, for outdoor use, it is estimated to be about 7.5 %.



*Figure 7. Paint that has come off due to wear and underlying corrosion on a coated door.*

Figure 7 shows a door outdoors some years after painting. To remove the rust and paint that has already cracked and started coming off, the door

would typically be scraped and sanded before it is re-painted. During removal, the potential release of plastics depends on if the area is shielded to prevent spreading by wind, and to what extent the solid waste is collected. It is more likely that sanding and blasting will cause direct release of microplastic particles, whereas material generated by scraping is easier to collect and dispose of but can also degrade into microplastics if left outside.

In Sweden, there are regulations on maintenance of facades and roofs. When a surface area is over 500 square meters it should be washed or blasted. The responsibility lies with the property owner who has to notify the municipality before the work is begun (Klimat- och näringslivs departementet, 2013). The property owner or contractor is also responsible for protecting the surroundings from disturbance such as noise, dust, and water splashes from cleaning. However, it is not known to what extent this is followed. Random inspections would provide a better picture of how well this is followed. If smaller areas are going to be washed or blasted, no notification is necessary, but the property owner and the contractor are still required to not release waste nor affect the surrounding environment.

For interior paint, it is assumed most of the waste generated is collected so microplastic emissions are most likely low. 5-30 % of exterior paint is collected according to Paruta *et al.* meaning that the rest is released into the environment through different pathways. At end of life, they estimate that roughly 10 % of the losses from all architectural paint are lost as dust from demolitions. Dust formation during demolitions has been studied a lot, primarily because fine particles in the air are a known hazard to human health. To some extent it is reasonable to assume that some residue paint on walls is spread via the fine dust formed during demolitions; however, there is no quantitative data available regarding this. Paruta *et al.* estimated that microplastic release originating from paint during demolitions is 10 % and that overall the total release of microplastics from all the different parts of the life cycle of architectural paints according to Figure 8 is 3 573 kilo tons.

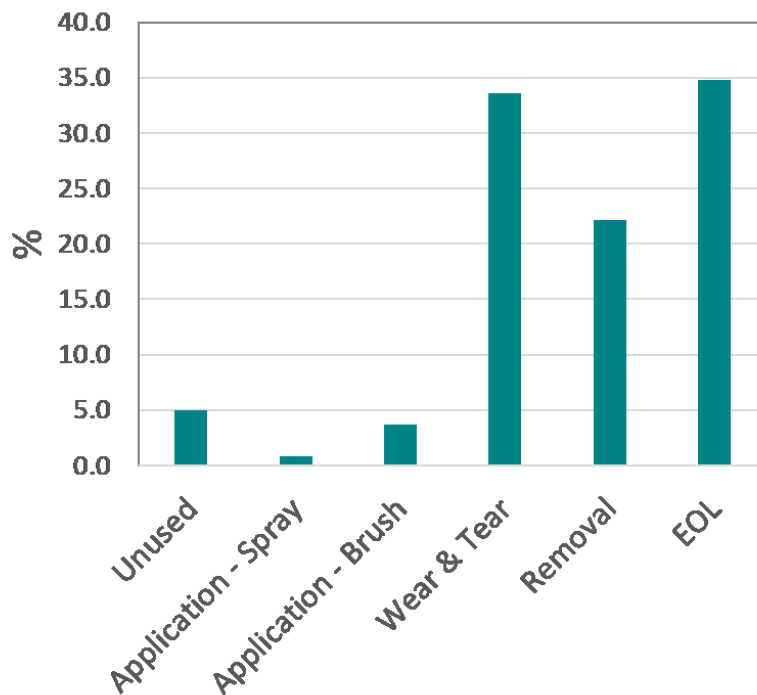


Figure 8. Estimate of the largest micro-plastic release areas during the life-cycle of architectural paints. (Paruta et al., 2022)

After demolitions most of the paint will follow the supporting material and end up in a recycling process of concrete, in a land fill, or in waste to incineration. As mentioned, wood is typically grinded down into smaller pieces that are more manageable at end of life before finally being incinerated. If wood is painted or treated, the paint is not removed; however, the treated wood when classified as hazardous waste is collected in a separate waste stream and sent to incineration, and thus will not be grinded down as finely as the untreated wood<sup>56</sup>.

### Monitoring

Dust from demolitions has been analyzed mainly to monitor dust formation, but the exact quantity of microplastic emissions from architectural paint and coatings is not known. There should be potential to screen for microplastics near/at demolition sites.

In an ongoing project in France, performed by RISE Institute De La Corrosion, an accelerated weathering test is set up where the release of microplastics (and particles) from styrene acrylic based paint, applied on concrete facades, is studied.

<sup>5</sup> Personal communication with Maria Ahlm, Jan-Olov Sundqvist, Alexandra Almasi June 2023.

<sup>6</sup> Personal communication with Jon Nilsson-Djerf på Avfall Sverige 2023-06-13.

## Antifouling paint and hull coatings

Hull coatings and antifouling (AF) paint are both included in the term *Marine coatings*. The definition of marine coatings is ambiguous. Tamburri (2022) define marine coatings as any coating or coating system that is used on the outside of a ship, above or below the waterline. Others describe marine coatings as any coating applied to surfaces in the vicinity of the marine environment (including inland waters). Either way, these coatings cover a wide span of applications (superstructure, ballast tanks, inside potable water tank, on deck, boat hulls, structures of oil rigs, buoys, propellers etc.) and several of these coatings also fall under *Industrial coatings*. In this report, antifouling paint and hull coatings will be discussed as one separate sector, while other marine coatings are included in *General industry*.

The term hull coatings includes both corrosion protective coatings and AF paint. Corrosion-protective coatings are applied to metal surfaces and are mostly used on commercial vessels. While boat hulls of commercial vessels are generally painted with both anti-corrosion coatings and AF paint (except icebreakers where fouling is removed by the ice<sup>7</sup>), leisure boat hulls exclusively rely on AF paint (Unsbo et al., 2022). Hull coatings on commercial ships generally consist of several layers often composed of a primer (anti-corrosive), an intermediate (tie-coat) and a topcoat (antifouling or cosmetic finish) (Paruta et al., 2022; Tamburri, 2022)<sup>8</sup>. Due to the multilayer system on commercial ships, the film thickness can be twice as thick compared to the antifouling paint layer applied on leisure boats<sup>9</sup>.

AF paint is applied to boat hulls of leisure and commercial boats, and other submerged marine objects to prevent marine biofouling (growth of aquatic organisms) (M. Faber et al., 2021). It also serves to provide a smooth clean surface with minimum drag force to reduce speed loss and aid fuel saving (Soon et al., 2021)<sup>10</sup>.

The traditional **self-polishing** AF paint relies on a self-release mechanism where fouling organisms together with the paint are slowly released from the surface when the boat is moving. The binder is generally made up of acrylic polymers. One of the world's largest paint producers Jotun estimates

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<sup>7</sup> Personal communication with Jotun Sverige, 2023-05-26.

<sup>8</sup> Personal communication with Jotun Sverige, 2023-05-26.

<sup>9</sup> Personal communication with Jotun Sverige, 2023-05-26.

<sup>10</sup> <https://www.international-marine.com/>

that self-polishing paint accounts for approximately 95% of the antifouling paint put on the Swedish market<sup>11</sup>.

For **contact-leaking** AF paint (hard paint), the biocide (e.g., copper) is released through diffusion until it is entirely consumed, the binder in these paints does not erode and an intact depleted porous matrix paint is then left behind. **Ablative paint** (soft paint) is based on a seawater soluble rosin binder. Both biocide and paint are released into the water.

**Foul-release coatings** (FRC) are alternatives to biocide-containing paint. These coatings rely on silicone or fluoropolymers but all commercially available FRCs are based on silicone. The coating is composed of crosslinked silicone elastomers, often poly (dimethylsiloxane) (PDMS), providing a smooth layer to which the aquatic organisms cannot strongly attach. Fouling is then removed when the boat is moving (Bighiu, 2017; Lagerström et al., 2022).

Antifouling properties can be provided through physical or biocidal mechanisms. Soft paint (including self-polishing paint) and hard paint rely on biocidal mechanisms, while foul-release coatings does generally not contain biocides (M. Faber et al., 2021; Lagerström, 2019).

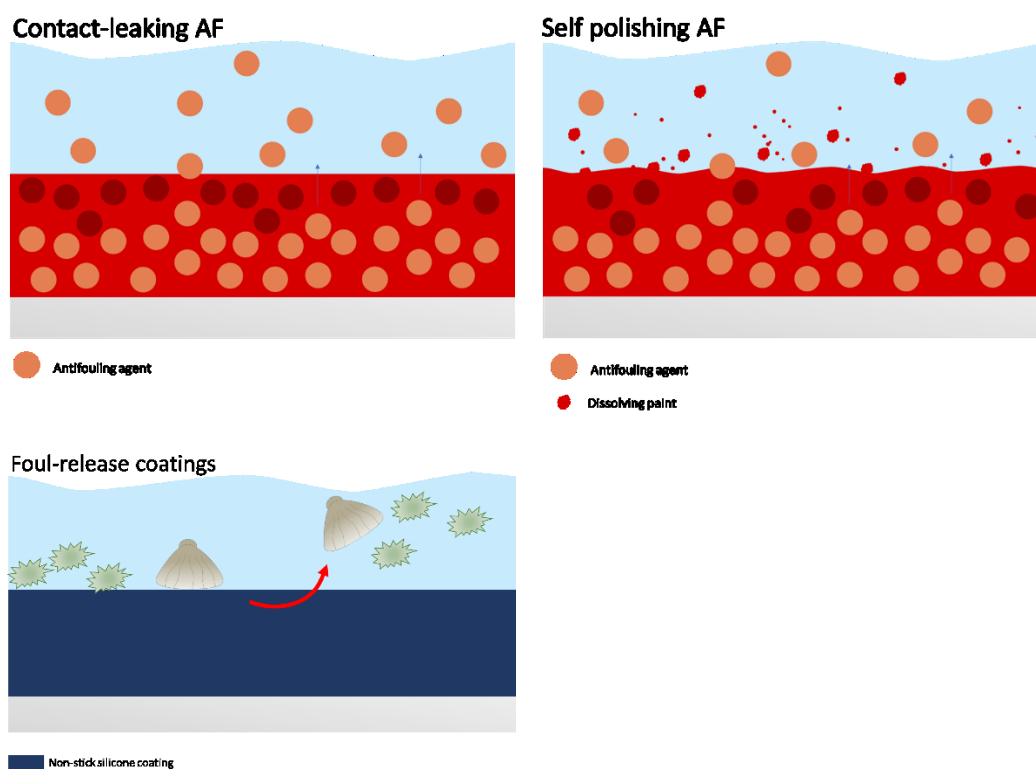


Figure 9. Mechanisms of contact-leaking (hard) antifouling paint vs self-polishing (soft) antifouling paint. In the self-polishing systems, the paint network is dissolved slowly in water. This will not result

<sup>11</sup> Personal communication with Jotun Sverige, 2023-05-26.

*in microplastics. In foul-release coatings, the surface is non-stick meaning different plants and organisms cannot attach to the surface. The red, respectively the blue layer depicted here are a simplification and may consist of several different layers, e.g. primer, top coat etc.*

## **AF paints and hull coatings in Sweden**

In 2020, “Båtlivsundersökningen”(Lagerqvist, 2021) estimated that there are 948 000 leisure boats in Sweden, whereof 864 200 that were seaworthy (remaining part is either subject to reparation or categorized as wreck). The fleet was dominated by small boats (44% of the total) e.g., small open boats with engines < 10hp, kayaks, and rowing boats. Around 20% of all leisure boats were painted with hull coatings where self-polishing AF paint is most used in Sweden, estimated to account for 95% of the antifouling paint sold<sup>12</sup>.

### *Restrictions on use of AF paint*

Different types of antifouling paint are allowed in different regions of Sweden. The conditions of use are established by the Swedish Chemicals Agency and based on the sensitivity of the marine environment to the toxic effect of the biocide of the paint, and on the fouling pressure. Biocide-containing hull coatings are forbidden in inland waters and different types of paint are allowed on the east and west coasts<sup>1314</sup>.

Moreover, AF paint intended for use on commercial vessels are restricted to commercial vessels only and may not be used on leisure boats. This is because they contain higher concentrations of active substance compared to AF paint intended for use on leisure boats<sup>15</sup>.

## **Microplastic emission**

Antifouling paint and hull coatings have lately gained increased attention as a source of microplastic emission (Dibke et al., 2021; Paruta et al., 2022). Hull coatings on commercial vessels have been pointed out as the major source of microplastic emissions within the marine sector on a global scale (Paruta et al., 2022).

The release of microplastic particles arise when paint particles are released during application (spill), use (weathering or collisions), in-water cleaning (IWC) of biofouling, maintenance (scraping and repainting), and at EOL (waste management) (Gaylarde et al., 2021; Paruta et al., 2022). The total

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<sup>12</sup> Personal communication with Jotun via email, 2023-06-09.

<sup>13</sup> <https://www.transportstyrelsen.se/globalassets/global/publikationer-och-rapporter/sjofart/tran-044-broschyr-batbottenfarg-a5-webb.pdf>

<sup>14</sup> <https://www.kemi.se/rad-till-privatpersoner/kemikalier-i-hemmet-och-pa-fritiden/batbottenfarger#h-Olikavillkorpavastkustenochostkusten>

<sup>15</sup> <https://www.transportstyrelsen.se/globalassets/global/publikationer-och-rapporter/sjofart/tran-044-broschyr-batbottenfarg-a5-webb.pdf>

emission as well as the leakage rate may vary between different activities (application, use, maintenance, EOL), types of coatings, and between the leisure and commercial sector. The EA report conducted by Paruta et al. (2022) suggested that the stages during a marine paint's life cycle that lead to the most emissions to nature are from wear and tear, removal, and end of life (see Figure 10) (Paruta et al., 2022; Tamburri, 2022).

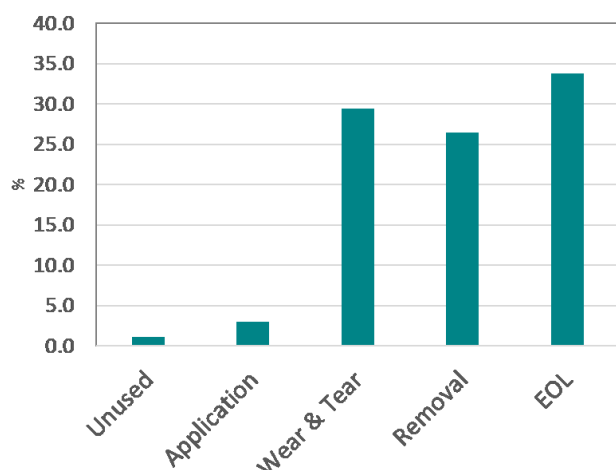


Figure 10. Estimated release of paint to the environment during the different stages of a marine coating. The total release was estimated as 911 tons annually. (Paruta et al., 2022)

### *Wear and tear*

The antifouling mechanism of self-polishing AF paint and soft AF paint rely on the release of paint matrix and biocide. These polymers are however generally understood to be released as hydrophilic and water-soluble polymers rather than particulate matter or microplastic particles (M.N. et al Tamburri 2022), and hence should not be considered microplastics. In such cases, the amount of paint released from hulls under water should be subtracted in flux calculations.

Hard paint and foul-release coatings, on the other hand, are not designed to be released into the water column but may still give rise to microplastic emissions during application and through weathering and degradation due to concurrent environmental factors (e.g., ultraviolet radiation, mechanical stress from wave and wind, seawater, and microorganisms) (Min et al., 2020).

Even if some silicone-based fouling is estimated to release no or little biocide it could potentially give rise to larger emissions of microplastics compared to other AF-paints<sup>16</sup>.

Today, there is little or no information available on the microplastic leakage rate from different types of hull paints when boats are in waters.

<sup>16</sup> Personal communication with Jotun 2023-05-26.



Representative emission factors are difficult to calculate due to the complexity of influencing factors such as UV radiation, water temperature, salinity (Tamburri, 2022).

#### *Maintenance (Removal and re-application)*

Large emissions have been estimated during maintenance work of commercial and leisure boats, when coatings are removed, and a new layer of paint is applied (Gaylarde et al., 2021). Dibke *et al.* (2021) also indicated that large emissions take place during use when boats are at sea. Even if some studies provide estimations on emissions, their calculations are often based on several assumptions and use different loss types and leakage rates. Furthermore, the definitions of microplastic seems to vary. Several studies equalize microplastic with polymer content of the coating (Paruta et al., 2022) while others argue that the whole paint flake should be considered (e.g., The European Council of the Paint, Printing Ink, and Artist's Colours Industry (CEPE)). This makes it difficult to compare numbers from different reports and studies.

Most studies look globally or focus on specific countries, and the influencing parameters may be different in Sweden (paint type, climate, use pattern, performance of boat maintenance).

Given the nature of maritime traffic and considering the potential spread of particles through wind and water, emissions ending up in Sweden do not necessarily equal the emissions of microplastics by Sweden. Many ships driving in Swedish waters are painted in other countries, subsequently leaving behind emissions in Swedish waters, and vice versa. Similarly, a large portion of the debris found on the beaches in Bohuslän are estimated to originate from other countries (Svärd, 2013), and a similar scenario might be expected for microplastic emissions from ships. Development of emission factors are challenging. In Sweden challenges arise from diversity in climate (south and north, west, east and central), seasonal variability, different types of paint and coatings allowed in different regions, user behaviour and environmental awareness, various methods of boat maintenance, differences between the commercial and leisure sectors, and finally since there are no standardized methods available for measuring the release of microplastics.

#### *Maintenance of Leisure boats in Sweden*

Maintenance of leisure boats in Sweden are often performed in close vicinity to the sea.

According to the guidelines for Swedish marinas published in 2012 all boats painted with hull paint should be cleaned at specified surfaces with flush plates, and wastewater should be filtered.

The survey “Båtlivsundersökningen 2020” indicated that 76% of the boat owners perform maintenance by themselves, while only 5% have the boat serviced by a boatyard/marina (Lagerqvist, 2021). Despite the guidelines, most boat owners perform cleaning, scraping, and repainting where the boats are parked, and do not collect their waste (Ejhed et al., 2018). The paint scraped off generally ends up in the surrounding environment (Eklund et al., 2014).

A study performed in 2018 showed that in the city of Stockholm only a few marinas were equipped with a specific washing area where wastewater and particulate material is collected and treated (Ejhed et al., 2018). Since then, more than 10 new hull washing areas have been installed in the area, but there are still many marinas that lack the infrastructure.

Even where advanced wastewater treatment plants have been installed, the efficiency of capturing microplastic particles is unknown. For example, there is often a lack of routines to control the status of the filters before they need to be replaced or cleaned. And the filter capacity with respect to the number of boats that can be washed per hour without overloading the system is often unknown.

Quality checks have furthermore focused on the emissions of biocides rather than on microplastic leakage. The situation in Stockholm may not be representative for the rest of Sweden since The Environmental Administration of Stockholm has been working more actively with the topic compared to other parts of Sweden.

However, a study on the release of biocides from hull washing areas on the Swedish west and east coasts indicated that a major part of the leakage takes place when boats are in use and during high-pressure cleaning before the waste and wastewater reaches the first step in the water treatment plant (See figure 11). This indicates that most of the paint released during high-pressure cleaning on a hull washing area will be separated in the flush chute separator and only a minor part enters the water treatment plant (Ytreberg, 2012). Hence, if more boat owners wash their boats on hull washing areas, the microplastic leakage could be largely reduced.

Even if the focus has been on biocides rather than microplastics, the same scenario could be expected for microplastic leakage since the larger fragments collected in the first step (flush chute separator) are constituted of paint flakes.

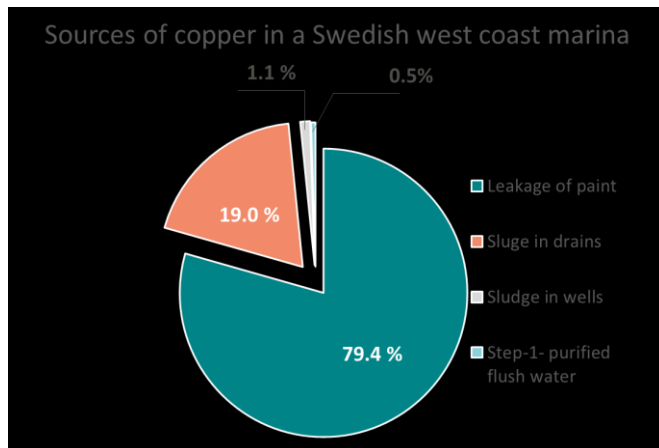


Figure 11 Approximate leakage of copper during one boat season, data from ITM 215 (Ytreberg, 2012).

A recent study investigated paint particle emissions from decontamination of hull paint applying six decontamination methods commonly used by owners of leisure boats. Their results showed that methods such as scraping and grinding give rise to particle sizes that are easily spread by wind, thus indicating higher risk of leakage to the environment (Lorén et al., 2021). In drive-in boat washes fouling is removed by rotating mechanical brushes under water, and the waste is collected in an enclosed basin around the boat to avoid spread of organic material and paint residues. However, a pre-study conducted by the University of Gothenburg and Vågenkonsult indicated increased concentrations of paint particles in adjacent water directly after washing, compared to before washing. Unsuitable paints on the boat hulls that were washed, and lack of maintenance of the enclosing barriers around the water basin was observed as contributing to the spread of particles (Hassellöv et al., 2011). This shows the importance of maintaining the system, and spreading information about the conditions for using a drive-in boat wash (types of AF paint used and when it was applied).

#### *Maintenance of Commercial ships in Sweden*

AF paint and hull coatings used for commercial vessels generally have a longer lifespan compared to AF paint designed for leisure boats. According to the SOLAS regulation (International Convention for the Safety of Life at Sea) maintenance of the protective coating system shall be included in the overall ship's maintenance scheme where a complete survey of the hull must be performed twice within a five-year period.

Hull cleaning on commercial vessels during in-service periods (between full maintenance in dry docking) has often been carried out through in-water cleaning (IWC) performed by divers or remotely operated systems

(Tamburri et al., 2020). During IWC paint particles are released from the hull either by brushing or water jet where the brush-based technology is most used. The type of brush used may vary depending on the curvature of the surface and fouling situation. During cleaning paint particles are often released from the hull directly into the surrounding water. The release depends on the type of antifouling paint, fouling organisms attached, and cleaning method (Granhag et al., 2023).

Recently, capture technology in association with IWC has been developed to trap paint emissions and the previous simple in-water cleaning technique has transit into a safer in-water cleaning and capture (IWCC) technique (Tamburri et al., 2020). However, the waste handling depends on the operator and type of system. Different capturing systems are available and described by (Granhag et al., 2023).

An industrial standard for in-water cleaning with capture that includes wastewater quality requirements has been developed by industry in cooperation with hull cleaning companies (“Industry standard on in-water cleaning with capture,” 2021). The concentration and size of paint particles in the effluent and surrounding water can be analyzed for total suspended solids (TSS) and particle size distribution (PDS). (Granhag et al., 2023). Sampling design for water quality has been suggested for example by (Tamburri et al., 2020).

In Sweden, in-water cleaning is performed by divers at sea and in ports but no information on the use of the IWCC techniques were found. Paint particles released from biocide-containing AF paint should be handled as hazardous waste according to the Swedish waste regulation. However, biocide-free AF paint is not covered by the regulation but may still give rise to microplastic particles.

Hull maintenance of commercial ships in Sweden is performed in dry docks and can be categorized in three steps; 1. *Cleaning*, 2. *Pre-treatment* and 3. *Painting*. Ships are initially cleaned with a high-pressure washer, followed by pre-treatment<sup>17</sup>. Wastewater is often managed in associated wastewater management systems. However, even if shipyards have installed filters in their wastewater treatment plant, to reduce emissions, the efficiency of these filters to separate microplastic particles are generally unknown (Ejhed et al., 2018)<sup>18</sup>.

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<sup>17</sup> Personal communication with Oresund Drydocks AB 2023-06-01

<sup>18</sup> Personal communication with Oresund Drydocks AB 2023-06-01

Requirements on wastewater treatment depend on the type of operating permit. Shipyards having older permits may have no requirements at all, while more recent permits only have vague requirements stating that wastewater treatment is required<sup>19</sup>. There are however requirements on maximum concentrations of e.g., copper in effluent wastewater, and the concentration of copper could be expected to somewhat correlate to the amount of microplastic released.

Microplastic particles are spread into the air during blasting and some shipyards have methods of limiting the spread while others don't (Ejhed et al., 2018)<sup>20</sup>. When it comes to the application of paint, 99% of the coatings applied in dry docks during maintenance are applied through spray painting<sup>21</sup>. During spray painting a large fraction could be expected to be lost to the environment. For example, Paruta *et al.* (2022) estimate that 15% are leaked due to overspray.

Even if dry docking often takes place abroad (e.g., Denmark, Poland, Germany, China, South Korea)<sup>22</sup>, there are still four shipyards performing maintenance on larger ships in dry docks in Sweden. These are Oresund Drydocks AB (Landskrona), Falkvarv (Falkenberg), Stockholms reparationsvarv, and Oskarshamns varv<sup>23</sup>. Table 4 present the maintenance procedure at Oresund Drydocks. They estimate that around 50-60 ships are managed every year.

Table 4. Maintenance procedure at Oresund Drydocks.

Step	Method	Waste management
<b>1 Cleaning</b>	Salts and fouling are cleaned off using high-pressure washing.	Paint particles are released and contained in the wastewater. The wastewater flows into a chamber and are subsequently filtered before finally led out into the sea.

<sup>19</sup> Personal communication with Oresund Drydocks AB 2023-06-01

<sup>20</sup> Personal communication with Oresund Drydocks AB 2023-06-01

<sup>21</sup> Personal communication with Oresund Drydocks AB 2023-06-01

<sup>22</sup> Personal communication with Jotun, via e-mail, June 2023.

<sup>23</sup> Personal communication with Oresund Drydocks AB 2023-06-01

<b>2 Pre-treatment</b>	Pre-treatment can be carried out using four different methods: <ol style="list-style-type: none"> <li>1. Grinding</li> <li>2. Traditional grit-blasting with metal-containing particles</li> <li>3. Water blasting which has been increasingly used during the past years.</li> <li>4. A combination of 2 and 3 with grit injection into high pressure water</li> </ol>	A larger amount of waste is created during traditional grit-blasting. Waste collection is primarily carried out directly after blasting using manual brushing and robot brushing. The waste is then collected by an approved transport and finally sent to recycling. In some cases, the waste can be put on a landfill.
<b>3 Painting</b>	The coating systems on both topside (above waterline) and bottom (below waterline) consist of three system levels, all applied by spray-painting: <ol style="list-style-type: none"> <li>1. Primer (for attachment)</li> <li>2. Intermediate (paint)</li> <li>3. Topcoat (refinish and for the bottom antifouling)</li> </ol>	No waste collecting system. At Oresund Drydocks however, to prevent spread of particles, management approval is required for painting when wind speed exceeds 6 m/s.

While shipyards only carry out maintenance, the shipping companies are the ones deciding the type of coating systems to be used. This decision is taken when the ship is painted for the very first time and the same coating system will be continuously used in subsequent maintenance. Paint is supplied by the shipping companies. The companies applying the paint report the volumes of unused paint (numbers of unopened units) to the shipyard who then estimates the volumes of paint used. Unused paint is either returned to the paint supplier or to the ship owner<sup>24</sup>.

*Guidance on hull cleaning and surveillance inspections for enforcement*

“Skrovmålet” was a platform for cooperation among national authorities, with the aim to reduce negative effects of hazardous substances in antifouling paints for leisure boats. In 2021, the platform provided recommendations on safe removal of antifouling paint from hulls. Suitable methods of removal are described and include blasting with sand or carbonic acid, gel coating and scraping, grinding, and dry scraping.

The network and objectives of Skrovmålet was later assimilated within action no. 17 of the Swedish programme of measures according to the Marine Strategy Framework Directive. Within action 17, as a complement

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<sup>24</sup> Personal communication with Oresund Drydocks AB 2023-06-01

to the recommendation (above) for local enforcement authorities, the Swedish EPA developed guidelines<sup>25</sup> for safe maintenance of leisure boats and the correct disposal of the discarded coating

Furthermore, guidance on hull cleaning methods of commercial ships (action 15) and leisure boats (action 17) aimed at operators and enforcement authorities are currently under development. The work is coordinated by The Swedish EPA and involves development of guidelines on hull cleaning methods (including requirements on e.g., filtering methods for minimizing the dispersion of hazardous substances, as well as Invasive Alien Species (IAS) and other fouling organisms and micro plastics) and waste management. Within action 15, a compilation of knowledge of available in-water cleaning techniques for ship hulls (including filtering and minimizing the spread of hazardous substances) was produced in 2023.

Even if most focus have earlier been on the biocides, microplastic emissions have lately gained increased attention and in their opinion in consultation on unintentionally produced microplastics The Swedish EPA mentioned that emissions of microplastics could possibly be included in the knowledge compilation of in-water cleaning techniques.

### ***Boats at their End of Life***

Boats at their end-of-life face different possible fates. Abandoned leisure boats are often encountered in areas close to housing or sea. In “Båtlivsundersökningen 2020” it was estimated that around 85 000 leisure boats in Sweden are at their end-of life. This corresponds to 9% of the total number of leisure boats.

Unlike e.g., cars, boats are currently not covered by producer responsibility (even if the Swedish Agency for Marine and Water Management has recently proposed the implementation of such a responsibility<sup>26</sup>) and municipal recycling centres do not generally manage boats since boats are regarded as operational waste (and not municipal waste)<sup>27</sup>. However, there are still some municipal recycling facilities accepting boats to be handed in<sup>28</sup>.

Båttretur is a national network for collection and recycling of leisure boats in an environmental manner. The network is a cooperation between Sweboat,

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<sup>25</sup> <https://www.naturvardsverket.se/vagledning-och-stod/branscher-och-verksamheter/skrovsanering-av-batbottenfarg/>

<sup>26</sup> <https://www.havochvatten.se/arkiv/aktuellt/2023-09-04-uttjanta-och-overgivna-fritidsbatar-vaxande-problem.html>

<sup>27</sup> Personal communication with Avfall Sverige 2023-06-13.

<sup>28</sup> Personal communication with Båtskroten 2023-06-13.

Båtskroten Sverige AB and Stena Recycling. Boat scrapping is managed by Båttretur Sverige AB. The network is nationwide with around 30 recycling centres around Sweden. Private persons, boat clubs, shipyards, municipalities, or other operators are included actors able to hand in their boats for scrapping. A variety of boats are managed e.g., small, and large boats, wooden boats, sailboats with fiberglass<sup>29</sup>.

Scrapping a leisure boat is however associated with both time and cost. The boat must be transported to the recycling centre which then charges a fee of 3 500kr/ton<sup>30,31</sup>. Abandoned boats may be left in the environment for many years, contributing to leaking of paint and other chemicals. To reduce the number of abandoned boats the Swedish Agency for Marine and Water Management announced a scrapping campaign between 2018-2020, resumed 2022 and will continue during 2023. The campaign is led by Båttretur and includes boats with weight 100kg – 10 ton<sup>32</sup>. Around 200 leisure boats are scrapped by “Båtskroten” every year. However, during the years of the scrapping campaign the number has increased to 500-700<sup>33</sup>. According to “Båtlivsundersökningen 2020” 49% of all boat owners have no interest in scrapping a wreck or repair object. Given the number of boats scrapped each year it is obvious that many end-of-life boats appears in the environment, giving rise to microplastic emissions.

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<sup>29</sup> <https://xn--btretur-exa.se/>

<sup>30</sup> [https://www.havochvatten.se/miljopaverkan-och-atgarder/miljopaverkan/foreningar-och-farliga-amnen/fritidsbatar/skrotning-av-fritidsbatar.html#con-contact\\_heading](https://www.havochvatten.se/miljopaverkan-och-atgarder/miljopaverkan/foreningar-och-farliga-amnen/fritidsbatar/skrotning-av-fritidsbatar.html#con-contact_heading)

<sup>31</sup> <https://batunionen.se/miljo/batmiljo-for-batklubbar/batatervinning/>

<sup>32</sup> [https://www.havochvatten.se/miljopaverkan-och-atgarder/miljopaverkan/foreningar-och-farliga-amnen/fritidsbatar/skrotning-av-fritidsbatar.html#con-contact\\_heading](https://www.havochvatten.se/miljopaverkan-och-atgarder/miljopaverkan/foreningar-och-farliga-amnen/fritidsbatar/skrotning-av-fritidsbatar.html#con-contact_heading)

<sup>33</sup> Personal communication with Båtskroten via e-mail 2023-06-02.





*Figure 12 Leisure boats at a recycling facility, photo by Maria Rindstam at Båtskroten Sverige AB.*

End-of-life ships with a gross tonnage (GT) above 500 are covered by the EU regulation on ship recycling, 1257/2013 and must be recycled at authorized recycling centres<sup>34</sup>. The ships are handed in to certified shipyards (for such activities) in Europe or at similar facilities outside Europe. The boat is then cut into pieces and the scrapping material is subsequently sold<sup>35</sup>. Only one commercial vessel has been scrapped in Sweden during the last five years<sup>36</sup>.

The Swedish Transport Agency has currently no information about the number of ships scrapped every year, or the total number of end-of-life boats in Sweden<sup>37</sup>. This could however possibly be provided from the boatyards or docking companies.

### **Monitoring**

As concluded by (Unsbo et al., 2022) there is generally little information available about the actual presence and distribution of microplastic particles originating from antifouling paints and hull coatings and most studies have focused on biocides. No harmonized methods for monitoring of microplastic emission from hull paint exists in the EU. However, initiatives are taken not only on EU level but also by the paint industry. The paint industry takes initiatives aiming at finding new knowledge about microplastic emissions

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<sup>34</sup> <https://www.naturvardsverket.se/verktyg-och-tjanster/ansokan-om-tillstand/auktorisering-av-anlaggningar-for-fartygsatervinning/om-fartygsatervinning>

<sup>35</sup> Personal communication with Oresund Drydocks AB 2023-06-01

<sup>36</sup> Personal communication with the Swedish Transport Agency via e-mail, June 2023.

<sup>37</sup> Personal communication with The Swedish Transport Agency 2023-06-16.

from AF paint and hull coatings, and at developing new methods of measuring the release under standardized conditions (Gondikas et al., 2023).

## General industry

Industrial coatings are defined by protective properties rather than aesthetics, even if they can provide both<sup>38 39</sup>. Use applications include e.g., aircrafts, infrastructure, fences, roller coasters, pipelines, petrochemical applications, oil and gas, cargo containers, power generation, offshore, mailboxes, indoor wood applications, and marine coatings (therein antifouling paint). Corrosion-protective coatings on steel or concrete account for the most used industrial coatings<sup>40</sup>(AkzoNobel, 2023; Beckers Group, 2023; Makhlouf, 2011). Annual costs associated with corrosion and preventative measures are large. This is understandable since corrosion can lead to structural failures with dramatic consequences such as failures of bridges, buildings, aircrafts, and gas pipelines (Sørensen et al., 2009).

Anticorrosive coating systems often consist of multiple layers with different properties. Typically, a primer with anti-corrosive properties will be applied first. It may contain zinc or other inhibitive pigments to give it anti-corrosive properties. The primer is often followed by an intermediate coat that has some different functions. It is partly used to build thickness but also to promote transport of aggressive species to the substrate surface. At the same time, it must have good adhesion to both the primer and the topcoat. The final layer, the topcoat, must have good gloss and colour retention as well as resistance to weathering. The protective mechanism can be either by having a barrier effect, inhibitive effect, or galvanic effect. (Sørensen et al., 2009). Industrial coatings are generally applied by spray painting but other methods include electro coating and dip coating. (Makhlouf, 2011).

### *Marine coatings*

In this report marine coatings include protective coatings used in marine environments e.g., coating systems used on the topside and superstructure of a ship, cargo containers, pipelines, bridges, wharfs, and buoys. Hull coatings and architectures in the vicinity of the sea are not included in this section as these are discussed separately.

Various coatings are used within the marine sector. Even if all marine coatings provide corrosion protective properties, they are also fine-tuned to serve other specific functions in their area of use. For example, coatings

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<sup>38</sup> <https://www.cepe.org/about-the-industry/>

<sup>39</sup> <https://coatings.org.uk/page/Industrial>

<sup>40</sup> <https://coatings.org.uk/page/Microplastic-Paint-in-the-Ocean>

used on the outside of structures are also provided with low solar absorbance. Deck coatings must have non-skid functions to prevent slippery surfaces<sup>41</sup> while cargo tanks carrying liquid cargo faces other challenges when getting in contact with different chemicals.

Paint used on commercial ships can be described in a paint-lifecycle. This paint-lifecycle can be divided into three parts i.e., painting of the newly constructed ship, repainting during maintenance in drydocks (every 3-5 year), and continuous reparation work onboard while at sea. Each part accounts for 1/3 of the total volumes of paint used during the lifecycle of a ship<sup>42</sup>.

Since 1/3 of the paint used during the life of a ship are used on touch-up jobs carried out onboard the ship, the same amount could be expected to have been lost to the environment. Touch-up jobs are generally performed using rollers or brushes while repainting during maintenance are carried out by spray painting.

According to the SOLAS regulation (International Convention for the Safety of Life at Sea) passenger vessels must dry dock for inspection of the underwater part of the hull twice during a five-year period, all other commercial vessels once during the same period. During drydocking, top side and boot top are generally re-coated for maintenance reasons (the same applies to the bottom part but this was discussed in the section on antifouling paint). Even if there are no requirements on re-coating the areas above the water this is often preferred to be carried out while the ship is docked and out of use. Top side and boot top coatings are also subjected to weathering, and will be worn down over time, and to passenger vessels the appearance is of high importance. Maintenance of these coatings during dry docking is necessary to maintain its protective function and appearance. This means that top sides and boot tops go through similar procedure as the bottom part during dry docking. This was earlier discussed in more detail in the section “Antifouling and hull coatings” of this report<sup>43</sup>.

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<sup>41</sup> <https://www.international-marine.com/in-focus/safety-and-efficiency-on-non-slip-decks>

<sup>42</sup> Personal communication with Jotun 2023-05-26.

<sup>43</sup> Personal communication with Oresund Drydocks AB via e-mail, June 2023.

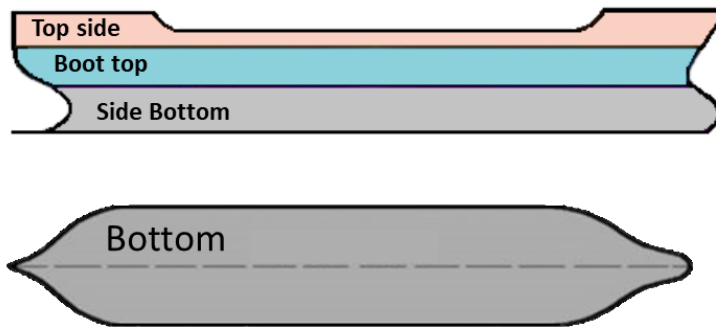


Figure 13 Different parts on a commercial ship.

### Infrastructures

Infrastructures include systems such as water supply, communication systems, ports and harbours, bridges, tunnels, power generation, rail- and road constructions, trains, and busses. Beyond these infrastructures involved in essential functions, playgrounds, sports facilities, and other outdoor objects are also covered by the definition (e.g., fences, walls). Associated buildings e.g., at airports or sports facilities will however not be discussed in this section, since they are covered under Architecture.

Paints and coatings used for infrastructure are often applied by spray painting when large areas need to be covered. Other methods of application suitable for some objects include brushing, rollers, or dip coating<sup>44</sup>.

Some constructions are coated abroad (during construction) and thereafter shipped to Sweden. This is especially the case for steel bridges<sup>45</sup>. Other constructions often coated abroad are:

- steel constructions e.g., frame structures for buildings, some types of roadside barriers, and sandwich elements for building
- building parts made of wood e.g., playground equipment or prefabricated noise barriers<sup>46</sup>.

During maintenance the worksite is often covered with e.g., protective plastic or something similar, in order to reduce over spraying and paint particles ending up in the environment. When a surface is going to be painted, some over spray is usually accounted for when planning how much paint should be purchased based on previous experience, but how much paint is released to the environment is not known. Of the paint lost, some percentage may account for e.g., uneven application or for paint trapped in

<sup>44</sup> <https://www.aexcelcorp.com/resources/guides/industrial-coatings-guide#:~:text=Industrial%20coatings%20protect%20materials%20and,type%20requiring%20carefully%20crafted%20formulating.>

<sup>45</sup> Personal communication with Jotun 2023-05-26.

<sup>46</sup> Personal communication with NCC via e-mail, June 2023.

the protective plastic. However, some paint could be expected to have been lost to the environment and those amounts may vary depending on e.g., the degree of coverage and weather conditions.

Often rehabilitation of these structures can be more difficult than coating a new structure or repairing one that has been completely sandblasted. One of the difficulties is that the surface preparation of the existing coating is complicated. When spot painting, small and isolated rust spots are removed, and these surface areas need to be located and removed without damaging the rest of the surface still in good condition. Three techniques are generally used for bridge maintenance: spot cleaning, overcoating, and complete recoating. Galvanizing and oxidized steel are other common ways to protect industrial constructions from corrosion; however, for large sections the possibility to do this is limited and in such cases coating with paints is usually preferred. Old coating is typically removed during maintenance by dry abrasive blasting, wet abrasive blasting, or wet blasting. Dry abrasive blasting is efficient, but it is difficult to contain the airborne particles that arise during this process. Wet abrasive blasting is a more environmentally friendly as the particles can be contained; however, there is an increased risk for rusting, which can occur shortly after this kind of treatment (Iizuka, 1988).

NCC estimates that around 80% of all coated construction objects are precoated during manufacturing before reaching their destination<sup>47</sup>. This; however, also includes building constructions and the share of precoated objects used in construction of infrastructure could possibly be even higher.

#### *Industrial production and processes*

Protective coatings are also used in different industrial process systems e.g., the production or packaging of food, pharmacy, feed, textiles, chemicals, and other. For use in these process systems, coatings may face other challenges compared to coatings used in the marine environment. For example, many materials are in direct contact with valuable chemicals (critical additives, high-value end products) and must not only resist corrosion and breakdown, but also stay inert, and not contaminate the product<sup>48</sup>.

Microplastic emissions from these coatings could be expected to be small. Machines and equipment are industrially coated under controlled processes with regulated waste management. Little or no microplastic release takes place during operations since these are carried out in controlled indoor

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<sup>47</sup> Personal communication with NCC via e-mail, June 2023.

<sup>48</sup> <https://www.jotun.com/ww-en/industries/solutions-and-brands/tankfast/overview>

environments. At end-of-life, parts are sent to recycling where coatings are destroyed during metal melt down, and no longer regarded as microplastic<sup>4950</sup>.

### *Indoor painted objects*

Even if outdoor painted objects account for the larger part of paint-related microplastic emissions, paints used on indoor objects may account for a large share of the total amount of paint used. While the report focuses on painted outdoor objects, painted indoor objects will only be briefly discussed.

Indoor painted objects include e.g., furnishings (kitchen cabinets, paintings, decorations, ornaments, lamps), furniture, wooden toys, accessories, and sports equipment. Many of these objects are painted before reaching retail stores and subsequently arriving at the end user ready-painted. However, compared to other areas of use, indoor painted objects are generally repainted for aesthetic rather than functional reasons. Depending on the size and availability of working spots, painting may take place outdoors, in a garage, in an available workshop, or inside a house. Application is most likely carried out using a brush or roller. These objects often have high second-hand value and the number of owners and repainting layers may vary widely. When reaching their final end-of-life stage, the objects are in most cases handed in at recycling centres or thrown away as household waste. Small emissions are expected at this stage for these objects.

Microplastic emissions may arise during sanding and paint application when objects are painted outdoors. The order of magnitude of microplastic emissions related to this activity is unknown, at least in part due to the lack of information about the number of repaint jobs performed and where they take place.

### *End-of-life*

During end of life, metals are often considered high value and will be recycled. Coated metals will most likely be combusted during the metal-reworking process and it is not expected that a large amount of microplastics from paint will be released compared to the rest of its service

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<sup>49</sup> Personal communication with Emma Larsson at Beckers Industrial Coatings AB, June 2023.

<sup>50</sup> Personal communication with Per-Erik Sundell June, 2023.

life. From other kinds of materials, such as concrete, there might be a larger number of formations of microplastics from paint during demolitions<sup>51,52</sup>.

### **Microplastic emission**

Generally, a lot of the industrial applications for outdoor use e.g., oil rigs, pipelines, refineries, steel bridges, etc. are constructed to last a long time. Even though it is difficult to provide reliable data on the emissions, Paruta *et al.* assumed that 70 % of paint will be handled and disposed of properly at end of life from these kinds of applications. (Paruta et al., 2022).

If a business is classified as environmentally hazardous, which is common for a lot of paint producers, this means a permit from the country board is needed. The permit states how large your annual production volume is allowed to be, and inspections will be carried out by the local municipality to make sure that the company follows regulations and demands defined in the permit. The only likely emission of microplastics at this stage would be if there is intentionally added microplastics in the paint or its raw materials, and there is an accident causing a spill outdoors. But accidents are not the norm and cannot be followed by any indicator. Companies work to minimize the risk of such accidents by for example not having floor drain inside the production area, not handling chemicals outdoors, and managing a spill if it were to occur quickly according to their routines<sup>53</sup> (Lst Stockholm, 2023).

Instead, it is estimated that weathering and maintenance are the primary activities contributing to paint microplastic emissions, and exterior building paint, antifouling paint on ships, and high-performance coatings on bridges and road markings have been pointed out as especially contributing areas<sup>54</sup>. Paint particles released from the exterior of objects due to weathering will be released directly into the environment. Maintenance of infrastructures, offshore rigs, and other constructions are carried out onsite and large emissions can be expected during this work. Blasting is often used for cleaning surfaces of these types of structures. Paruta *et al.* have estimated that 60 % of all paints in general industry applications will eventually end up in the environment. The amounts estimated by Paruta et al., for different parts of the life cycle are presented in Figure 14. Since it may be difficult to prevent dust from spreading when surfaces are sanded, it seems reasonable

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<sup>51</sup> Personal communication with Avfall Sverige 2023-06-13

<sup>52</sup> Personal communication with Personal communication with Maria Ahlm, Jan-Olov Sundqvist, Alexandra Almasi at IVL Swedish Environmental Institute, June 2023

<sup>53</sup> Personal communication with Emma Larsson at Beckers Industrial Coatings AB, June 2023.

<sup>54</sup> <https://coatings.org.uk/page/Microplastic-Paint-in-the-Ocean>

to estimate that the removal of old paint during maintenance is one of the greater contributing areas of possible microplastic emissions. But in Sweden, precautionary measures are required during maintenance of buildings. It can be assumed that all outdoor paints will end up in the environment from wear and tear, so it is also reasonable to assume that this part of the life cycle is one of the main contributors to microplastic emissions from industrial paints. The assumed proportion of microplastics released from use application seems rather high. Often the estimations are based on over spraying, this is often well known since it is necessary to know the volume of paint needed for an object and over-spraying is often included in the estimations of the total volume of paint needed. However, the amount of paint from over spraying that ends up in the environment is not known. If spraying is performed indoors, it can be assumed that little or no emissions to the environment happen. If spraying is performed outdoors, this will depend on further factors such as temperature and wind, but the majority of over spraying most likely ends up on the protective covers around the area where the object is being coated. The release of microplastics proposed by Paruta *et al.* is presented in figure 14. It shows which parts in a paint's lifecycle contribute most to microplastic release. The release during application seems somewhat high and in total they have estimated that 60 % of all the paint will be released to the environment, which also seems like an overestimate.

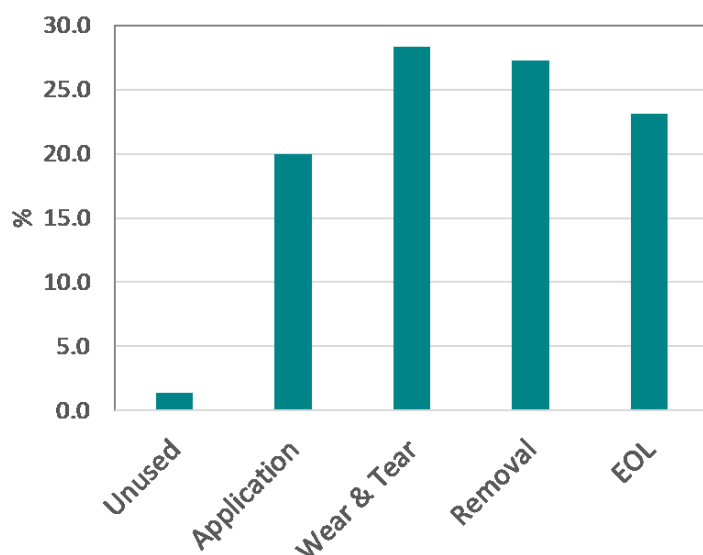


Figure 14. Estimate of the largest micro-plastic release areas during the life-cycle of general industry coatings. (Paruta *et al.*, 2022)

## Monitoring

There is generally little information available about the actual presence and distribution of microplastic particles originating from general industrial



paints. No harmonized methods for monitoring of microplastic emission from these applications exist.

## Automotive

Cars are often coated with several different layers, most commonly: a primer, a primer surfacer and a topcoat or a basecoat followed by a clearcoat. The primer is often applied by electro disposition and the other layers by spraying. The most common automotive coatings are based on polyesters, alkyd resins, acrylic resins, amino resins, polyurethanes, polyisocyanates, epoxy resins and some cellulose esters.

Electro deposition is based on transport of electrically charged particles in a medium to a surface with an opposite charge. The automobile body can be immersed in an electrodeposition bath. By the flow of electricity, the charged particles cover all the surface of the automobile body and results in a very evenly coated surface. For example if a polyester has carboxylic acid end groups, these can become negatively charged and applied using this method (Poth, 2008).

According to the report by EA, the largest part of material losses is accounted for during spraying/application. In larger production facilities, companies have harsher requirements on for example VOC emissions. They are generally good at working in enclosed areas and minimizing release of paint to the environment. Furthermore, spraying is performed indoors so the leakage to the environment can be estimated as low, even if there is a lot of over-spraying.

Smaller service garages and companies may have a lower requirement on following up and reporting release of waste and environmentally hazardous materials. Potentially this means that some paint might be released into the environment to a greater extent compared to larger industries. However, when vehicles are repainted, it is also mostly done indoors in a parking garage or service garage. It is therefore unlikely that the volumes of environmental microplastic leakage is comparable to the repainting of constructions, buildings, boats, and other objects outdoors. Some microplastics may be released during scratches and other road accidents, but the amount of paint that comes off in these situations is not large compared to other sectors. Large surfaces are not sanded down outdoors and you rarely see paint flaking off a car which is more common in the other mentioned sectors (Poth, 2008).

When a car is recycled, it is turned into scraps, after which mainly the metal parts are melted and recycled. Non-metal parts such as coatings and some plastic components are incinerated (Yue, 2012).

### **Microplastic emission**

Emissions of microplastics can arise from wet paint during application if it contains intentionally added microplastics, or from dry paint upon removal during maintenance or weathering. Poor waste management during maintenance or scraping is also a potential risk for release of microplastics.

According to Paruta *et al.* 28 % of all automotive coatings will eventually end up in the environment where a large part of material losses is accounted for during the application. However, as already discussed, this is usually done in a controlled indoor environment, so it stands to reason that the leakage rates to the environment are still lower than other stages of the life cycle. Moreover, as mentioned already, the wet paint should not be considered as microplastics unless it contains intentionally added microplastics. Compared to other sectors wear and tear as well as removal has a low micro-plastic leakage rate.

There is a general lack of knowledge about the total contributions of emission of microplastics from paint and therefore estimations are often based on theoretical calculations focusing on either one or a few sectors. The results vary depending on the causes that have been accounted for, and which wear and tear as well as removal rates have been used.

Paruta *et al.*, 2022 used a new modelling approach for different causes of emission, including e.g., wear and tear and removal processes. These calculations: however, are based on several assumptions e.g., loss rates and number of repaint jobs. The largest environmental emissions of microplastics from this sector are assumed to come from end-of-life, according to EA this is due to the mismanagement of waste. But in the report, there was no specific analysis or study on automotive paint at the end of life. Instead, it was assumed that the fate of paint is the same as the rest of automotive solid waste. Even though the end of life is the highest risk for microplastic leakage, the volume is still quite low compared to that from architectural coatings, and lower than that from general industry applications as well as marine coatings. Figure 15 shows an overview of the microplastic release during the different stages of paint in automotive applications. (Paruta et al., 2022)

When vehicles are discarded, they are fragmented into smaller parts and the metal is often recycled, during which most of the paint that consists of organic material is incinerated during metal reprocessing.

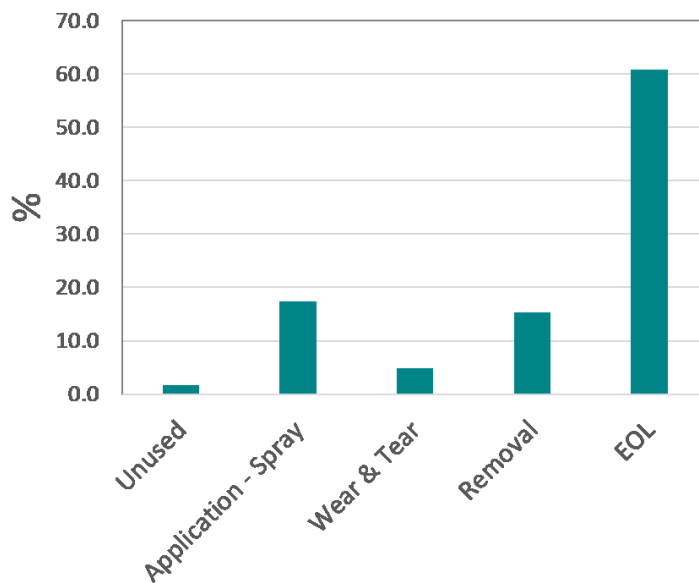


Figure 15. Estimate of the largest micro-plastic release areas during the life-cycle of automotive coatings. (Paruta et al., 2022)

### Monitoring

No harmonized methods for monitoring of microplastic emissions for automotive coatings exists.

## Areas of use with a higher risk of leakage of microplastics

As earlier discussed, during paint application in a controlled environment, such as in a factory or industrial process, leakage to the environment should be minimal. Most losses that cause microplastic release to the environment occur when paints are applied outdoors or used in applications outdoors and released from wear and maintenance (M. Faber et al., 2021), regardless of sector. During application of non-industrial paints, in particular during consumer use, there is potentially a large amount of mishandling of paint brushes and other tools. Often it is stated on the packaging or in documentation such as the safety data sheet that the paint should not be washed off in the sink, but residues if not more left in the brushes and other tools can be assumed to still end up in the sewage system. The Swedish Paint and Adhesive Association (SVEFF) also have instructions on their website on how to handle paint waste and how to wash brushes and rollers after use (SVEFF, 2023). However, as discussed, most of this is not necessarily microplastics at this point since the paint is not cured. It may however contain intentionally added microplastics to some extent. Another important aspect is that if the paint sticks to different surfaces in the sewage

system and cures, it may subsequently form microplastics when it later breaks down to smaller fragments.

Even if AF paint and hull coatings do not account for the largest share of the total volume of paint put on the Swedish market, the risk of leakage to the environment from these sources is high. A major part of the emissions ends up in close vicinity to the source (e.g., harbours) and generally sensitive areas. The concentration of paint particles nearby the source could possibly be expected to be higher for AF paint and hull coatings, compared to architectural paint. Especially for urban areas with large areas of asphalt where it is likely that paint released from buildings is washed away by rain and enters the sewage system. No information about concentrations of paint-related microplastic particles in the vicinity of likely sources (or in stormwater or domestic wastewater) was found. However, the topic is being discussed and new initiatives are taken. Knowledge about the actual concentrations of microplastic particles from paint in areas associated to a possible source would provide further understanding on paint-related microplastic emissions.

## **Alternatives to plastic-containing paints and varnishes**

While coatings are commonly made with a polymeric binder, there are some alternatives that are free of synthetic polymers and thus would not lead to any microplastics. Polymer-free paint for outdoor applications has been explored, in which graphene and lime ( $\text{CaCO}_3$ ) are used instead.

Improvements have been made; however, the coatings are quite rigid and brittle. For applications made from materials that expand and shrink this can easily lead to cracks in the coating. But it can be good as an indoor wall paint, where the material does not move much (M. Faber et al., 2021). Lime-based coatings are therefore mostly suitable for stone, brick, and terracotta.<sup>55</sup>

Mud paint is another alternative that can be used on wood and is commonly applied to wood facades. The paint is made from pigment that has been extracted from clay, burned, and then mixed with vegetable oils (typically linseed oil). The linseed oil cures to some extent with oxidation, but the dry paint is still biodegradable (Falun Rödfärg, 2023) (Lazzari and Chiantore, 1999) (Morsch et al., 2017). There are also vitriols, such as iron sulphate and copper-based wood stains. These can be applied to change the colour of

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<sup>55</sup> <https://www.archiexpo.com/architecture-design-manufacturer/lime-based-coating-3832.html>

wood but provide no protection against biological attack or moisture (Swedish Wood, 2023). There is also wood that is treated with fire retardants and moisture protected.<sup>56</sup> For metal substrates other alternatives for corrosion protection are galvanizing, using metal alloys that form protective oxide layers, and using corrosion inhibitors.

Some powder coatings are also free of polymers (M. Faber et al., 2021). They might still contain substances that are not good for the environment; however, these coatings will not lead to microplastic emissions.

Not all mineral-based coatings contain nanoparticles; however, many contain substances such as titanium dioxide, calcium carbonate, and zinc oxide that according to the European Chemical Agency (ECHA) are to some extent used in nano form within the EU. This means that the paints could contain nano-particles which can have potential negative impacts on health if inhaled. This could be a handling risk for workers if they are exposed to dust formed by these components for example when blending paint ingredients.

## **Areas of use and situations where plastic-containing paints and varnishes are preferred**

Even though there are some alternatives to paints and coatings containing polymeric binders, for a lot of applications these are still the most suitable alternatives. They offer the protection necessary for the application and thanks to the widespread availability of polymers and additives, the coating can really be tailored to suit a wide range of products. Moving forward, focus should not be on trying to exclude paint, but rather on how it is managed in the different stages of its life cycle.

## **Regulations and ongoing work**

### *ECHA restriction*

Paints are a source for both primary and secondary microplastic emissions. The majority of microplastic emissions from paint are in the form of secondary microplastics by release of fragments of cured paint. Secondary microplastics will not be targeted by the restriction proposed by ECHA, which therefore suggests that this regulation will not have a large impact on the amount of microplastics released from paints and coatings. (M. Faber et

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<sup>56</sup> <https://organowood.com/>

al., 2021). However, as part of the Plastic Strategy and the Circular Economy Action Plan, the European Commission has launched an initiative to address the release of unintentionally added microplastics into the environment. The initiative includes labelling, standardization, certification, and regulatory measures for the main sources of microplastics, and the release of microplastic from paint has been under discussion<sup>57</sup>.

## Proposal for indicators of the dispersion of microplastics from paint into the environment

When establishing indicators, it is important to consider parameters such as:

- Representativeness - does it represent the situation in Sweden?
- Continuity of data – can the same type of data be continuously used and available over time?
- Uncertainties – how large are the uncertainties? Would the effect of policy measures be indicated or unclear?
- System boundary
- Cost – If the indicator needs to be continuously evaluated, is the cost for collecting the necessary data reasonable?

The purpose of indicators is not to get absolute values but rather allow measurement of trends and changes over time.

In the literature, different kinds of modelling (Paruta et al., 2022) and indicators (Vorkamp et al., 2023) have been presented to give an estimate of the quantity of microplastics release into the environment . However, the models cannot be suggested for use to produce suitable indicators for any of the different categories at this stage. Even if existing environmental indicators are available, they are generally specific for a certain condition (Vorkamp et al., 2023). The models are based on several assumptions and the parameter values used in the literature may not be representative for Sweden. When using models, a lot of underlying data is needed, and this data would have to be continuously updated and applied to Swedish conditions.

It is also important to consider the consistency of the intended indicator or set of indicators. Changes to a model will not provide a constant indicator that can be followed over time. Moreover, much needed data is lacking. Additional analytical studies of paint microplastics in the environment that

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<sup>57</sup> [https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12823-Utslapp-av-mikroplaster-atgarder-for-att-minska-miljopaverkan\\_sv](https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12823-Utslapp-av-mikroplaster-atgarder-for-att-minska-miljopaverkan_sv)

cover both the different stages of a paint's life cycle as well as different paint categories would be needed to obtain a more accurate estimation. Standard measurements and sampling methods also need to be established before the data from experiments can be applied as a reliable indicator that can be followed over time.

Different types of paint and different brands have varying life spans. Durability increases the life span of a paint or coating, and increased life span means a reduced number of repainting jobs. Paint products are also continuously developed and subject to changes. Such changes may affect the lifespan. Producers are generally continuously working to develop products with a longer lifespan, although in some situations this may not always be favourable (M. Faber et al., 2021).

It can be difficult, almost impossible, to know for sure from where a microplastic found in the environment originates from. But a good indication that it most likely originates from paints and coatings is if it contains titanium dioxide.

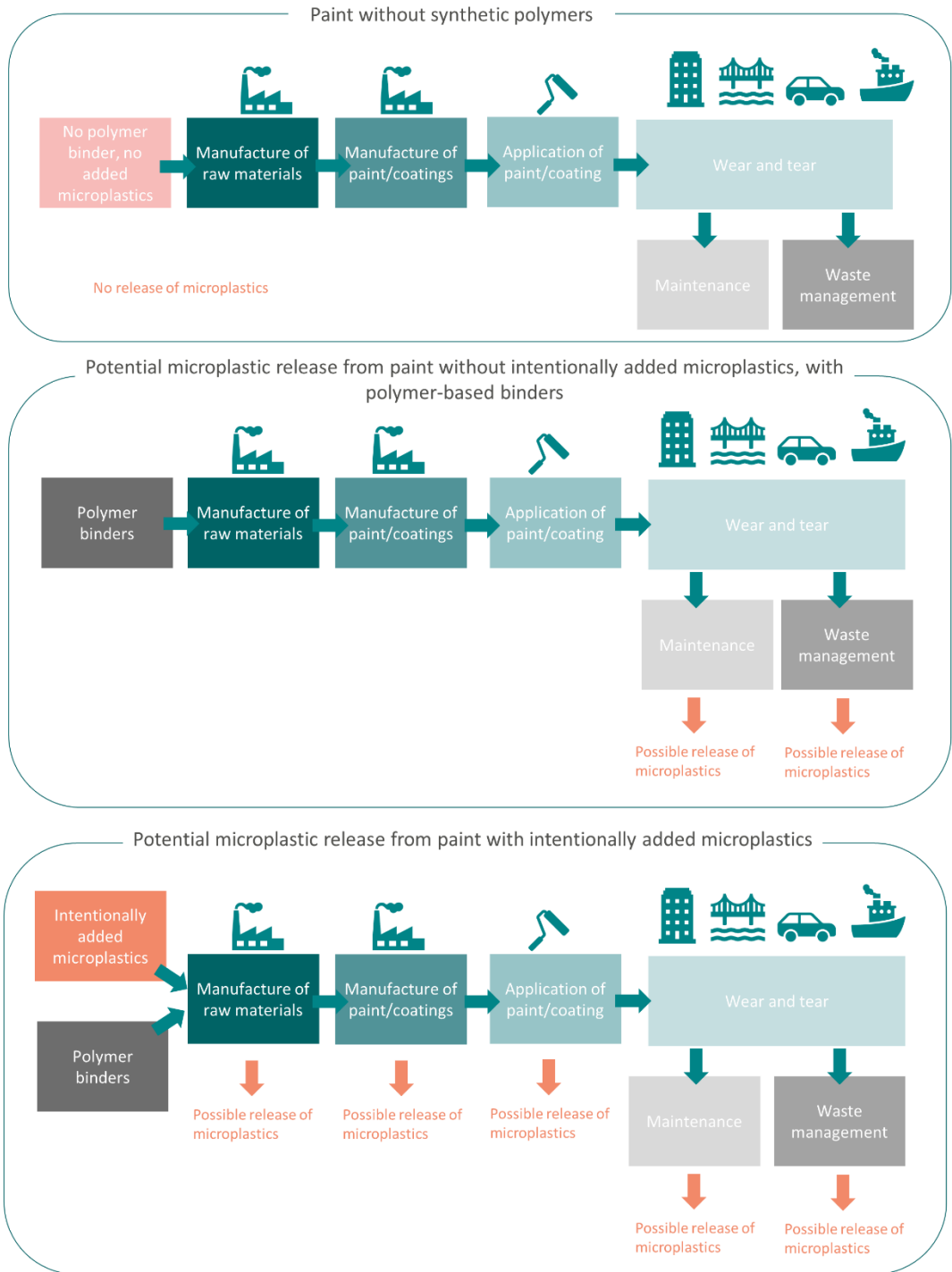
If a coating does not contain any polymeric binder or intentionally added microplastics such as fillers coated with polymer, it can be assumed that the coating will not result in any microplastic release. However, if a polymeric binder is used, there is risk of microplastic leakage. Most leakage occurs either due to wear and tear or improper handling of waste during maintenance and EOL. A third possibility is if intentionally added microplastics are used in coatings, microplastics can also be released during different manufacturing processes if paint or raw material residue is not handled properly. (Figure 16 shows an overview of the comparison of different kinds of paint systems and where potential microplastic emissions may originate from depending on whether the paint contains polymeric binders, intentionally added microplastics, or no polymers at all).

Intentionally added microplastics has been regulated via REACH legislation. This means that raw material suppliers will have to report the content of intentionally added microplastics in their products. In some applications, added microplastics will also be restricted for use. (European Commission, 2022b).

Some monitoring of microplastic release could be achieved by collecting water samples from wastewater and rainwater run-off that might contain microplastics from architectural coatings, particularly in urban areas.

Paint microplastics should only be considered to be the dry ingredients in the paint which do not evaporate and stay in the paint after curing. Therefore, a proposed indicator is a comparison of the yearly reported paint

volumes in the Swedish product register, excluding VOC and water content. If the paint does not contain polymeric binders or intentionally added microplastics, these paints should be excluded from paint microplastic assessment all together.





*Figure 16. Different stages of the coating process, which might lead to microplastic leakage into the environment depending on the kind of paint (paint with non-polymeric binder, synthetic polymeric binder, or synthetic polymeric binder together with intentionally added microplastics).*

The annually reported volumes of all paint put on the Swedish market can be compiled from the Swedish Product Register at the Swedish Chemicals Agency. According to legal requirements, businesses that manufacture or import 100 kg or more per year of a chemical product that has tariff numbers included on the customs numbers list, in Annex 1 of the Chemical Products and Biotechnical Organisms Ordinance must be reported to the Swedish Chemicals Agency<sup>58</sup>. Chemical composition, application area, function, and annual amounts (in tonnes) are included in this reporting. Companies categorize their products according to available industry and function codes. To get an overview of the products put on the Swedish market, the data in the product register needs to be filtered according to these codes.

From the data provided by the Swedish Product Register, figures representing the volume of industrial coatings (including automotive) are difficult to extract. Moreover, as industrial applications are often coated abroad, arriving in Sweden as ready-coated products, the volumes of these paints will remain unreported. Therefore, only indicators for architectural paint and AF paint/Hull coatings are proposed here.

Limitations with the Swedish product register is that to some extent all foreign companies may not always realize their obligation and might not do the reporting; however, we assume that the majority of companies complete the reporting. Furthermore, the general requirement in Europe according to REACH and CLP is to only report hazardous chemicals when chemical products are sold. The hazardous components should be stated in the safety data sheets for the products, but many polymers are often not classified and are therefore excluded. It can therefore be difficult to know the exact polymer and binder content of a product if there are several steps in a supply chain. Also, to determine the total volume of paint used, the waste should be subtracted from the total amount. However, there is no data available on the composition of paint that has been collected at waste stations, so it is only possible to establish an overview of the total volume of all paint used on the market. It is not possible to accurately assess the VOC and water content, which will not contribute to microplastics.

To address this challenge, the data from the Swedish product register could be compiled in different ways as indicators. One method would be to gather

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<sup>58</sup> The Swedish Product Register (2023, December) <https://www.kemi.se/en/products-register>

data on all volumes of paints sold in Sweden, excluding discarded residue. Second, data could be gathered on all paints sold in Sweden, excluding VOC and water. And lastly, the total volume of paints placed on the market in total could be followed. An overview of which data is useful from the Swedish product registry is presented in Table 5.

*Table 5. Suggested data from the Swedish Chemicals Agency to use as or determine indicators to follow the potential release of microplastics from paints.*

<b>Data Source</b>	<b>Data and methodology</b>	<b>What is covered</b>
<b>Data from Swedish Chemicals agency</b>	Volume of all paints, independent on composition (total tons)	The whole market for coatings placed on the Swedish market
<b>Data from Swedish Chemicals agency</b>	Volume of all paints, independent on composition (total tons), volume of residue paint disposed as hazardous waste should be excluded (subtracted)	The whole market for coatings in Sweden that is used
<b>Data from Swedish Chemicals agency</b>	Volume of paints containing synthetic polymers and/or pre-polymers and/or intentionally added microplastics. VOC and water excluded.	The whole market for coatings containing synthetic polymers in Sweden, excluding the “wet content”

### *Uncertainties*

The data provided by the Swedish Chemicals Agency can be expected to represent the amount of exterior and AF paint put on the Swedish market every year quite accurately. However, since loss rates and release conditions in Sweden are not known, the use of these amounts as indicators should be viewed as derived via a simplified method and only indicative of trends in potential quantities of microplastics that could end up in the environment from coatings. Changes in paint formulations with respect to solvent content as well as the total volume of paints placed on the market would be indicated by using this data. Improved waste management and other changes in routines and work would not be observable from this data.

Furthermore, these indicators will not account for emissions of microplastics from coated objects within general industry, automotive industry, or ships and boats that have been constructed or painted in other countries. Most of the emissions from this latter activity are expected to come from weathering during usage and IWC-cleaning.

The data from the Swedish Chemicals Agency is expected to contain information covering the main types of paint products put on the Swedish market, but some uncertainties remain because of the following:

- Not all paint products require reporting (if annual quantities are below 100 kg). and hence there will be unreported content that contributes to microplastic release to some extent
- Companies choose how they categorise their products and the categorisation of similar products may vary between different industries and companies. This means that products of the same type could end up being reported as different categories. However, in general it can be assumed that the categories exterior paint, AF paint and hull paint represent the sectors well.
- Reporting is not required for chemicals present at a concentration below 5% and not classified as hazardous. This means there are likely relevant ingredients of unknown identity and concentration. However, information about the total percentage of reported content is available, which provides information on the magnitude of unreported ingredients. As an example, in 2021 around 88% of the total mass of hull paint products were reported.
- Paints can sometimes be reported as families meaning that an entire paint family can be covered by only one report. In these reports, it is accepted for concentrations of ingredients to be reported as intervals and the actual concentration of solvents are unknown; however, paints within these groups should be quite similar.
- Paints containing unclassified polymers in a concentration of <5% will be undetected when calculating the total amount of polymer-containing paints and coatings.

Since these figures do not disclose the actual amount of paint used, but rather the amount on the marker, it is desirable to find other indicators to complement these figures to fill in the missing information. Such information could for example be obtained from volumes of unused paint. This could potentially be provided by recycling centres if they record the volumes of unused paint handed in. However, not all unused paint is handed in to recycling centres, material handed in may contain diluted paint (e.g., wastewater from cleaning off paint from brushes), or old dry paint where solvents have evaporated, creating uncertainty in assessing the volume of unused paint if reported by these centres.

# Indicators

## **Indicators for architectural coatings**

To obtain an estimate that covers the entire market in Sweden, it is suggested that the total amount of architectural paints and coatings placed on the Swedish market should be followed annually. Annual figures of the volume of paint put on the Swedish market can be provided from The Swedish Product Register at the Swedish Chemicals Agency. Potential complementing but not yet proposed indicators are discussed under “Proposal for continued investigations”.

This proposed indicator is similar to the indicator proposed in a previous report on indicators for microplastic flows (Unsbo et al., 2022). However, while Unsbo et al. (2022) suggested considering only the polymer content of paint as microplastic, we propose that cured paint be considered microplastic. By calculating the microplastic content based on the polymer content, certain uncertainties emerge, e.g., polymers are often not classified as hazardous and hence not required to be reported if contained in concentrations < 5% of the mixture. However, this uncertainty does not accompany the proposed indicator.

## **Indicators for antifouling and hull coatings**

As previously mentioned, annual figures of the volume of paint put on the Swedish market can be provided by The Swedish Product Register at the Swedish Chemicals Agency. Potential complementing but not yet proposed indicators are discussed under “Proposal for continued investigations”.

## **Indicators for coatings used within the general and automotive industries**

Within both general industry and the automotive industry, many objects are coated industrially outside Sweden and thereafter generally only require touch-ups when needed, making it difficult to estimate the quantity of microplastics that might be released from these applications in Sweden. Sales data from the Swedish product register only covers products sold in Sweden or imported to Sweden. This data might give some information on paint that is used for touch-ups and repainting in Sweden during maintenance. The general industry sector is challenging to follow because it includes so many different sectors, in which practices and routines vary and data around microplastic leakage is scarce. Therefore, no indicator could currently be proposed for this sector.

## Proposals for continued investigations

Microplastic release from paints and coatings is a relatively new field. Although there are several studies on microplastic particles in the environment, there is still a lack of knowledge in this area. The following major questions remain:

- More extensive studies, on how much paint is released from different objects, are needed.
- What happens during the ageing process of painted objects (e.g., EF may change during the life cycle)?
- What is the environmental fate of paint released from different types of objects?
- When will the release become toxic or have negative impacts on the environment or health?
- What is the environmental impact of microplastics from paint?

### Health effects on organisms

Studies on the effects of microplastics on animal cells *in vitro* suggest that microplastic exposure may cause inflammation and lesions; however, there is currently no widespread evidence of what the impacts of microplastic exposure on human health are. The consumption of plastic is growing and since it is a persistent material that degrades very slowly in nature, more studies and research is needed to address the effects of microplastics on different organisms, and even specifically exposure to microplastics from paint. The difference between environmental and health effects caused by microplastics derived from paint compared to microplastics from other sources is not known, but paint often contains many different additives and typically different polymers than plastic from other applications. It is already known that larger plastic objects cause problems to organisms. Just one example is that of a sperm whale which was found in Indonesia in 2018, which had 115 plastic cups, four plastic bottles, 25 plastic bags, and many more objects in its stomach. In total, 1000 different objects were found that together added up to six kilograms of plastics (News , 2019).

Ingestion of microplastic-containing food and inhalation are considered the major routes of human exposure to microplastics. Microplastics have been found in mussels, commercial fish, table salt, sugar, and even bottled water (Karami et al., 2017; Li et al., 2016; Liebezeit and Liebezeit, 2013; Neves et al., 2015; Oßmann et al., 2018). Even if the plastic pieces themselves are not dangerous, microplastics may release toxic chemicals and act as vectors for dangerous microorganisms (Cole et al., 2011; Kirstein et al., 2016).

## **Measuring microplastic emissions from paint**

There is a lot of theoretical and to some extent analytical data on microplastic emissions from paint, but many calculations and estimates available are based on different results and methods. While it may not be possible to get widespread data regarding paint microplastic release, it would still be useful to compile more data and perform more testing according to a set standard method such as some model studies and accelerated aging tests. Placing panels with coating material in different environments and weighing before and after exposure at specified times to follow the loss rate is one suggestion. This would to some extent cover loss rates from wear and tear. Similarly, methods in which a defined surface is treated according to different standard practices used during maintenance (dry blasting, wet blasting, and scraping) and also using different kinds of substrates (i.e., metal, wood, concrete) are suggested. Weighing panels before and after will give an idea of how much is lost from the surface. An ISO standard for analysis of microplastics present in the environment is currently under development (ISO, 2023), but developing standards for testing the loss rate from coatings would also be useful. We also propose that inspections are performed at different construction and maintenance sites to get a better understanding of how common it is to collect waste in the form of sanded paint and paint flakes in outdoor conditions. Release during maintenance is probably the most difficult factor to predict because it can vary a lot between different people and companies.

Analysis of soil and water samples near relevant industries could also be interesting, but the release of microplastics is not expected to behave in similar ways to chemicals that are distributed on a molecular level. The specific spot chosen to take samples can vary a lot. Methods that are non-biased need to be established.

Furthermore, an issue with studying microplastics is that it can be difficult to know exactly what comes from paint and what originates from other types of plastics such as packaging. Below we suggest methods for analysing the particles.

## ***Identification of microplastics from paint***

Direct light microscopy has been used to analyse microplastics extracted from the environment and can be used to determine the particles based on shape, size, and colour. Horton *et al.* suggested that paint fragments can be identified since they have a lower polymer content than plastic from other applications such as packaging, which makes them more brittle. This will result in fragments with sharp angles. Other types of polymeric materials

tend to lead more frequently to fibres or spherical shapes (Horton et al., 2017). (Horton et al., 2017).

Fourier transform infrared spectroscopy (FTIR), in particular microFTIR, is used to further analyse paint particles. However, it is not usually possible to apply FTIR to all particles, instead a random sample mixture must be selected. Raman spectroscopy is another measurement that is used for higher accuracy (Horton et al., 2017; Lacerda et al., 2019; Suaria et al., 2020).

In a study performed by Song *et al.*, 12 times more paint particles were found compared to plastics in the southern coast of South Korea (Song et al., 2014, 2014). Lacerda *et al.* found 30 times more paint fragments than plastic in sea surface waters around the Antarctic peninsula. Analysis with FTIR on 28 different items showed that most plastics were composed of polyurethane (35%), polyamide (25%), polyethylene (21%), polystyrene (11%), and polypropylene (8%). Paint particles from hulls and decks were the most abundant (Lacerda et al., 2019, 2019). FTIR is a good tool for identifying the type of polymer that is most abundant in a material, as it can be used to distinguish particles from each other. Plastics in packaging often include polyethylene, polypropylene, polystyrene, and polyethylene terephthalate, while polymers used in coatings more commonly consist of other types of polyesters, polyurethanes, polyacrylates, polyamides, etc.

### ***Architectural paint and coatings***

For paint-related emissions from architecture in urban areas, measuring microplastics in stormwater at different locations could serve as a future indicator, A large portion of the paint released from buildings in urban areas may be flushed away by rain, eventually ending up in the sewage system.

Furthermore, complementing these measurements with measurements in soil near construction sites would provide additional understanding of the spread and fate of paint particles.

Whether the plastics come from paint or other sources is not easy to distinguish; however, paint often has a high content of titanium dioxide compared to other plastic products<sup>59</sup>.

### ***Data availability***

Today there are no standardized methods available for measuring and analysing microplastics in stormwater and due to the high fluctuation in

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<sup>59</sup> Personal communication with Emma Jansson at Sveriges Lim och Färgföretagare, May-June 2023.

flow and concentration at different locations, monitoring of stormwater is hard and costly. When an analytical standard is in place, it should eventually be possible to use the resulting data as indicator for the release of microplastics from paint over time.

### **Automotive**

Since EOL is estimated as one of the largest areas for microplastic release in the automotive industry, it would also be interesting to do measurements near car-scraping facilities or junkyards to see if microplastics can be detected and if these vary over time.

Compared to leisure boats, cars must always be registered, and it would therefore be quite easy to follow statistics on how many new cars are placed on the Swedish market annually, as well as how many cars are scrapped.

#### *Data availability*

There are not yet any standardized methods available for measuring or monitoring paint-related microplastic in the environment.

### **AF paint and hull coatings - Leisure boats**

#### *The number and sizes of boats and the number of boats that are painted*

The total number and sizes of boats could potentially serve as a complement to the total annual amount of antifouling paint and hull coatings put on the market. This could somewhat cope with the uncertainty that the annual amount of paint put on the market does not really equal the total amounts of hull paint applied to boats every year. If the information could further be complemented with figures on the numbers of boats painted every year it could provide good information on the volumes of paint used on leisure boats and hence the decrease or increase of microplastic release from this source. However, a reduction in microplastic emissions due to improved waste management methods during maintenance would not be captured.

#### *Data availability*

The total number of boats, sizes, and types of boats could be made available through a boat register. The state boat register in Sweden was closed in 1993, and today only a voluntary boat register exists, i.e., Svenska Båttregistret (SBR)<sup>60</sup>. The topic has lately been under discussion as a result of increased numbers of abandoned end-of-life boats, and the Swedish

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<sup>60</sup> <http://www.xn--svensktbregister-grb.se/omoss.php?menu=1>



Agency for Marine and Water Management recently proposed the introduction of a new boat register<sup>61</sup>.

The estimated share of boats painted every year has earlier been provided from “Båtlivsundersökningen”, which is published every fifth year. The Swedish Transport Agency intend to perform this survey continuously.

### ***Maintenance – performance and waste management***

Information on performance and waste management during maintenance could give a complementing view to the information provided from the above-mentioned indicators.

The number of boat owners performing maintenance at cleaning stations equipped with hull cleaning areas with and without waste management systems could indicate whether microplastic emissions to the environment from boat maintenance increase or decrease over time.

#### *Data availability*

There are currently no annual data available on the number of boat owners who carry out maintenance on their own. Such information has however been provided in “Båtlivsundersökningen” by the Swedish Transport Agency and is published every fifth year. The next investigation will be carried out during 2024 and published in 2025. *Båtlivsundersökningen* is intended to be continuously published<sup>62</sup>.

Requirements by municipal environment protection inspections, on e.g., facility owners on reporting the number of boats washed at hull cleaning areas every year, could potentially provide annual data, but it is still unclear how this should be organized to provide reliable data. Another idea could be to install a measurement device for water usage on all high-pressure washing equipment, which could be reported at inspection, which would estimate the total boat hull area that has been cleaned per season.

### ***The number of scrapped boats and waste management at recycling centres***

An increase in the number of boats scrapped could indicate that the number of boats abandoned in the environment (no matter if it is in the garden, on the beach, in the forest, or elsewhere) decreased, hence less paint could be expected to leak into the environment from those boats.

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<sup>61</sup> <https://www.havochvatten.se/arkiv/aktuellt/2023-09-04-uttjanta-och-overgivna-fritidsbatar-vaxande-problem.html>

<sup>62</sup> Personal communication The Swedish Transport Agency email 2023-05-03.

#### *Data availability*

Båtskroten could provide the number of leisure boats they manage every year. However, boats handed in to municipal recycling centres or private scraps are not included.

#### **AF paint and hull coatings - Commercial boats**

##### ***The number of ships managed at dry docks***

The number of ships managed at dry docks every year would indicate if maintenance of commercial ships is being more commonly carried out in Sweden or abroad. A decreasing number would imply a reduction in microplastic emissions from this activity, even if active waste management routines are implemented. However, knowledge is still lacking on the efficacy of these measures, which requires further studies (Tamburri et al 2022).

#### *Data availability*

Information on the number of ships managed for maintenance at Swedish dry docks could be provided by the facilities or operators. This information would indicate an increasing trend in ship maintenance carried out abroad.

##### ***Cleaning methods used during drydocking***

Inspections or information on the cleaning techniques (blasting) and subsequent waste treatment used at the dry docks could potentially shed light on the microplastic emissions, since some methods appear to spread particles more easily than others.

#### *Data availability*

No information was found. However, since there are only four or five active dry docks in Sweden, inspections would be possible.

##### ***Waste management at dry docks***

Information on which waste management systems is used at different dry docks could indicate the spread of microplastic particles from hull coatings. Particles can be spread via wind, solid waste, or wastewater and methods of reducing the spread by all three pathways should be included.

Knowledge about the efficacy of different methods in collecting paint particles is required to assess the status of paint-related microplastic release during maintenance.

### *Data availability*

Information on waste management could likely be provided from shipyards (responsible for the dry dock). However, they may not have knowledge about the effect of the techniques in reducing the spread of paint particles.

### ***Information about In-water cleaning jobs performed in Sweden***

Data on the number of IWC jobs, the IWC techniques used, and the associated waste management systems in combination with measurements of paint-related microplastic particles in the surrounding water would provide information on the microplastic release arising from these methods. If the number of jobs is reduced and/or if the paint released to the water are efficiently collected, paint-related microplastic release will also be reduced.

### *Data availability*

Since no information on the number or type of IWC jobs performed in Sweden could be found, the contribution of this activity to microplastic release is difficult to estimate. Established requirements on reporting the number of cleaning jobs performed and the techniques used could provide this data.

No information on possible waste collection methods associated with IWC in Sweden has been found.

Like the case for drive-in boat washes, standardized or harmonized methods are recommended for measurements and no such methods are yet in place.

## **Estimated costs to calculate the indicator annually**

The proposed indicator is to follow the volume of paint placed on the market in Sweden that contains synthetic polymer binders. As the data is already provided by the Swedish Chemicals Agency, the costs of monitoring the indicator depend exclusively on the time required for compilation of the reported data, which should take about a week according to the Swedish Chemicals Agency. The estimated cost of the indicator is therefore assumed to be *low*.

## Concluding remarks

The sectors with the highest potential microplastic emissions from paint include architecture, antifouling and hull coatings, coatings in general industry, and the automotive industry. In Sweden, data on the volume of architectural paint and antifouling and hull coatings placed on the market can be readily obtained from the Swedish product registry. But data on volumes of paint from the general industry and automotive sectors are limited. Therefore, the recommended indicators for monitoring microplastic emissions from paint focus primarily on architectural coatings and antifouling and hull coatings, which should provide a comprehensive overview of trends over time.

Two different methods for calculating microplastic emissions from architectural and marine sector paints were used to estimate potential annual volumes. In the first method, emission factors for different parts of the paint's lifecycle were included and a range of solid contents based on a set of commercially available paints were used to provide a worst case, best case, as well as an average case scenario. By using this method, release of microplastics from architectural paint was estimated to be 209 – 3 700 tons/year and from antifouling and hull coatings to be 30-308 tons/ year.

The second method used only one set of emission factors, those presented by Lassen et al., (2015). Using this calculation, the estimated release was instead 190 – 570 tons/year from architectural coatings and 15 – 150 tons/year from antifouling and hull coatings. Lassen et al., (2015) also mentioned that the whole dry content should be considered and not just the polymer content, since the microplastic particles released will be composed of all the dry components of the paint. Using the first method gives higher resolution and greater range which we believe is more realistic and therefore represents our suggested approach.

Putting these numbers in relation to estimated quantities of microplastic emissions from other sources, it suggests that microplastic release from architecture and marine coatings are a substantial source of microplastics. For example, wear from road traffic is regarded as the largest source of microplastic emissions in Sweden, accounting for about 7 674 (tonnes/year) and it has been estimated that the release of synthetic fibres from textiles is between 8 – 956 tons annually. Emissions from industrial plastic pellet production was estimated to be between 12 – 235 tons (Magnusson et al., 2016).

Given that coatings typically need to meet various technical requirements to protect the underlying substrate from corrosion and wear, efforts to reduce

microplastic release from paint and coatings might incur higher costs compared to addressing other sources of microplastics such as direct littering.

To follow the microplastic emissions from coatings in Sweden over time we propose the indicators stated in Table 6.

*Table 6. Summary of proposed indicators for estimating the microplastic release from architectural and antifouling paint.*

<b>Indicator</b>	<b>Method</b>	<b>Scope</b>
Total dry weight (VOC and water excluded) of the <b>architectural paint</b> put on the Swedish market (kg/y), only including products that contain synthetic polymers.	For each category of paint products, annual weight of paint and to some extent a composition breakdown of the paint put on the Swedish market can be compiled from the information provided by manufacturers and importers of paint through their annual product registration to the Swedish Product register at the Swedish Chemicals Agency.  The cost for this indicator should be low since it is based on already available data.	The data reported to the Swedish Product Register generally include products imported or manufactured above 100 kg/year. Compositional data is generally available for ingredients classified as hazardous to health or to the environment, and unclassified components at concentrations above 5%. The compiled data are however expected to rather well represent the total volumes put on the Swedish market each year.
Total dry weight (VOC and water excluded) of the <b>antifouling paint and other hull paint</b> put on the Swedish market (kg/y), only including products that contain synthetic polymers.	For each category of paint products, annual weight of paint and to some extent a composition breakdown of the paint put on the Swedish market can be compiled from the information provided by manufacturers and importers of paint through their annual product registration to the Swedish Product register at the Swedish Chemicals Agency.  The cost for this indicator should be low since it is based on already available data.	The data reported to the Swedish Product Register generally include products imported or manufactured above 100 kg/year. Compositional data is generally available for ingredients classified as hazardous to health or to the environment, and unclassified components at concentrations above 5%. The compiled data are however expected to rather well represent the total volumes put on the Swedish market each year.

# References

- Abraham, T.W., Höfer, R., 2012. Lipid-Based Polymer Building Blocks and Polymers, in: *Polymer Science: A Comprehensive Reference*. Elsevier, pp. 15–58. <https://doi.org/10.1016/B978-0-444-53349-4.00253-3>
- AkzoNobel, 2023. Industrial Coatings | AkzoNobel [WWW Document]. URL <https://www.akzonobel.com/en/about-us/our-businesses/industrial-coatings> (accessed 5.24.23).
- Alcro, 2023. Måla putsfasader [WWW Document]. Alcro Färg. URL <https://alcro.se/tips-rad/mala-utomhus/mala-puts-betong> (accessed 5.10.23).
- American Coatings Association, 2013. Life-Cycle Assessment of Architectural Coatings [WWW Document]. American Coatings Association. URL <https://www.paint.org/coatingstech-magazine/articles/life-cycle-assessment-of-architectural-coatings/> (accessed 5.2.23).
- Ansdell, D.A., 1999. 10 - Automotive paints, in: Lambourne, R., Strivens, T.A. (Eds.), *Paint and Surface Coatings (Second Edition)*, Woodhead Publishing Series in Metals and Surface Engineering. Woodhead Publishing, pp. 411–491. <https://doi.org/10.1533/9781855737006.411>
- Båtmiljö.se, 2023. Lagstiftning och tillåtna båtbottenfärger [WWW Document]. Båtmiljö. URL <https://batmiljo.se/mala-baten/valja-bottenfarg/miljovanligt-system-for-bottenfarg/> (accessed 9.22.23).
- Beckers Group, 2023. High-performance coatings for domestic appliances [WWW Document]. Beckers Group. URL <https://www.beckers-group.com/en/applications/domestic-appliances/high-performance-coatings-for-domestic-appliances> (accessed 5.24.23).
- Belzunce, M.J., Solaun, O., Oreja, J.A.G., Millán, E., Pérez, V., 2004. Chapter 12 - Contaminants in sediments, in: Borja, Á., Collins, M. (Eds.), *Elsevier Oceanography Series, Oceanography and Marine Environment of the Basque Country*. Elsevier, pp. 283–315. [https://doi.org/10.1016/S0422-9894\(04\)80050-3](https://doi.org/10.1016/S0422-9894(04)80050-3)
- Bentley, J., Turner, G.P.A., 1997. *Introduction to Paint Chemistry and principles of paint technology*, Fourth Edition. CRC Press.
- Bighiu, M.A., 2017. Use and environmental impact of antifouling paints in the Baltic Sea.
- Bleile, H., Rodgers, S.D., 2001. Marine Coatings, in: Buschow, K.H.J., Cahn, R.W., Flemings, M.C., Ilshner, B., Kramer, E.J., Mahajan, S., Veyssière, P. (Eds.), *Encyclopedia of Materials: Science and*

- Technology. Elsevier, Oxford, pp. 5174–5185.  
<https://doi.org/10.1016/B0-08-043152-6/00899-8>
- Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin* 62, 2588–2597.  
<https://doi.org/10.1016/j.marpolbul.2011.09.025>
- Costa, J.P. da, Avellan, A., Mouneyrac, C., Duarte, A., Rocha-Santos, T., 2023. Plastic additives and microplastics as emerging contaminants: Mechanisms and analytical assessment. *TrAC Trends in Analytical Chemistry* 158, 116898. <https://doi.org/10.1016/j.trac.2022.116898>
- Cousinet, S., Ghadban, A., Fleury, E., Lortie, F., Pascault, J.-P., Portinha, D., 2015. Toward replacement of styrene by bio-based methacrylates in unsaturated polyester resins. *European Polymer Journal* 67, 539–550. <https://doi.org/10.1016/j.eurpolymj.2015.02.016>
- de Meijer, M., 2001. Review on the durability of exterior wood coatings with reduced VOC-content. *Progress in Organic Coatings* 43, 217–225. [https://doi.org/10.1016/S0300-9440\(01\)00170-9](https://doi.org/10.1016/S0300-9440(01)00170-9)
- Dibke, C., Fischer, M., Scholz-Böttcher, B.M., 2021. Microplastic Mass Concentrations and Distribution in German Bight Waters by Pyrolysis-Gas Chromatography-Mass Spectrometry/Thermochemolysis Reveal Potential Impact of Marine Coatings: Do Ships Leave Skid Marks? *Environ Sci Technol* 55, 2285–2295. <https://doi.org/10.1021/acs.est.0c04522>
- ECHA, 2023. Substances restricted under REACH [WWW Document]. URL <https://echa.europa.eu/substances-restricted-under-reach/-/dislist/details/0b0236e1807e2bc1> (accessed 5.24.23).
- Ejhed, H., Fråne, A., Wränge, A.-L., Olshammar, M., 2018. Mikroplast i Stockholms stad (No. C334). IVL Swedish Environmental Research Institute, Stockholm.
- Eklund, B., Johansson, L., Ytreberg, E., 2014. Contamination of a boatyard for maintenance of pleasure boats. *J Soils Sediments* 14, 955–967. <https://doi.org/10.1007/s11368-013-0828-6>
- Environmental exposure to microplastics: An overview on possible human health effects, 2020. . *Science of The Total Environment* 702, 134455. <https://doi.org/10.1016/j.scitotenv.2019.134455>
- EPODEX, 2023. Betongfärg 2K | Stenfärg 2K | Alla färger | CONCRETE PAINT 2K. EPODEX Sverige. URL <https://www.epodex.com/se/produkt/betongfarg-2k-stenfarg-2k-alla-farger-concrete-paint-2k/> (accessed 5.18.23).
- European Commission, 2022a. Measures aiming to reduce the presence in the environment of unintentionally released microplastics from tyres, textiles and plastic pellets (Text).

- European Commission, 2022b. COMMISSION REGULATION (EU) .../... of XXX amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles. European Commission.
- Faber et al., 2021. Paints and microplastics Exploring recent developments to minimise the use and release of microplastics in the Dutch paint value chain (No. RIVM report 2021-0037).
- Faber, M., Marinković, M., de Valk, E., Waaijers- van der Loop, S., 2021. Paints and microplastics. Exploring the possibilities to reduce the use and release of microplastics from paints. Feedback from the paint sector. Rijksinstituut voor Volksgezondheid en Milieu, The Netherlands. <https://doi.org/10.21945/RIVM-2021-0037>
- Falu Rödfärg, 2023. Start page [WWW Document]. Falu Rödfärg. URL <https://falurodfarg.com/en/> (accessed 5.10.23).
- FAQ - Questions and Answers about Lead Paint and Lead Paint Laws [WWW Document], 2017. . UNEP - UN Environment Programme. URL <http://www.unep.org/explore-topics/chemicals-waste/what-we-do/emerging-issues/global-alliance-eliminate-lead-paint/faq> (accessed 8.11.23).
- Gaylarde, C.C., Neto, J.A.B., da Fonseca, E.M., 2021. Paint fragments as polluting microplastics: A brief review. *Mar Pollut Bull* 162, 111847. <https://doi.org/10.1016/j.marpolbul.2020.111847>
- Gaylarde, C.C., Neto, J.A.B., da Fonseca, E.M., 2020. Paint fragments as polluting microplastics: A brief review. *Marine Pollution Bulletin* 162.
- Gondikas, A., Mattsson, K., Hassellöv, M., 2023. Methods for the detection and characterization of boat paint microplastics in the marine environment. *Frontiers in Environmental Chemistry* 4.
- Gradient Corporation, 2022. Literature Review of Coatings-Related Microplastics. Gradient Corporation.
- Granhag, L., Mehran, J., Ytreberg, E., 2023. BEST PRACTICE FOR CLEANING OF SHIP HULLS. Chalmers University of Technology.
- Hann, S., Sherrington, C., Jamieson, O., Hickman, M., Kershaw, P., Bapasola, A., Cole, G., 2018. Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products. Eunomia, UK.
- Hassellöv, M., Gondikas, A., Mattsson, K., Samuelsson, P.-O., 2011. Läckage av mikroskopiska båtbottnfärgspartiklar från båtborsttvättar – en förstudie.



- Horton, A.A., Svendsen, C., Williams, R.J., Spurgeon, D.J., Lahive, E., 2017. Large microplastic particles in sediments of tributaries of the River Thames, UK – Abundance, sources and methods for effective quantification. *Marine Pollution Bulletin* 114, 218–226. <https://doi.org/10.1016/j.marpolbul.2016.09.004>
- Iizuka, H., 1988. A statistical study on life time of bridges. *Doboku Gakkai Ronbunshu* 1988, 73–82. [https://doi.org/10.2208/jscej.1988.392\\_73](https://doi.org/10.2208/jscej.1988.392_73)
- Industry standard on in-water cleaning with capture, 2021.
- International Labour Office, 2012. *Encyclopedia of Occupational Health and Safety* 5th edition.
- ISO, 2023. ISO 24187 [WWW Document]. ISO. URL <https://www.iso.org/standard/78033.html> (accessed 9.18.23).
- Karami, A., Golieskardi, A., Keong Choo, C., Larat, V., Galloway, T.S., Salamatinia, B., 2017. The presence of microplastics in commercial salts from different countries. *Sci Rep* 7, 46173. <https://doi.org/10.1038/srep46173>
- Kirstein, I.V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Löder, M., Gerds, G., 2016. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. *Marine Environmental Research* 120, 1–8. <https://doi.org/10.1016/j.marenvres.2016.07.004>
- Klimat- och näringslivsdepartementet, 2013. Miljöprövningsförordning (2013:251) [WWW Document]. URL [https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/miljoprovningsforordning-2013251\\_sfs-2013-251/](https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/miljoprovningsforordning-2013251_sfs-2013-251/) (accessed 7.18.23).
- Konsumentverket, 2023. Försäljning av fordon [WWW Document]. Konsumentverket. URL <https://www.konsumentverket.se/foretag/regler-per-omradebransch/motor--bil-bat-och-motorcykel/forsaljning-av-fordon/> (accessed 5.9.23).
- Lacerda, A.L. d F., Rodrigues, L. dos S., van Sebille, E., Rodrigues, F.L., Ribeiro, L., Secchi, E.R., Kessler, F., Proietti, M.C., 2019. Plastics in sea surface waters around the Antarctic Peninsula. *Sci Rep* 9, 3977. <https://doi.org/10.1038/s41598-019-40311-4>
- Lagerqvist, M., 2021. *Båtlivsundersökningen 2020: En undersökning om båtlivet i Sverige*. The Swedish Transport Agency, Sweden.
- Lagerström, M., 2019. Occurrence and environmental risk assessment of antifouling paint biocides from leisure boats.
- Lagerström, M., Wrangle, A.-L., Oliveira, D.R., Granhag, L., Larsson, A.I., Ytreberg, E., 2022. Are silicone foul-release coatings a viable and environmentally sustainable alternative to biocidal antifouling

- coatings in the Baltic Sea region? *Marine Pollution Bulletin* 184, 114102. <https://doi.org/10.1016/j.marpolbul.2022.114102>
- Lassen, C., Hansen, S.F., Magnusson, K., Norén, F., Bloch Hartmann, N.I., Rehne Jensen, P., Nielsen, T.G., Brinch, A., 2015. Microplastics - Occurrence, effects and sources of releases to the environment in Denmark (No. 1793). The Danish Environmental Protection Agency.
- Lazzari, M., Chiantore, O., 1999. Drying and oxidative degradation of linseed oil. *Polymer Degradation and Stability* 65, 303–313. [https://doi.org/10.1016/S0141-3910\(99\)00020-8](https://doi.org/10.1016/S0141-3910(99)00020-8)
- Lejars, M., Margailan, A., Bressy, C., 2012. Fouling Release Coatings: A Nontoxic Alternative to Biocidal Antifouling Coatings. *Chem. Rev.* 112, 4347–4390. <https://doi.org/10.1021/cr200350v>
- Li, J., Qu, X., Su, L., Zhang, W., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016. Microplastics in mussels along the coastal waters of China. *Environmental Pollution* 214, 177–184. <https://doi.org/10.1016/j.envpol.2016.04.012>
- Liebezeit, G., Liebezeit, E., 2013. Non-pollen particulates in honey and sugar. *Food Additives & Contaminants: Part A* 30, 2136–2140. <https://doi.org/10.1080/19440049.2013.843025>
- Lorén, A., Engelhart, K., Bredberg, A., 2021. Material och produktion kemisk problemlösning (No. RISE Rapport ; 2021:09). RISE Research Institutes of Sweden, Materials and Production, Chemistry, Biomaterials and Textiles.
- Lst Stockholm, 2023. Tillsyn av miljöfarlig verksamhet [WWW Document]. URL <https://www.lansstyrelsen.se/stockholm/miljo-och-vatten/miljofarlig-verksamhet/tillsyn-av-miljofarlig-verksamhet.html> (accessed 6.12.23).
- Magnusson, K., Eliasson, K., Fråne, A., Haikonen, K., Hultén, J., Olshammar, M., Stadmark, J., Voisin, A., 2016. Swedish sources and pathways for microplastics to the marine environment (No. C183). IVL Swedish Environmental Research Institute.
- Maiti, S., Ray, S.S., Kundu, A.K., 1989. Rosin: a renewable resource for polymers and polymer chemicals. *Progress in Polymer Science* 14, 297–338. [https://doi.org/10.1016/0079-6700\(89\)90005-1](https://doi.org/10.1016/0079-6700(89)90005-1)
- Makhlouf, A.S.H., 2011. Current and advanced coating technologies for industrial applications, in: *Nanocoatings and Ultra-Thin Films*. Elsevier, pp. 3–23. <https://doi.org/10.1533/9780857094902.1.3>
- Min, K., Cuiffi, J.D., Mathers, R.T., 2020. Ranking environmental degradation trends of plastic marine debris based on physical properties and molecular structure. *Nat Commun* 11, 727. <https://doi.org/10.1038/s41467-020-14538-z>

- Morsch, S., van Driel, B.A., van den Berg, K.J., Dik, J., 2017. Investigating the Photocatalytic Degradation of Oil Paint using ATR-IR and AFM-IR. *ACS Appl. Mater. Interfaces* 9, 10169–10179. <https://doi.org/10.1021/acsami.7b00638>
- Nejad, M., Cooper, P., Nejad, M., Cooper, P., 2017. Exterior Wood Coatings, in: *Wood in Civil Engineering*. IntechOpen. <https://doi.org/10.5772/67170>
- Neves, D., Sobral, P., Ferreira, J.L., Pereira, T., 2015. Ingestion of microplastics by commercial fish off the Portuguese coast. *Marine Pollution Bulletin* 101, 119–126. <https://doi.org/10.1016/j.marpolbul.2015.11.008>
- News , C.B.C., 2019. Whale dies with 100 kg ball of plastic trash in its stomach | CBC News [WWW Document]. CBC. URL <https://www.cbc.ca/news/science/whale-plastic-100kg-1.5381205> (accessed 8.9.23).
- OECD, 2009. Coating Industry (Paints, Lacquers and Varnishes), Series on Emission Scenario Documents.
- OSHWiki, 2017. Isocyanates - OSHwiki | European Agency for Safety and Health at Work [WWW Document]. URL <https://oshwiki.osha.europa.eu/en/themes/isocyanates> (accessed 9.22.23).
- Oßmann, B.E., Sarau, G., Holtmannspötter, H., Pischetsrieder, M., Christiansen, S.H., Dicke, W., 2018. Small-sized microplastics and pigmented particles in bottled mineral water. *Water Research* 141, 307–316. <https://doi.org/10.1016/j.watres.2018.05.027>
- Paiano, A., Gallucci, T., Pontrandolfo, A., Lagioia, G., Piccinno, P., Lacalamita, A., 2021. Sustainable options for paints through a life cycle assessment method. *Journal of Cleaner Production* 295, 126464. <https://doi.org/10.1016/j.jclepro.2021.126464>
- Paruta, P., Pucino, M., Boucher, J., 2022. *Plastic Paints the Environment* (No. ISBN 978-2-8399-3494-7). Environmental Action.
- PCI, 2021. Long-Life Coatings | 2021-08-11 | PCI Magazine [WWW Document]. URL <https://www.pcimag.com/articles/109126-long-life-coatings> (accessed 5.2.23).
- Popov, B.N., 2015. Chapter 13 - Organic Coatings, in: Popov, B.N. (Ed.), *Corrosion Engineering*. Elsevier, Amsterdam, pp. 557–579. <https://doi.org/10.1016/B978-0-444-62722-3.00013-6>
- Poth, U., 2020. *Polyester and Alkyd Resins*. Vincentz Network GmbH & Co KG.
- Poth, U., 2008. *Automotive Coatings Formulation: Chemistry, Physics und Practices*. Vincentz Network GmbH & Co KG.

- Renovia, 2019. Paint vs. Coating, What is the Difference? [WWW Document]. Renovia. URL <https://renovia.com/paint-vs-coating-what-is-the-difference/> (accessed 9.22.23).
- ResinCoat, 2023. Resincoat Outdoor Patio Paint | Concrete Floor Paint | Resincoat [WWW Document]. URL <https://www.resincoat.co.uk/en/outdoor/455-resincoat-outdoor-patio-paint.html> (accessed 5.18.23).
- Sharing insights elevates their impact [WWW Document], 2023. . S&P Global. URL <https://www.spglobal.com/commodityinsights/en/ci/products/acrylic-surface-chemical-economics-handbook.html> (accessed 4.24.23).
- Song, Y.K., Hong, S.H., Jang, M., Kang, J.-H., Kwon, O.Y., Han, G.M., Shim, W.J., 2014. Large Accumulation of Micro-sized Synthetic Polymer Particles in the Sea Surface Microlayer. *Environ. Sci. Technol.* 48, 9014–9021. <https://doi.org/10.1021/es501757s>
- Soon, Z.Y., Jung, J.-H., Loh, A., Yoon, C., Shin, D., Kim, M., 2021. Seawater contamination associated with in-water cleaning of ship hulls and the potential risk to the marine environment. *Marine Pollution Bulletin* 171, 112694. <https://doi.org/10.1016/j.marpolbul.2021.112694>
- Sørensen, P.A., Kiil, S., Dam-Johansen, K., Weinell, C.E., 2009. Anticorrosive coatings: a review. *J Coat Technol Res* 6, 135–176. <https://doi.org/10.1007/s11998-008-9144-2>
- SSAB, 2023. Metal coatings for coils and sheets [WWW Document]. SSAB. URL <https://www.ssab.com/en/brands-and-products/steel-categories/metal-coatings> (accessed 5.9.23).
- Suaria, G., Perold, V., Lee, J.R., Lebouard, F., Aliani, S., Ryan, P.G., 2020. Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition. *Environment International* 136, 105494. <https://doi.org/10.1016/j.envint.2020.105494>
- Sundt, P., Schulze, P.-E., Syversen, F., 2014. Sources of microplasticpollution to the marine environment (No. 1032). Norwegian Environment Agency Miljødirektoret, Norway.
- Svärd, B., 2013. Ren och Attraktiv kust i Bohuslän – bakgrund och fakta.
- SVEFF, 2023. Mer om miljö och hälsa [WWW Document]. SVEFF - Sveriges Färg och Lim Företagare. URL <https://www.sveff.se/milj-och-hlsa> (accessed 9.13.23).
- SwAM, 2012. Båtbottentvättning av fritidsbåtar (No. Diariennr. 701-11). Havs- och vattenmyndigheten.
- Swedish EPA, 2022a. Rätt plast på rätt plats –kartläggning av plastflöden (Delleverans av regeringsuppdrag) (No. NV-09904-21).

- Swedish EPA, 2022b. Microplastics : Presentation of government commission on sources of microplastics and proposed measures for reduced emissions in Sweden.
- Swedish EPA, 2022c. Rätt plast på rätt plats – kartläggning av plastflöden.
- Swedish EPA, 2021. The Swedish EPA's roadmap for the sustainable use of plastics : Inspiring action..
- Swedish Wood, 2023. Surface treatment of exterior wood [WWW Document]. Swedish Wood. URL <https://www.swedishwood.com/building-with-wood/construction/surface-treatment/> (accessed 8.11.23).
- Tamburri, M.N. et al, 2022. Understanding the potential release of microplastics from coatings used on commercial ships. *Frontiers in Marine Science* 9, 1074654. <https://doi.org/10.3389/fmars.2022.1074654>
- Tamburri, M.N., Davidson, I.C., First, M.R., Scianni, C., Newcomer, K., Inglis, G.J., Georgiades, E.T., Barnes, J.M., Ruiz, G.M., 2020. In-Water Cleaning and Capture to Remove Ship Biofouling: An Initial Evaluation of Efficacy and Environmental Safety. *Frontiers in Marine Science* 7.
- Teaca, C.-A., Rosu, D., Mustata, F., Rusu, T., Rosu, L., Rosca, I., Varganici, C.-D., 2019. Natural Bio-Based Products for Wood Coating and Protection against Degradation: A Review. *BioResources* 14, 4873–4901.
- Tikkurila, 2023. Different types of industrial metal coatings [WWW Document]. Tikkurila. URL <https://tikkurila.com/industry/different-types-industrial-metal-coatings> (accessed 5.9.23).
- Turner, A., 2021. Paint particles in the marine environment: An overlooked component of microplastics. *Water Research X* 12, 100–110. <https://doi.org/10.1016/j.wroa.2021.100110>
- Unsbo, H., Rosengren, H., Olshammar, M., 2022. Indicators for microplastic flows (No. SMED Report No 21). SMED.
- Vorkamp, K., Ryberg, M., Fauser, P., Bach, L., Fries Linnebjerg, J., Strand, J., 2023. Indicators for plastic pollution. Nordisk Ministerråd.
- Weiss, K.D., 1997. Paint and coatings: A mature industry in transition. *Progress in Polymer Science* 22, 203–245. [https://doi.org/10.1016/S0079-6700\(96\)00019-6](https://doi.org/10.1016/S0079-6700(96)00019-6)
- Ytreberg, E., 2012. Spridning av biocider från båtar – Undersökning av olika källor och dess bidrag.
- Yue, K., 2012. Comparative Analysis of Scrap Car Recycling Management Policies. *Procedia Environmental Sciences* 16, 44–50. <https://doi.org/10.1016/j.proenv.2012.10.007>

- Zhang, Y., Li, Y., Wang, L., Gao, Z., Kessler, M.R., 2017. Synthesis and Characterization of Methacrylated Eugenol as a Sustainable Reactive Diluent for a Maleinated Acrylated Epoxidized Soybean Oil Resin. *ACS Sustainable Chem. Eng.* 5, 8876–8883.  
<https://doi.org/10.1021/acssuschemeng.7b01673>
- Zhou, W., Wang, Y., Ni, C., Yu, L., 2021. Preparation and evaluation of natural rosin-based zinc resins for marine antifouling. *Progress in Organic Coatings* 157, 106270.  
<https://doi.org/10.1016/j.porgcoat.2021.106270>