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The biocarrier escape routes

Identifying leaks through a Product Chain Organisational study

Master's thesis in Industrial Ecology

AGNES TUNSTAD

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
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Pictures by Agnes Tunstad if not stated otherwise.

Cover: Escaped biocarriers in Bohuslän, Sweden, October 2021, by Agnes Tunstad.

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Abstract

Biocarriers used in the Moving Bed Bioreactor process serve a good operational purpose, cleaning wastewater that would otherwise pollute the ocean without using toxic chemicals. But, incidents occur when biocarriers escape from the process and leak into the sea. The good purpose is lost, and the carriers become harmful marine plastic waste. These process leakages are within human and natures best interest to prevent, which means taking full responsibility for an extended length of the product's life cycle.

The biocarriers are suspended HDPE/PE plastic objects for housing and protecting microbes separating wastewater from nitrogen compounds. Applied in thousand or millions into the wastewater processes for municipal and industrial purposes, they add surface for the microbes to more efficiently treat wastewater and comply well with capacity and seasonal changes. Complication of biocarrier leakages is the added environmental impact from plastic pollution, including micro- and nano-plastics as carriers break down to smaller particles when exposed to wear and UV-light.

Production, system installation, operation and waste management are the four phases in the life cycle approached in this thesis. The actors for each phase are identified to build the understanding of the Product Chain Organisation (PCO) of biocarriers. The PCO study method visualises interconnections, actor influences, system failures and possible sustainable system changes to detect, support and develop measures and strategies for better management of biocarrier processes with a mitigated impact from leakages. Quantification of the problem remains deficient due to non-specific categorisation in beach litter monitoring. Experiences and witnesses from beach litter actors along with estimations in data collected describes this litter as abundant across the north-east Atlantic coastal areas.

To prevent and reduce biocarrier leakages, three levels of recommendation is concluded by the project. The first is the internalisation of externalises by the process owners given by additional barriers assigned for leak prevention. The second is surveillance and permit approval to increase system requirements from regional regulators. The third is higher instances of regulators and international collaborations to regulate this type of marine plastic pollution and make additions in required risk assessments to specify biocarrier leaks.

Keywords: Biocarriers, biomedia, MBBR, marine litter, PCO, actors.

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I am ever so thankful for my supervisors at the Swedish Agency for Marine and Water Management, Johanna Eriksson and Dr. Jonas Pålsson, that introduced, guided and aided me with resources, contacts and expertise throughout the project, along with introducing me to the exciting work of OSPAR.

Lastly, a significant acknowledgement to Professor Henrikke Baumann. As the supervisor and examiner of this thesis, she has provided invaluable guidance and expertise in the methodological and marine litter research fields. As the head of the IE master programme, she has also given me helpful advice in following and sorting my interests and ambitions in choosing my study path, for which I am very glad.

Since this thesis finalises my time at Chalmers University of Technology, the autumn has also included several moments of reflection. I am grateful for the friendships and knowledge acquired here with an education I will continue to build upon — insights about my ambitions, capabilities and maybe most significant, the importance of self-trust for advancement.

Agnes Tunstad, Gothenburg, January 2022

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Introduction

The health of our ocean is of most significant importance for the health of this planet with ecosystems, animals and humans. Still, pollution and disturbances occur every day in the ocean, making humans' environmental impact build up. The accumulation of plastic marine litter in the ocean has become a global problem, and other than uninterruptedly creating ecological disturbances, it is an unnatural element in our nature.

A question raised when developing objectives and actions for tackling marine litter is how to approach some of the most common litter objects and make involved actors (the sources) more accountable for preventing the leakages into the ocean. Single-use plastics have received the predominant attention by policy-makers and media naturally due to the dominant occurrence in marine monitoring. However, some other objects are climbing the list as very abundant beach litter findings, one of them being tiny plastic objects called biocarriers, biomedia or suspended sewage filters. This thesis will hereafter denote them as *biocarriers*.

Figure 1.1: Biocarriers found on a beach after leakage from a salmon farmer in Hvide Sand, Denmark (Kruse, 2021)

1.1 Problem description

Biocarriers are used in what are supposed to be closed systems in wastewater treatment processes. There, they separate biological waste or remove nitrogen compounds from wastewater without requiring the addition of chemicals. The technology can hence be seen as more environmental than other available and further better than if no treatment was applied. Still, unintentional losses of biocarriers occurs somewhere in the life cycle and the biocarriers can be found on coastlines where they instead have become an addition to the marine plastic pollution.

The design of biocarriers is aimed for a density and form to easily travel in the water column since that is the actual purpose in the wastewater treatment process. They are considered dysfunctional if floating on the surface or sinking to the floor. Since the biocarriers are designed for advantageous positioning in the water, they unfortunately also acquires an extra spread capability once in the ocean. Good for the adventurous biocarriers and not so good for the environmental champions trying to catch them.

Rivers and ocean currents spread the little carriers fast, and catchment areas from a leakage can be across seas from their origin. Once washed up on the beach, the different designs and shapes of biocarriers can be the start of a sequence of detective work to conclude the original whereabouts and thus discover a system that has failed. Biocarriers are rarely known or correctly identified in society and rarely have their own category in beach litter monitoring programmes.

Figure 1.2: Biocarriers of type K1 (AnoxKaldnes) and BWT 15 (Biowater technology) found at a beach-cleaning activity outside Lysekil, Sweden in September 2021.

Several measures are taken within national borders and internationally to fight the growing marine plastic pollution. This thesis was initiated with the Swedish Agency for Marine and Water Management (SwAM), as input was sought to develop marine litter mitigation measures within a new regional action plan on marine litter for OSPAR (Oslo-Paris convention) to put in operation for the North-east Atlantic during spring 2022.

OSPAR has several reference beaches for monitoring marine litter that are left alone from other beach cleaning activities in order to gather information and data on what kind of litter that frequently wash ashore. Categorisation of the litter remains unspecific for biocarriers so far. The collected data thus relies on the monitoring individual to include comments of specific findings as in table 1.1. Non-governmental organisations (NGOs) assigned by governmental agencies work to monitor reference beaches for gathering data on beach litter amounts and fluctuations. They are prevalent in most coastal nations with examples such as Keep Sweden Tidy, Keep the Archipelago Tidy Association in Finland, Keep the Estonian Sea Tidy and FEE Latvia. These organisations work as national opinion leaders aside from the beach litter monitoring, organising societal engagement and knowledge sharing. Keep Sweden Tidy is the organisation who monitors the OSPAR beaches in Sweden. From the year of 2018 to 2020, the given approximations of biocarriers found at the reference beaches can be seen in table 1.1.

Table 1.1: Approximate number of biocarriers within category 48 at the Swedish OSPAR reference beaches in between 2018-2020 (Keep Sweden Tidy, personal communication, 2021)

	Name	2018			2019			2020		
		spring	summer	autumn	spring	summer	autumn	spring	summer	autumn
SE06	Ängklåvebukten	22	11	259	17	9	305	162	100	0
SE05	Edsvik	885	149	29	519	21	102	570	0	0
SE04	Haby	a	a	a	0	a	a	4	a	b
SE07	Grönevik	41	16	21	0	b	0	6	b	b
SE08	Barrevik*	a	a	a	a	a	a	a	a	a
SE09	Gröderhamnsvik	0	0	0	b	a	0	b	a	b

0 = other subject were registered in category 48 but not biocarriers. a = no registered subjects at all in category 48. b = there are a number of subject categorised as 48 but they are not specified.
**Objects in other categories were specified which indicates that even if objects in the category were searched for, none were found.*

Due to the material and size of biocarriers, they pose a threat to animals through ingestion and to the environment when worn down to microplastics. In Denmark, they also raise the concern of children ingesting them at beaches (Bolvinkel, 2014). Losing the often hundreds of thousand biocarriers used in a purification process to the environment, eventually ending up in the ocean, is also a costly affair for the plant, where a cost of approximately €500 per m^3 of biocarrier occur (Bailly et al., 2018). It should therefore lie in the best interest of all parties to prevent losses.

1.2 Purpose

As biocarriers unintentionally end up on the coastlines where they pose a threat to marine wildlife and ecosystems, the purpose of this project is to provide input for policy-making in developing mitigating efforts of marine plastic pollution concerning biocarriers.

1.3 Aim

The thesis aims to understand and explain why, how and because of who biocarriers become marine litter. The research questions to support the aim are:

- What are the main causes for leaks of biocarriers into the ocean?
- Who has the influence to prevent and recover leakages of biocarriers?
- What alarm system and recovery procedures exist for biocarrier leakages?
- How can further leakages of biocarriers be prevented?

1.4 Demarcations

Considerations were not given to how biocarriers could be re-designed and developed to mitigate its environmental impact, only how biocarriers, originally an environmental technology, end up as plastic pollution.

Similarly, no investigation was performed on the reactor designs or the advantage of the different variants, nor to appoint any superior design in terms of leakage prevention.

One of the first reports on biocarriers as plastic pollution came from The Surfrider Foundation Europe in 2018, *Sewage Filter Media And Pollution of the Aquatic Environment* (Bailly et al, 2018). It was used as the first exposure to this environmental issue. In the following chapter, background on biocarriers and existing remediation measures are presented.

2

Background

The following chapter gives an introduction to the technology, theoretical characteristics, advantages and the history of wastewater treatment, followed by national regulations concerning wastewater treatment plants and the applicability of industrial ecology to understand socio-material flows.

2.1 The biocarrier technology

Freely moving suspended biocarriers are used in a popular biological wastewater treatment technology called *Moving Bed Biofilm Reactors (MBBR)*, used worldwide to separate biological waste and nitrogen compounds from wastewater. An ease of use, high cleaning capacity and low construction cost have made them a feasible solution for both new constructions and upgrades of existing plants in sizes from private households to municipal wastewater treatment plants and industrial operations. The technology is not sensitive to seasonal variations in either temperature or capacity, making it even more suitable for northern regions.

2.1.1 The evolution of wastewater treatment

As the industrial revolution dawned in the late 19th and early 20th century, population grew along with technological and economical advancements. People experienced an increased living standard and many where lifted out of poverty. But as urbanisation grew so did the unsanitary conditions of living in the cities (Daigger, 2014).

Waterborne systems for water and wastewater services emerged during the 20th century in the developed world and has become one of the most significant engineering accomplishments for improving public health. The wastewater treatment technology of Activated Sludge (AS) is the dominating biological treatment process till this day for both municipal and industrial plants and was characterised in its present form during the early 20th century (Stensel & Makinia, 2014). As urbanisation is continuously an increasing trend, up to 70% of humanity is expected to live in the urban areas at the middle of this century which puts further pressure on the current sewage systems to expand capacity. Technological advancements in the field of water treatment has therefore continued since the start and will continue further to optimise efficiency regarding time, space and pollutant removal.

2.1.2 Biological treatment with moving carriers

Already in the 1930s efforts where made to improve nitrogen removal with side-stream processes to the AS by adding suspended carriers for biofilm growth, forming a hybrid process (Stensel & Makinia, 2014). The small plastic carriers used today are the result of the development by Kaldnes in the 1980s, a Norwegian company that later united with the Swedish company Anox and became AnoxKaldnes and in 2007 was bought by Veolia (Bailly et al., 2018).

Since the development of the MBBR in Norway, several other companies has adopted the technology, providing solutions with biocarriers for a various range of industries and applications. The function of the biocarrier is essentially to house and cultivate bacteria more surface efficient, to metabolise the waste and transform it into less harmful forms that can be discharged without impacting algae or plants.

That old facilities can increase their capacity and upgrade their nitrogen removal without having to construct new basins has been a major advantage of MBBR systems, as the biocarriers increases the bacteria habitat (equalling more efficient cleaning) without requiring severe modifications to the plant size or site conditions.

Every carrier houses and protects growth of microbes for biofilm wastewater organisms for oxidation of organic compounds, ammonium reduction or nitrogen reduction (Lustig, 2012). Typically, a wastewater treatment plant (WWTP) uses one or a combination of the biofilm technology and the activated sludge (AS). As the development of wastewater treatment regulation has required an increasing reduction of nitrogen-compounds, a continued adaption of the biofilm technology is expected (Lustig, 2012).

Figure 2.1: Biocarriers in operation, housing bacteria for removal of nitrate.

The carriers are designed as little plastic wheels made of polyethylene (PE) or high-density polyethylene (HDPE) with a diameter of 0.5-5 cm (Bailly et al., 2018). After being added to untreated water, they are kept in motion by a rotational axis and/or aerial flow from underneath depending on aerobic or anaerobic process. The carriers will stay in the basin as long as the water levels are proportional to the plant (no overflow) and the biocarriers are circulating. No replacement or flushing is needed since they clean themselves by dropping dead bacteria to the basin floor as they collide in the movement.

The additional active surface for bacteria when using biocarriers is between 500 to 1500 m^2 when 100% filled. So that 1 m^3 of biocarriers provides a 500 m^2 surface (Lustig, 2012). The reactors are not filled to 100%, logically as that would hinder circulation and wastewater flow, rather somewhere around 40-70%. K1 and K1 Heavy from AnoxKaldnes is likely still the most used biocarrier in Sweden by professional actors (Lustig, 2012). AnoxKaldnes K2 are no longer used, but K3 is fairly common in smaller MWWTP. The flat carriers, called biochips by AnoxKaldnes, are constructed for hybrid processes and can provide 900m^2/m^3 (Biochip-P) and 1200 m^2/m^3 (Biochip-M)(Lustig, 2012). Industry processes commonly uses the AnoxKaldnes Natrix carrier, and all of them have an estimated life length of 20 years.

The MBBR technology is also applicable for recirculating aquaculture systems (RAS) as fish similar to humans release biological waste and their wastewater requires treatment before recirculating or discharge is approved (Ungfors & Lindegarth, 2014).

Figure 2.2: Moving biocarriers in the step after denitrification at Ryaverket, Sweden. Photo by Emelie Asplund via Gryyab.

2.1.3 Nitrogen removal in wastewater processes

Nitrate is toxic to living organisms in high concentrations, while the originally transformed ammonium is toxic already in low concentrations and therefore requires the treatment before release into the environment in the quantaties produced in society and industry today (Ungfors & Lindegarth, 2014). Nitrification is performed transforming ammonium into nitrite and then further to nitrate through an aerobic process. In the denitrification process, the nitrate is further transformed to nitrogen in the anaerobic process to become harmless as all nitrogen is removed from the water into the atmosphere.

2.1.4 Proximity of control system

Since the early 1970s, automatic control has received a more significant responsibility for running the wastewater treatment facilities than before as the load variations were thought to require more human adjustments and surveillance. Adjusting aeration demand and periodicity along with other system control is now vital and advanced implementation for the increased complexity in wastewater systems (Olsson et al., 2014).

Measurements with sensors and other instruments are used for feedback controls to adjust for load variations. Such system collected data with correct interpretation is transformed and used to optimise the plant operation to keep it running in an efficient manner for the current effluent requirements by automatically controlling pumps, compressors and valves. As the plant complexity has increased, the automatic control has become more crucial for good operation without requiring additional specific process knowledge of every step in the wastewater treatment system (Olsson et al., 2014). More advanced systems have allowed for an unmanned operation that is desired at night and weekends and saves operational costs.

Advanced control systems are reliable, but failures still occur due to insufficient knowledge of process dynamics in implementation or insufficient communication. Sensors may be wrongly positioned or sampling frequencies unrealistic (Olsson et al., 2014). As wastewater influent usually varies substantially in flow rates and concentrations (weather, seasons and peak loads may all affect) the plant rarely operates at steady state but instead continuously adjusts to fend off transient behaviour. Internal disturbances within the plant facility include human errors, which can also cause substantial operational issues.

2.2 Wastewater treatment regulation

The EU regulation on wastewater treatment became stricter during the recent decade, which required large reconstruction within Swedish wastewater treatment plants (Swedish EPA, 2013). The Swedish Environmental Protection Agency (EPA) coordinates the environmental work of Sweden and provides guidance for the other authorities and organisations according to the set regulations. At this time, the Swedish regulation of wastewater treatment plants was considered rather scattered by the agency themselves and work has since been focused on clarifying the existing guidance. The Swedish EPA & Svenskt Vatten stated that 2100 municipal wastewater treatment plants serviced 90% of the Swedish population in 2013 with 95% of that wastewater going to 470 of the plants. Estimately, 150 of those had some kind of nitrogen removal.

The application for receiving permission to operate a wastewater treatment plant reviews terms about effluent, limits and best available technology from an environmental viewpoint. The system design and technical specifications are assessed of risks and possible environmental impacts.

The county administration board is the assigned surveillance authority in Sweden for a wastewater treatment plant serving more than 2000 people, but they can delegate that responsibility to the local municipality. A plant serving 2000 people, or below, must only report their activity to the municipality, who become their surveillance authority. The external surveillance and inspections are performed every third year at the plants and follows protocols to check objectives according to a prioritisation (Swedish EPA, 2019).

Permission is also required in Sweden for aquaculture operations, which can be a complex process involving several authorities (Ungfors & Lindegarth, 2014). SwAM is the responsible authority for policy making and control for both fisheries and environmental legislation but it is the county administration board who receives the permission applications. If permission is given for operating the fish farm, then SwAM remains as the responsible authority but the county administration board will conduct the surveillance. General rules of consideration in the Swedish environmental code (MB:1999) applies the precautionary principle and reversed burden of proof, thus safety measures are to assure that best available technology prevents negative impacts on public health and the environment.

2.3 Plastic pollution remediation measures

Marine plastic pollution is a global environmental challenge, and waste management is appointed by Watkins & ten Brink (2017) as a sector that could improve its contribution to solving plastic pollution immensely, along with the wastewater infrastructure. Preventing plastic leakages to the ocean is a considerable economic opportunity as the material only has value if it remains in its value chain.

European (EU) laws and international frameworks do not address plastic pollution from industrial leakages specifically, but most nations do have legislation on the broader matter of environmental pollution. Thus frameworks exist to prevent leakages if only implemented adequately. When plastic leakages into the ocean occur, several nations might be affected, which then involves several national regulations. Depending on the type of plastic leakage and its size, different procedures exist and the responsibility of remediation might shift. Several agencies, organisations and companies usually get involved in the remediation. The EU commission discussed the specific topic of plastic pellets pollution in 2014 but decided that the member states themselves should put up such regulations (Karlsson et al., 2018).

Karlsson et al. (2018) conducted *The unaccountability case of plastic pellet pollution*, where they looked at spill from a plastic pellet producer in Stenungsund, Sweden. Plastic pollution from pellets is similar to one of the biocarriers in some aspects, and the study becomes an interesting comparison as it discusses legal frameworks and accountability applicable for industrial operations that create ecological disturbances through plastic leakages.

Another interesting comparison is the study of Royle et al. (2022), presenting an assessment tool for deciding the most suitable responses to mitigate a plastic pollution problem. The study points out the need to direct policy responses on specific items and to identify the value chain actors and influences when prioritising measures. Identifying patterns and the different processes existing in the increased complexity of systems is sufficiently correlated with visualisations to facilitate feasible initiatives and consensus for decision-makers. Royle et al. (2022) demonstrates the use of the assessment tool by presenting the application within plastic pollution remediation measures in the Maldives.

Plastic pollution is a complex challenge for society. Initiatives from governments are increasing, but efforts are still falling short. Befriending more evidence-based frameworks thus aids understanding of waste magnitudes and prioritised decision-making on national and international levels (Royle et al., 2022). To apply an industrial ecology perspective on flow, can facilitate the understanding of sociomaterial relations.

2.4 The industrial ecology perspective on flow

Industrial ecology (IE) is a trans-disciplinary field that studies the flows of materials and energy in industrial systems, aiming to reduce the industry's environmental impact. The industrial metabolism, meaning the product cycles within industrial systems, is oftentimes linear in present times where the end-of-life phase rarely circulate back to its cradle stage. Industrial ecology then provides the theoretical background and framework to connect industrial activities with ecology.

Within IE, one aspect is that in order to reach the desired ecological sustainability, there is a need to understand the connection between humans actions and the material flows (Baumann & Lindkvist, 2021). To combine the social and material dimensions is what constitutes the sociomaterial approach to flow studies. This has been proven a useful perspective on flow when designing sustainable intervention within industrial ecologies as it supports *change*. Identifying suitable points of intervention, called sociomaterial interaction points (SMIPs), are important for decision-makers to guide where chain and actors can be influenced (Baumann & Lindkvist, 2021).

A system mapping of the involved actors, the sociomaterial relations and the points of interaction for sustainable system change could be of importance to aid understanding of and provide measures to mitigate the impact from leaking biocarriers. This will be further explained in the following method chapter.

3
Method

The method described in this chapter was designed with an open, investigative and exploratory approach. It desired to find links and understand interconnections between both actors and between the actors and the product chain. It might therefore be useful for other projects with similar aims.

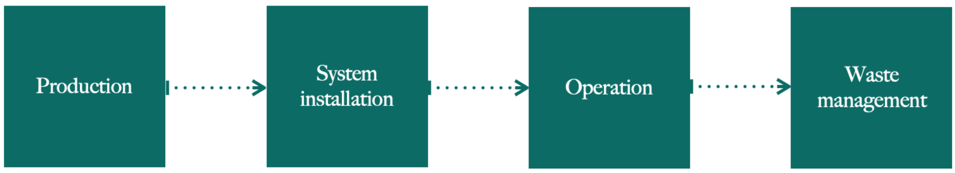


Figure 3.1: The life cycle phases considered in this project

The project considered the technical operation of biocarriers together with the actors in the life cycle as it can confirm how a particular actor's influence can contribute to a desired sustainable system change which may become an essential part of the life cycle assessment field. A Life Cycle Assessment (LCA), follows a products flow from a specified beginning to a specific end, e.g. extraction of raw material to managing its waste. It has the methodological characteristics of being very technical and detailed in product information and quantities (Baumann & Tillman, 2004). This study considered the typical life cycle phases found within LCA namely production, installation (or distribution), operation (more typically referred to as 'user phase') and waste management. To these processes, the network of actors were added, including the people, companies, organisations and authorities that interact with the biocarrier flow in a way that nurtures it continuation or existence.

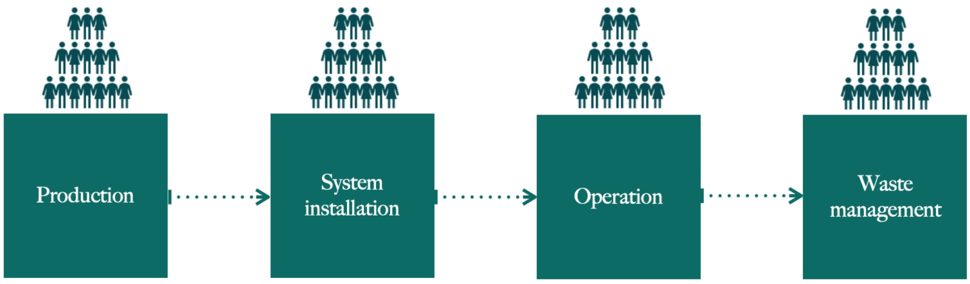


Figure 3.2: The actor network is included in a PCO study as an addition to the traditional product flow boxes.

Including the actor perspective to the LCA creates the Product Chain Organisational study (PCO), visualised in figure 3.2 with the actor network concerned in a PCO added over each life cycle step. This extension of the LCA can further aid a more sustainable management and governance concerning a product flow (Baumann, 2012). The sociomaterial approach, presented in section 2.4, was added to the system perspective to understand the product chain and identify interaction points.

3.1 Using a multi-method

The method design should enable the quest for answering the research questions and validate the results. To formulate recommendations on how to prevent biocarrier leakages, a multi-method study approach with a socio-material perspective on flows in industrial ecology (IE) was used.

The design of this qualitative study applied a reflexive process, so that collection and analysis of data, developing theory and refocusing the research questions was a simultaneous procedure and the different steps influenced each other. This allows to reconsider and modify the project design as the study develops to respond to new insights (Maxwell, 2008).

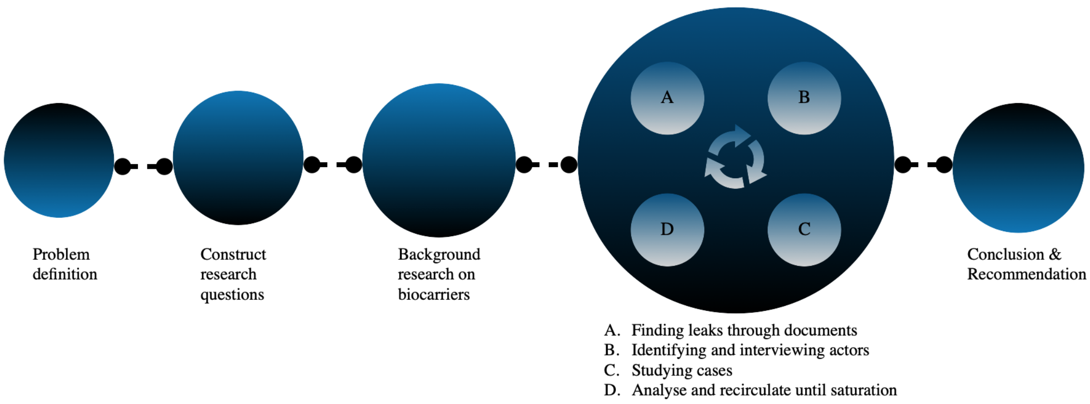


Figure 3.3: The study design aims to be a reflexive process in its execution, thereof depicted with steps A, B, C and D in a iterative loop.

In the multi-method, document studies and interviews were used to perform critical incident studies and systems mapping to visualise and understand the product chain organisation. One document study searches for occurred leakages, and another finds relevant actors. The interviews aimed to discover the interconnections and influences among the actors and, along with the critical incident studies, gave insights into how prevention could be improved. Ethical concerns were incorporated into the entire length of the study, especially concerning the interview participants who presented their views and understandings of the issues.

3.2 Critical incident studies

To clarify the issue of biocarrier leakages and their connections to actors, incidents were searched and identified. Of all leakages found, three were chosen to be described more in-depth in a critical incident study.

Following the flow of actors connected to a product can be a difficult search. Therefore, the methodological approach of critical incident studies can contribute to understanding the relations and interconnections. Perrow (1999) then offers a conceptual framework for distinguishing accidents that is useful when trying to understand the underlying causes of biocarrier leakages.

In his book about normal accidents, Charles Perrow (1999) argues that the increasing complexity within our systems creates inevitable accidents. Perrow uses examples of a much higher system complexity than this project (space ships and nuclear power plants), but the content remains relevant; that added complexity, also those of precautionary measures, makes the system prone to fail at some point. Perrow (1999) argues that even though our increased system complexity creates a higher risk of accidents, the risk can be decreased by better understanding the nature of potential risks. The apparent improvements of better training for operation, more safe designs and increased system control are given as solutions.

The scope of the incidents were set to circulate the prevailing conditions, the occurrence and the consequences. Chosen study-objects was to provide useful material to understand both the background and surrounding events to a leakage. The incident evidence was collected through multiple sources, mainly news articles and personal communication with involved actors. The evidence collected was the system in focus, technologies, timeline, remediation actions, and alarm functions, along with lessons learned and lessons taught. Incidents were first searched for using keywords such as biocarrier, biomedia, WWTP leakage in newspaper archives.

The reporting of the critical incident studies then aimed to make sense and organise the data to reveal key learning's and understandings, following both the timeline of the incident and the exchange of information between actors.

3.3 Systems mapping

A systems mapping was performed to identify actors in the biocarrier product chain to piece together phases with actors and phases with leaks. All the critical incidents identified were put in place to assign life cycle relevance awaiting further analysis described in section 3.4. To understand how actors regulate the sociomaterial flow of biocarriers, a series of interviews were performed.

A qualitative approach was applied to the interviews, more profoundly investigating the actors' experiences for a more thorough understanding of the events in the product chain that led to leakages. Therefore, the data sampled was mostly non-numerical, although estimations of biocarrier quantities were desired to create a realistic understanding of the problem.

To find adequate representatives, snowball sampling was used. Snowball sampling is depending on the previous interviewee to suggest the next interviewee, presumably from their professional network. Initial relevant actors were found through the document study. The sampling is then to continue until data is saturated, or in this case, till the time frame required that the project moved forward to process and analyse the collected data up to that point. This is a particularly useful approach where difficulties in finding a sample of representatives for the whole is present (Naderifar et al., 2017).

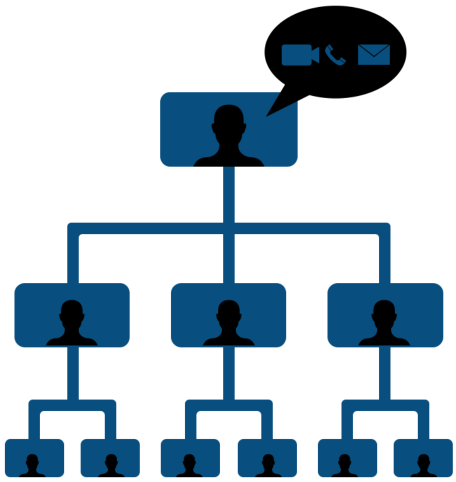


Figure 3.4: The snowball sampling finds new interview objects by recommendations from the previous.

A framework of semi-structured questions was formed where elaboration in certain areas of importance for a specific interviewee was encouraged. All interviewees were asked about their particular operation and relation to biocarriers, their knowledge about leakages and their thoughts and insights about the potential development of the product, process and recovering procedures. The base formula for interview questions is presented in Appendix A.

The interviews used the format of digital tools, telephone or meetings in person where initial contact was made by email with introduction of the study and its purpose. The interviews were then scheduled and conducted, and the data were processed for further analysis. In total, 14 interviews were conducted with additional brief contacts with also other actors. Mainly, the interviewees worked with regulation on a regional level or as NGOs or worked with installing biocarrier systems. One visit was made to a regional wastewater treatment plant, and three beach litter activities were attended on the Swedish west coast during the autumn of 2021.

Table 3.1: The origin of actors providing data for the project along with their life cycle relevance.

Country	Actor	Phase	Format
SE	Water company	Production/installation	Telephone
SE	Marine installations	Installation	Visit
SE	MWWTP	Operation	Visit
FR	Environmental NGO	Waste Management	Zoom
DK	Aquaculture	Operation	Email
SE	Private pond owner(s)	Installation/Operation	Email
SE	Paper plant	Operation	Telephone
SE	Environmental NGO	Waste Management	Telephone
SE	Environmental NGO	Waste Management	Email
DK	Environmental NGO	Waste Management	Email
SE	National coordinator	Waste Management	Visit
SE	Local/regional regulator	Installation/Waste Management	Email
DK	Local/regional regulator	Installation/Waste Management	Email
SE	Opinion leaders	Waste Management	Email

Several additional actors where contacted and searched for but not available, including aquaculture installation companies and other national opinion leaders and national co-operations. Additionally, a webinar on acute plastic pollution organised by the Oslofjorden Recreational Outdoor Council and a conference on national co-operation for oil spill prevention was attended to explore the settings of the existing collaboration and network around leakage prevention and remediation of environmental pollution. This aimed to reach a description of responsibilities among the Nordic countries, with further addition from documents and contacts with local and regional regulators.

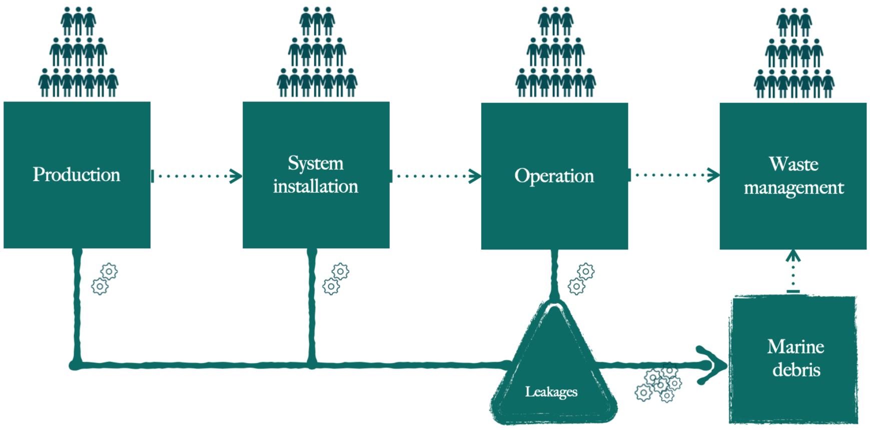


Figure 3.5: Flow chart model with the actors and leaks from the phases before waste management added. Leakages end up in the ocean and becomes marine litter, where beach cleaning is required as a more complex route to reach the waste management phase.

Most frequently, the actors appointed that although they are employees and therefore representatives of their respective organisation, much discussed during the interviews can be seen as their own personal insights and understandings. Therefore, the report underlines the importance of acknowledging this as an ethical consideration and decided to keep some viewpoints departed for organisation names and individual names when presented in the result chapter.

3.4 Embedded critical incidents in the PCO

The collected data from interviews gathered information concerning the actors organisation, their knowledge of the leakage problematic, their experienced influence and role as actors in the life cycle of biocarriers and their thoughts and insights about solutions and developments for prevention of leakages. 16 news articles from Swedish, Norwegian, Danish and French newspapers prominently gave data and information of occurred incidents which was then complemented by email communication with involved companies, organisations, authorities and the report by Bautista (2021), Strand (2019) and Surfrider (2018).

The product chain with embedded critical incidents was analysed using a cause-effect approach. Such an analytical framework helps to determine the connections between social and environmental factors since merely correlation between events does not secure causality in the cause-effect chain. Antonakis et al. (2010) states that causality can be established once three criteria are fulfilled; an order of sequence between events, the co-dependence following events, and that other causes can be eliminated. By identifying the elements of these criteria in the events, the causality in the cause-effect chain of biocarrier leakages can be established. This creates the understanding of suitable measures and responses required by regulators.

The applied method can, after suggestions according to Baumann & Lindkvist (2021) when approaching sociamaterial flows, be summarized as these set of steps:

1. Describe critical incidents
2. Identify sociomaterial action points by finding human interactions
3. Map the system and organisations based on documents, observations and interviews
4. Synthesise the findings by composing the overview and analyse influences from the actor network

By performing the product chain organisational study, the resulting inventory can be used to formulate recommendations for decision-making in management and policy procedures regulating the use of biocarriers. Identifying actors who have influence on the procedural flow from production to waste management can clarify where points of opportunity for change exists.

The following chapter presents the results from the first step, describing three critical incidents.

4

Mechanisms of biocarrier leakages

A total of seventeen leakages were found, where the findings within three critical incidents in the Nordic countries are described more in-depth in this chapter. Chosen incidents each had a relevant characteristic for understanding the operations and system complexities. The first study of an incident in Hvide Sand shows the importance of system surveillance and multiple barriers. The second study in Vansbro depicts the complexities in assigning responsibility for remediation, and the third case in Hisøy is an example of what is called a "normal accident" (Perrow, 1999) which is when a streamline of absurd or insignificant events leads to a more significant accident in the increasing complexity of our systems.

4.1 Hvide Sand leakage

At the beginning of March 2021, a land-based salmon producer located very close to the water on the inner coast of Ringkøbing fjord experienced a malfunction in the bottom plate in one of the plants biofilter reactors. Atlantic Sapphire, the salmon producer, then called for Billund Aquaculture, who installed and designed their RAS facility, to repair the bottom plate so the issue would be resolved before any significant problems occurred.

Figure 4.1: Danish findings of biocarriers on beaches (Kryger, 2021)

During the reparation, a large portion of the biocarriers kept in the tank unintentionally blocked the outflow of the water, causing them to slip out with the outlet. The description of the reason is unclear with no further explanations given when contacting the salmon farm or the installation company. Still, it was stated that this was not meant to happen but did not stir any alarm since the system was equipped with additional mesh at the outlet endpoint. This endpoint was situated slightly above the ocean surface, usually releasing treated spill water into the Ringkøbing fjord. The mesh at the endpoint had the purpose of capturing escaped carriers in case of an incident solely and was put in place at the initiative of Ringkøbing-Skjern municipality but operationally by the company itself, as it was not a part of the original design and implementation of the RAS facility. It, therefore, had no purpose for the daily operations of the business and was left out of frequent supervision.

Due to the recent ice-breaking after the Nordic winter, the mesh had been torn down by the ice and therefore failed its purpose as security net. So at the reparation of the bottom plate, approximately half a million of the facility's black little biocarriers leaked into the fjord (Kryger, 2021).

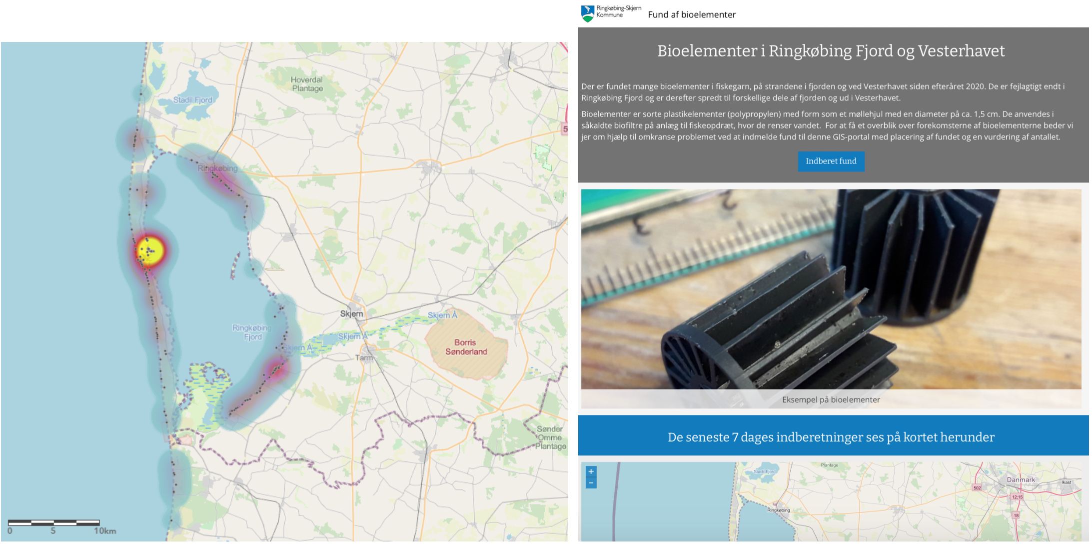


Figure 4.2: The website https://bioelementer.rksk.dk constructed by the municipality (right), and a map of findings (left)(Ringkøbing-Skjern Kommune, 2021).

The Danish municipality of Ringkøbing-Skjern is the environmental authority of this area. They were informed of the incident by the company itself as soon as it was discovered and proceeded to construct a website for aiding the recovering of the biocarriers (Ringkøbing-Skjern Kommune, personal communication, September 30, 2021) where members of society could report findings with location and quantity to steer the clean-up operations of the salmon factory. They also sent out alerts and information to inhabitants and fishers to aid the recovery (Ringkøbing-Skjern Kommune, 2021). A consultancy company that works with environmental accidents of various sorts was also involved in consulting in the recovery.

A local NGO called OMHU, performing beach cleaning initiatives in the region, got contacted by Atlantic Sapphire (or the reverse) to aid the recovery with personnel. Since the pandemic still hoovered with its public restrictions, they informed locals to search the beaches themselves instead of gathering in too large groups. But they also put together an event for beach cleaning on the Saturday after the accident (Kryger, 2021). After this, Atlantic Sapphire agreed with OMHU to perform monthly clean-ups on their account to continuously remove biocarriers that float ashore.

According to news articles, the biocarriers had not been dangerous to the fish or birds (Kryger, 2021) since no carriers were found in dissected animals. The company had to be in further contact with the municipality after the accident, where an action plan for preventing additional leakages was requested. The city filed no police report but warned the company that this was not to happen again. However, the company had experienced leakages of biocarriers also in 2018 and 2019 according to the news articles, although no further information has been found about the scope of those leaks.

Already at the time of the meeting, the company had announced improvements to the facility. The changes included an additional mesh at the inflow of the outflow pipe, an improved end mesh of the outflow and an extra mesh inside the facility. Three gates would now prohibit the biocarriers from getting out. They also added supervision of the outflow mesh to their daily operations (Kryger, 2021).

4.2 Remediation organisation in Vansbro

Vansbro is a city by the river Västerdalälven in Sweden. In the late summer of 2018, people discovered that an significant amount of white plastic objects started to fill the riverbanks. Apparently, on August 30th, the regional wastewater treatment plant experienced a malfunction that caused a leakage of 35-40 m^3 biocarriers.

Figure 4.3: Recovery in progress. Photo by private/Älvräddarna (Lundin, 2018)

The remediation was estimated by the responsible company Dala Vatten & Avfall to have recovered approximately 97-98% of the released biocarriers with the help of 30 volunteers from a local group called FRG and from Dala Vatten & Avfall after a month of work. The estimated cost of managing and executing the recovery was 1-1,5 million SEK. FRG put in 3950 hours during 33 days to collect 42 m^3 of carriers according to Eriksson (2020), which is a larger amount than the initially stated leak. The environmental NGO Älvräddarna (the river rescuers) later filed a police report of the incident against the treatment plant since they disagreed on the success of the recovery and claimed that 20 of the original 50 ton released was left in the river (Forssell, 2018).

The river rescuers found that similar incidents had occurred earlier from the facility, thus claimed that measures should already have been taken. The plant confirmed previous leakages but of significantly smaller size, around 0,1m^3 and that they had proceeded their investigation in concluding the system error. According to municipal documents found, overflows had occurred on three separate occasions during 2018 (Wikholm, 2018). The overflows were supposed to be redirected before the MBBR to secure the carriers from escaping. However, clogged grills were concluded to cause the biocarriers to run. The county administrative board, responsible for the plant inspections, visited the facility to verify that measures were taken to prevent further leakages. Additional mesh to hinder escaping biocarriers had then been put in place, and the board concluded that deficient maintenance of the system was the reason for the accident (Forssell, 2018).

The MBBR was added to the plant in 2007, and additional operational surveillance implementations. Despite the addition of MBBR, the facility was said to require substantial upgrades to prolong its operation in 2018 and reconstruction was planned for 2020 (Wikholm, 2018). The police report was never proceeded with (River rescuers, personal communication, 2021).

Figure 4.4: Biocarriers found after the leakage in Sweden in 2018. Photo by Niclas Jolhammar/Vansbro räddningstjänst (Forssell, 2018)

4.3 A normal accident in Hisøy

At a spill in Norway in June 2015, approximately 17,61 m^3 of biocarriers escaped from the wastewater treatment plant at Hisøy in Arendal municipality, equivalent to 5-6 million biocarriers or around two truckloads (Stavelin, 2017). The facility had just put their reconstructed facility in operation, and three new bioreactors were filled with 140m^3 of biocarriers.

Sixty-two million NOK and three years of planning had gone into the project to improve the facility and Biowater Technology AS was the contractor (Stavelin, 2017). At the first test operation on May 7th in 2015, a smaller size leak occurred that was quickly dealt with. No comments on system improvement where however given. One month later, on June 3rd, the chief engineer at the WWTP got a phone call. A nearby beach was filled with biocarriers, presumably from their facility. The carriers had leaked along with wastewater into the waters outside of Hisøy, and Biowater immediately closed down the new facility.

Figure 4.5: Biocarriers found after the leak in Norway (Aas, 2015)

The municipality called in 30 people to aid the recovery as soon as they knew of the incident. Already by this point, the carriers had been found by people along the coast in Merdø, Tromøya, Tromlingene, Rævesand, Torungene, Gjessøya. The recovery was work demanding, and 4-16 employed people worked at beaches and from boats the following days to remove the plastics (Aas, 2015; Bratland, 2015) along with aid from 2 people of the fire brigade (Bratland, 2015). Neither the municipality employees nor Biowater knew why the incident had happened.

They considered several causes and concluded that a capacity overload due to the recent heavy rainfalls in the region along with clogged pipes and water levels sensors that were out of order had failed to alarm that unfiltered wastewater had filled up in the bioreactor. Then two valves closed too slowly so that water had the time to escape through a valve that should not have been open (Stavelin, 2017).

The incident occurred in the minimal time frame of 56 seconds, and no person was present at the process hall due to epoxy treatment of the facility floor, which is toxic to inhale. Re-paint work in the process hall was also the reason for sensors being removed which then gave no alert to the supervisors. The installation company had a long record of successful implementations (Stavelin, 2017) but suggested that this one maybe had been pushed in its attempt to use the original facility to the largest extent to avoid reconstruction.

Figure 4.6: Biocarriers recovered from a beach after the leakage in Norway in 2015, photo by Erik Holand (Aas, 2015)

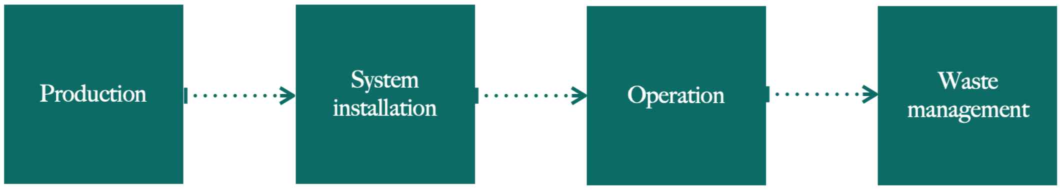
The plant was concluded to have been faulty in its design. Additional reconstruction was taken on by Biowater Technology AS to prevent further similar incidents after this leakage. The suggestion of additional mesh to capture accidental escaped biocarriers was considered in afterthought, but it was never made a demand by the municipality or regulators (Stavelin, 2017).

The biocarriers have since been found during several years along the south Norwegian coast, the Swedish west coast, and Denmark (Strand, 2020). The municipality and the wastewater treatment plant did not blame the installation company for the incident, who also covered the remediation cost with their insurance. The cost of the remediation was estimated to be 1 million NOK and the additional reconstruction of the plant facility to 4 million NOK. However, as the primary reconstruction landed on 49 million, they still managed to fit the budget into the original project roof of 60 million (Stavelin, 2017). The municipality also recognised that years of surveillance at the beaches would be required to collect all bicocarriers (Ellingsen & Aas, 2015).

From these three in-depth studies of incidents, there is reason to believe that improvements in both system design (failed barriers; failed alarm functions) and recovery procedures are necessary for a better management of biocarrier processes. All these three incidents had extensive remediation, which was not the case in all of the 17 incidents found. But uncertainties of responsibility and reliance on NGOs to clean up are observable. Following this chapter is the system mapping of the biocarrier product chain organisation, where actors life cycle relevance and the remaining incidents found are presented.

5
Biocarrier product chains

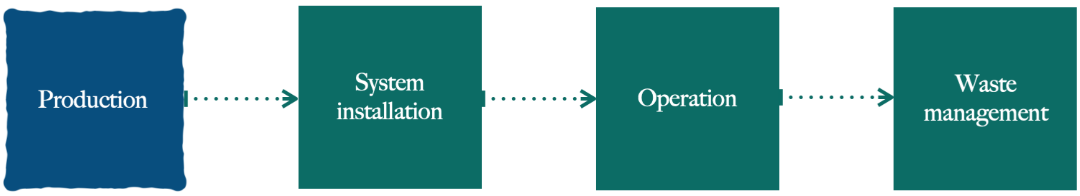
The following section will go into more detail at every life cycle stage. Connected actor are presented, sometimes parted into groups of belonging to more easily visualise the organisations assembling the product chain of biocarriers.



For every phase, the additional critical incidents found when searching for leakages are presented (along with the already presented in chapter 4) to appoint the phase most prone to such incidents. This clarifies where interventions for improved prevention measures is most suitable.

5.1 Production phase

This section presents the results collected in relation to the production and related procedures. This is the start of the life cycle journey for biocarriers, as the little plastic pieces are designed, produced and distributed.



Actors of influence in this phase includes the water companies and the plastic producers. They handle initial quantities and transportation of biocarriers. Storage and transportation of the biocarriers almost exclusively occur in large (1 m^3) sacks. If left out in the open, leakages might happen easily if not careful (heavy rain or vandalising). This is acknowledged in the report by Surfrider from 2018 and was further discussed with an installation company for marine vessels who are required to re-distribute the biocarriers from the large sacks to smaller ones in order to transport them through the narrow environment in a marine vessel.

The larger water company contacted confirmed that correct management of biocarriers waiting for operational use is of importance as keeping the sacks outdoors exposed to sunlight can damage the plastic material, making it crack before operational time is over and thus break into smaller pieces. This consideration concerns both the production and system installation phases since transportation and storage links them.

Storage and transportation in sacks further highlights the transportation actors as relevant and prevalent for possessing the correct knowledge. Actors for trademarks of professional use are below separated from other brands as tracing sources of leaked biocarriers often starts with identifying the brand and thereafter identifying what kind of source is possible. As the trademarks for professional use are only sold to regulated plants, such leakages can be more simple to conclude by revising nearby treatment facilities than for a brand that is possible to purchase for all.

5.1.1 Trademarks for professional use

The water companies are the large professional actors who design and trademarks their respective reactor designs and carriers. Veolia (AnoxKaldnes), Suez and Biowater are three large companies providing biocarrier products and solutions for both municipal and industrial uses (Bailly et al., 2018). The water companies have their own plastic producer suppliers who produce their patented biocarrier designs located at various places in the world. The project has had no contact with such suppliers of plastic products. But since the larger manufacturers of the MBBR systems are the actual designers and developers of the biocarriers, they are of interest as actors for this phase.

Biocarriers that are found in coastal zones as marine litter can be identified by their shapes and sizes and linked to their original trademark which can harm the reputation of water companies environmental care (AnoxKaldnes/Lind, personal communication, 2021). The larger water companies therefore performs R&D to improve their products not only in biological removal efficiency but also resilience in deteriorating when mismanaged in a facility (broken carriers may more easily escape) and educating customers before turning over operation of a plant. Alternative materials of biocarriers as a possible solution to the plastic pollution at a leak are discussed within research at AnoxKaldnes but not yet in business (AnoxKaldnes/Lind, personal communication, 2021).

5.1.2 Brands for private purchase

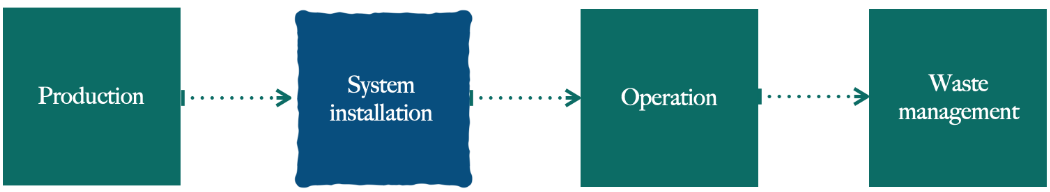
The list of brands and design of biocarriers is increasing, with various examples directing their branding for specific process purposes e.g. aquaculture, fish ponds or private households. Searching the internet for purchasing biocarriers is not a difficult procedure with several websites selling different brands. A popular small-system-carrier is the K1 or K1 micro which is not the same as, but very similar, the original K1 design from AnoxKaldnes. Conversations with Koi pond owners have also discovered that these carriers are commonly called *Kaldnes* in their communities, after the original patented design similarly to how other products are referred to as a specific trademark although sold as other trademarks (Private owners, personal communication, 2021). Evolution Aqua (2017) is an English manufacturer providing K1 carriers for private purchases and re-sellers of specific hobby equipment then extends the reach of the product, like Koibutiken (2021). The Small Boss is a Chinese plastic producer whose biocarrier products can be found on e.g. Alibaba. RK Plastic A/S, a Danish plastic manufacturer, sells carriers called RK BioElements for Aquaculture processes resembling the carriers showed in section 4.1.

There exists "fake producers" of biocarriers, as can be read in the Surfrider report (Bailly et al., 2018). These products may include the wrong plastics, making them unfeasible and therefore a wasteful plastic product.

Figure 5.1: K1 and K1 micro media acquired by hobby owners of fish ponds

5.2 System installation

In designing, implementing and installing the wastewater treatment systems, the biocarriers are transported to their operational site in big sacks. The system is then prepared and the sacks are transferred to the basin manually. Installation companies provides the system knowledge, they therefore influence the quality of the MBBR process before it is handed over to the operational unit to run the facility.



The time frame around the installation phase of systems using moving biocarriers has been stated by several of the interviewees to be the most prevalent source of leakages and the installers to be the most influential actor to prevent leakages.

Table 5.1: Examples of biocarrier leaks in the installation phase. The first one is previsouly presented in section 4.3

Location	Year	Amount	Source	Installation
NO	2015	N/A	Hisøy	MWWTP
DK	2014	N/A	Mølleåværket	MWWTP
SE	2014	$2m^3$	Omholmen/Sotenäs	MWWTP

The second leak mentioned in table 5.1 is from what is known as the most advanced wastewater treatment plant in Denmark at that time. Thousands of plastic biocarriers started washing ashore at the beaches in Charlottenlund, in the Sound, and eventually the source was concluded at Mølleåværket who was in the start-up phase of their plant upgrade using MBBR. The human error was appointed as cause of leak, since an operator had incorrectly opened a valve that let the biocarriers slip out. An additional valve was later added with configuration to decline being opened simultaneously with the first valve along with additional mesh that would prevent the carriers from reaching the nearby Sound (Andersen, 2014).

The third leak mention in table 5.1 concerns an incident at a smaller municipal wastewater treatment plant in Sotenäs, Sweden, where in 2014 the plant was upgraded to include biocarriers. At the start-up of the reconstructed plant, a pump was reversed and the flow went the opposite direction of what was intended. The biocarriers thus escaped from the plant. Surprisingly, no recovery of the biocarriers was attempted (Bautista, 2018).

The three-parted division of actors concerning this phase intends to distinguish the impacts of a leak. A large-scale implementation creates prevalent leaks for several years, while small-scale and hobby-owned systems have smaller leaks that might be easier to interfere with.

5.2.1 Large-scale professional systems

The large water companies Veolia, Suez, Biowater and Flootech all have extensive summaries and decades of experience from large-scale MBBR implementations. Additional companies providing these services exist that the project did not look into.

All systems in this sector are designed specifically for the plant either as new facilities or reconstruction of old ones. When updating an old wastewater treatment plant to improve nitrogen removal for example, the MBBR system has been a common choice due to its adaptability to existing construction and basins. Some companies only focuses on RAS-implementations for Aquaculture facilities where some have larger summaries of implementations than others. AquaMaof have 50+ large-scale installations and more to come (AquaMaof, 2021). Billund Aquaculture who construction the system mentioned in section 4.1 has a list of 130 implementations (Billund Aquaculture, 2020).

5.2.2 Smaller professional systems

All systems are not specifically designed for the given facility, but also among the smaller professional systems most are. Marine vessels require wastewater treatment in some regions before released from the vessel and since larger cruise ships can take several thousand passengers they require treatment systems who can deal with black and grey water from several thousands.

The increasing requirements on treatment before release from vessels is an improvement to help prevent further pollution of the ocean, especially the more sensitive regions of the Baltic sea, the Arctic regions and outside Alaska. Expectations are that further regions will be added to the list of strictly regulated black and grey water disposal areas and therefore the implementation of biocarrier systems is expected to rise. When implementing such a system by reconstructing the treatment system on a vessel, it is preferred to use the old tanks and rebuild them to fit the MBBR system to increase cost-effectiveness. A system calculation method given by the interview with an installation company is to account for 20 litres of tank volume per person and then fill the tank with 60% biocarriers. For a very large cruise ship of 1000 passengers that gives 12 m^3 of biocarriers used.

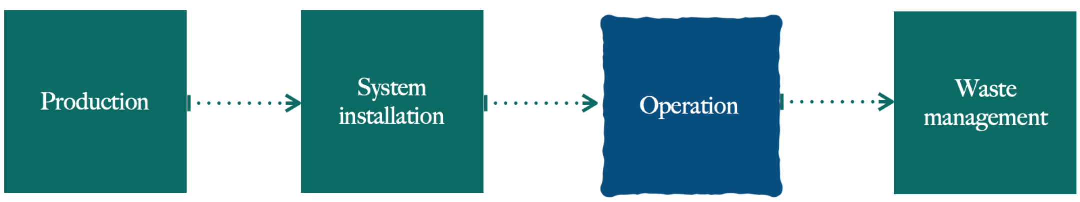
Although large ships can house such large amounts of biocarriers and a vessel being close to the water, the system deployed on a moving vessel have a different configuration than on land where all exits must be closed. All points of outflow, even vents in the tank roof, are therefore equipped with mesh to capture biocarriers on the run.

5.2.3 Micro-systems

There exists numerous companies who provide system installation services for private households, called micro- or mini-reactors, and even more people who put together their own systems for private use in garden ponds or aquariums for preventing diseases in the fish pond.

5.3 Operation

In this life cycle step, the biocarriers operate and serve their purpose - cleaning dirty water. Therefore, this phase includes the widest part of actors as every stakeholder using biocarriers in their system is relevant. It also has been the trickiest actors to conclude since the implementation area of this technology is expanding.



A rather noticeable portion of the known leakages are related to the operational phase as can be seen in table 5.2. If the biocarriers where managed correctly when proceeding to the waste management and discarded and recycled, the operational phase would be the longest period of flow stagnancy in the life cycle of biocarriers as they can remain for two decades in the system if operated correctly. Additional causes of leakage are insufficient storage and transportation along with wrongly managing the biocarrier process causing the carriers to break into smaller pieces and thus escape. These causes have not been found in examples but were given by experienced actors in the field.

Table 5.2: Examples of leakages from operating biocarrier processes

Location	**Year**	**Amount**	**Operator**	**Actor**
DK	2021	ca $2m^3$	Atlantic Sapphire	Aquaculture
FR	2020	$5m^3$	Corsica treatment plant	MWWTP
DK	2019	N/A	Atlantic Sapphire	Aquaculture
DK	2018	N/A	Atlantic Sapphire	Aquaculture
SE	2018	$35 - 40m^3$	Vansbro treatment plant	MWWTP
NO	2018	N/A	Vindafjorden unknown	N/A
IT	2018	N/A	Capaccio Paestum, Salerno	MWWTP
SE	N/A	$0,1m^3$	Vansbro treatment plant	MWWTP
DK	2017	N/A	Private/Roskilde Fjord	Garden ponds
SE	2016	$> 2m^3$	Munkedal treatment plant	MWWTP
SE	2016	$2m^3$	Idre treatment plant	MWWTP
SE	2016	$1m^3$	Tällbyn, Vamas	MWWTP
NO	2015	$17,61m^3$	Hisøy/Arendal	MWWTP
SE	N/A	N/A	Stöten, Vamas	MWWTP

The example in table 5.2 from Italy found 1875 carriers within an hour of beach cleaning a month after a large leak, where a wastewater treatment plant had lost millions (precise amount not stated) of carriers due to a design error in the plant. The Italian incident received large engagement from volunteers and NGOs who performed recovery work on beaches. It is also the only found case that went to court, prosecuting several of the involved actors (Bonnin, 2021).

The description of operational actors divides them into six sections after similarities in the their system configurations, sizes and purposes.

5.3.1 Municipal wastewater treatment plants

The most prominent users, most well known and with most considerable size of operation are the municipal wastewater treatment plants (MWWTP). These biocarrier systems can vary in size housing thousand or more usually millions of biocarriers.

In Norway, the municipal treatment plants in Lillehammer, Gardemoen and RA-2 are known to be some of the first plants to use the MBBR technology and many more are added to that list today. The Lillehammer facility was reconstructed for adding the MBBR process in 1994, with a total of 3840 m^3 reactor space for several process steps involving biocarriers and filled to 65%. That gives 2496 m^3 of biocarriers, which exemplifies a large implementation at that time. RA-2 in Strømmen, north of Oslo is one of the largest MWWTP in Norway. It uses in total 8260m^3 of AnoxKaldnes K1-media (Lustig, 2012).

The operational actors of municipal wastewater treatment plants have a somewhat more complex capacity configuration than other industrial areas that can size their treatment processes accordingly to their industrial operation. Municipal treatment plants must expect and plan for variations and changes in population and seasons. Cities may grow larger or depopulate.

One of the prime advantages of using the MBBR process is its resilience against capacity changes. But, sudden capacity extremes from heavy rainfalls with vast amounts of stormwater creates difficult inflows for facilities to manage. Often, the treatment process must be accelerated, and several steps may be skipped to fasten the flow through the process. If not, overflows occur, a reoccurring source of biocarrier leakages (Bailly, 2018).

The incident at the Munkedal facility in 2016 had an unknown cause, but the human error was given as the highest probability for the malfunction (Bautista, 2021). In Idre 2015, an estimated 2 m^3 biocarriers escaped (equivalent to approximately 900 000 plastic carriers), of which about 60% was recovered (Forssell, 2018). The municipal treatment plants in Vamas, owned by the company Malung-Sälen, experienced their leakages due to unexpected overflow (unspecific cause) and made improvements to their facilities with additional barriers after (Forssell, 2018).

5.3.2 Aquaculture

Following in operational size, and with a rising number of users, is the *aquaculture* industry. Fish is farmed to a greater extent, mainly salmon. The land-based production is increasing, which requires treatment of their industrial water that contains biological excrement from the fish and therefore needs to reduce ammonia levels.

Ungfors & Lindegarth explains the wide range of competence required for running an aquaculture facility. All from maintaining the health of the fish to market knowledge and farming techniques. The RAS facilities within the fish farming industry are increasing in Sweden considering the last couple of years but have also decreased slightly from the previous year. In 2020 there were 41 active RAS facilities (Jordbruksverket, 2021) compared with 72 production facilities in the year 2018 (SCB, 2019), but both years gave a total production volume of 5000 m^3. Compared to 2017, there was an increase in 55 facilities but a decrease for 2008 with a total of 84 RAS facilities.

In table 5.2, the accident in Vindafjorden in 2018 is not confirmed yet assumed to originate from a fish farm. As millions of biocarriers were found in the fjord, the municipality searched for the responsible operator. When all regional wastewater treatment plants could be excluded due to non-matching biocarriers, three hatcheries in Ryfylke and Vindafjord were a match for the biocarrier-brand. The fish farms could not find the leak but still took responsibility for the recovery. The police, however, dropped the case (Laugaland & Torgersen, 2018).

5.3.3 Paper and pulp, wine & other production industry

The list of industries using the MBBR technology to clean water from their plants is increasing and can operate systems sizes equal to the sectors mentioned previously.

Some industry uses the MBBR process for biological removal just like municipal wastewater treatment plant, while others use the biocarriers for COD removal, i.e. chemical oxygen-consuming substances. One such industry is paper and pulp processes, which require a lower percentage of biocarriers, around 34% in the reactors (BillerudKorsnäs, personal communication, 2021). The company interviewed implemented their MBBR processes in 2006 and 2019 and has not yet exchanged carriers similar to the majority. Neither have they experienced any difficulties with their system, and no other cases of leakages from paper and pulp plants, nor other similar production industries, have been found. The plant dimensions vary between facilities and processes. They can use the same installation designers and companies as the municipal wastewater treatment plants, meaning the larger water companies are delivering systems to these industries and smaller actors.

5.3.4 Maritime sector

The shipping and cruise industry is an increasing sector of wastewater treatment systems as regulations get stricter in an increased number of regions and the enormous number of passengers that a cruise ship can take.

According to MARPOL-regulations, all technology used at sea must get an approval. Such permits take time and effort to acquire, and thus an approved technology is rarely exchanged for a new one until the 20 years of the previous has finished. This procedure slows down the flexibility in chosen technology for wastewater treatment systems at sea. Therefore, the approved biocarrier-model for a company likely remains the same for the timeframe of approval.

An interview with a marine system installation employee (Gombrii, personal communication, 2021) explained how leaks could also occur from operating systems at vessels. As their company hands over the treatment system's operation to the ship personnel, the ones out at sea are responsible for the management. The responsible people on the ship often lack education in operating or managing a biocarrier system, which is then required in the package from the installation company. A specific example of biocarrier run-off was improperly welding the mesh tips after repainting behind a mesh barrier in the system. The fault was not unreasonable since the painter assumed that decent assembly was sufficient but did not consider the escaping capabilities of biocarriers. There are not many carriers who can disappear through a split that small, but insufficient knowledge in diverging from the system requirements can lead to other leakages. No larger leaks were however found within this sector.

5.3.5 Garden ponds

Diverging in size from aquaculture systems and often not installed by a professional company are the water purification systems of fish pond owners. These water systems are commonly closed to prevent infection in the pond from natural streams. The size of the treatment system varies given the size of the pond, where a pond of 35 m^3 would use somewhere around 130 litres of biocarriers.

Figure 5.2: Koi is a carp fish commonly owned for private fish ponds. Photo by Kumiko Shimizu on Unsplash

Questions to koi pond owners in Sweden via email suggested that although the knowledge they have sought to build their treatment system is acquired through their own research and hobby networks, it is a well-established activity requiring much effort and money from these amateurs to keep a healthy aquatic environment for their fish.

All systems are, however, not closed within this category. A beach litter monitoring study conducted in the southern parts of Roskilde Fjord in Denmark between 2016 to 2018 found 387 biocarriers, making it the top 3 most abundant item amongst their findings. This equalled 6% of the total. The biocarriers were exclusively the most found item in the spring of 2018, which was remarkable since they were not found in 2016. The scientist conducting the study, Strand et al. (2019), traced the leakage of biocarriers to a nearby private fish pond that had a small system with biocarriers treating the water from the pond and releasing it into the Roskilde Fjord. The owner was notified and corrected the system with a mesh at the outlet but did not know about the leakage, which encircles the importance of knowledge-sharing practices concerning leakage prevalence and system surveillance.

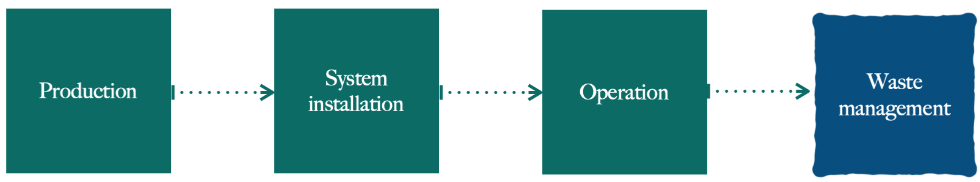
5.3.6 Households and remote or temporary sites

Many households have their own mini-reactors for treatment of their wastewater, with regional regulations putting up the requirements of their system. In Sweden, several companies have been found to offer this technology. The Surfrider investigations into such companies in France received statements that no carriers can leak from their installations (Bailly et al., 2018), which may be a truthful belief as these systems are closed. However, they are also not supervised even on an occasional basis. Smaller treatment plants for private households and compartments, if not correctly installed, could then provide leakages of noticeable size, but none have been found during the document study.

Remote wastewater treatment plants for temporary and/or mobile purposes are used during military operations, at oil and mining sites, refugee camps, construction sites, and in places with extreme weather conditions like deserts and glaciers (Bailly et al., 2018). Such facilities uses reactors of mini sizes which are commonly closed systems with no examples of biocarrier losses found for the project.

5.4 Waste management

The biocarriers have an expected operational time of 20 years before they are worn out and in need of replacement. Many operational actors have therefore not yet experienced the procedure of replacing the carriers in their system.



As initiated by section 5.3.5, monitoring beaches and concluding the source of discovered litter can be of use to find leakages of biocarriers, although time consuming. Even if recovery procedures are applied after a leakage, all escaped biocarriers are most likely not found and can then reappear several years after the incident as in the Hisøy incident (section 4.3). A summary of all exemplified leakages in the chapter is given in table 5.3 with a statement of remediation for each incident.

Actors in the stage of waste management handles the biocarriers after they have been operated. If used for 20 years and then discharged by the facilities, they would be managed as either recyclable material or go to incineration. Since the management of this waste, if it went from the operational phase and directly to its material treatment, is of the conventional kind and rather simple, the focus of actors in this phase followed a more complicated route to include all who manage the carriers on their travel through the oceans and removal from the coastlines. Thus, primarily the organisations conducting beach cleaning.

The environmental NGOs contribution to mitigate the plastic pollution has been considered in several interviews. Volunteers who live at site is a strength both at recovery and to get reports of sightings. Several examples of incidents has been discovered by people at the beaches and coasts e.g. Hisøy and Vansbro. Beach litter maps collecting information from both volunteers and companies highlights the essential contributions from both sides. NGOs are key to the success of recovery missions as they take part in established networks and distribute studies and information to responsible authorities and society.

When large accidents occur of a fast spreading plastic polluter as biocarriers, the plentiness of eyes and hands is vital for an effective and consistent remediation effort. KIMO international (Local Authorities International Environmental Organisation), and its national equivalents, works as an even larger platform for coordination and network in the North-East Atlantic and Baltic sea on local governmental level with the specific focus of healthy seas and beach cleaning. Such regulator networks are important for knowledge exchange and coordination for a joint voice to influence decisions on multiple levels.

Table 5.3: Summary of examples from section 5.2 and 5.3 with statement of recovery

Location	**Amount**	**Plant facility**	**Recovery**
DK	ca $2m^3$	Atlantic Sapphire	Yes, extensive
FR	$5m^3$	Corsica treatment plant	Yes, partly
DK	N/A	Atlantic Sapphire	N/A
DK	N/A	Atlantic Sapphire	N/A
SE	$35 - 40m^3$	Vansbro treatment plant	Yes, extensive
IT	N/A	Capaccio Paestum, Salerno	Yes, extensive
SE	$0,1m^3$	Vansbro treatment plant	N/A
NO	N/A	Vindafjorden unknown	Yes, partly
DK	N/A	Private/Roskilde Fjord	No/partly
SE	$> 2m^3$	Munkedal treatment plant	No
SE	$2m^3$	Idre treatment plant	Yes, partly
NO	$17,61m^3$	Hisøy treatment plant	Yes, extensive
NO	N/A	Hisøy treatment plant	N/A
DK	N/A	Mølleåværket	Yes, partly
SE	$2m^3$	Omholmen/Sotenäs	Yes, partly
SE	$1m^3$	Tällbyn, Vamas	N/A
SE	N/A	Stöten, Vamas,	N/A

The importance of municipal involvement in the beach cleaning was lifted in an interview with a regional coordinator of beach litter cleaning in Sweden (Västkuststiftelsen/Lachmann, personal communication, 2021). Municipalities are important to create opinion and educate society for involvement in beach cleaning events and voluntary work. But contracting entrepreneurs also have a more effective working procedure, and operates all year around. The combination has great value, to engage society but also get the job done. The importance of adding a category in the marine litter monitoring for receiving a more direct estimation of how prevalent this litter is was also discussed.

After having presented the findings of the product chain organisation, the focus will be to elaborate on interconnections among the actors and their various levels of influence to prevent leakages in the following analysis chapter.

6
Analysis

In this chapter, the collected data is interpreted to search for connections and meanings between information and actors. Purposeful insights into the product chain and actor network have been provided through the interviews, and the author makes additional elaborations. The categorisations of system risks is connected to suggestions from Perrow (1999). A cause-effect approach is used to follow the chains of events and actors of the biocarriers to identify system connections and develop problem solutions.

6.1 Causes

Our globally growing population requires expanded capacity of wastewater treatment in order to maintain sanitary conditions. This development of wastewater treatment is what increases the use of MBBR systems, driving technological developments, initially with good intentions. The first research question aimed to uncover the main causes for leaks of biocarriers into the ocean, which were divided into five categories, modified from the risk suggestions of Perrow (1999). The leakage causes in table 6.1 are categorised according to; system malfunctions, system environment (something to adapt to rather than change), human error, system design and system procedures.

Of the seventeen examples found, most leaks had not one of these causes alone but several. Section 4.3 portrayed an example of an upgraded municipal wastewater treatment plant that added new biocarrier technology with the least possible alteration to the old facility. Control systems were considered more reliable than simply adding physical barriers between the biocarriers and the outflow. The incident had both system design errors from reconstructing the plant, with several valves opened simultaneously or closing too slowly, in combination with failed warning systems and system environment effects from the overflow.

Suggestively, the events became the reason altogether, although being uncoupled elements of the system as neither are dependent or faulty due to the other. Antonakis et al. (2010) indicated that it is rather the order of sequence than a straight correlation between events that can establish the causality. Following this specific cause-effect chain emphasises the rapid time-frame of plural events that lead to an effect noticeable for several years, costing significant amounts of money, all due to defective planning.

Looking at the table in figure 6.1, the most prevalent route into the environment for the escaping biocarriers is the regular route through the pipe outflow. Thus the given recommendation of additional barriers in the system outflow could be assumed to hold and the normal route to be the focus of system intervention.

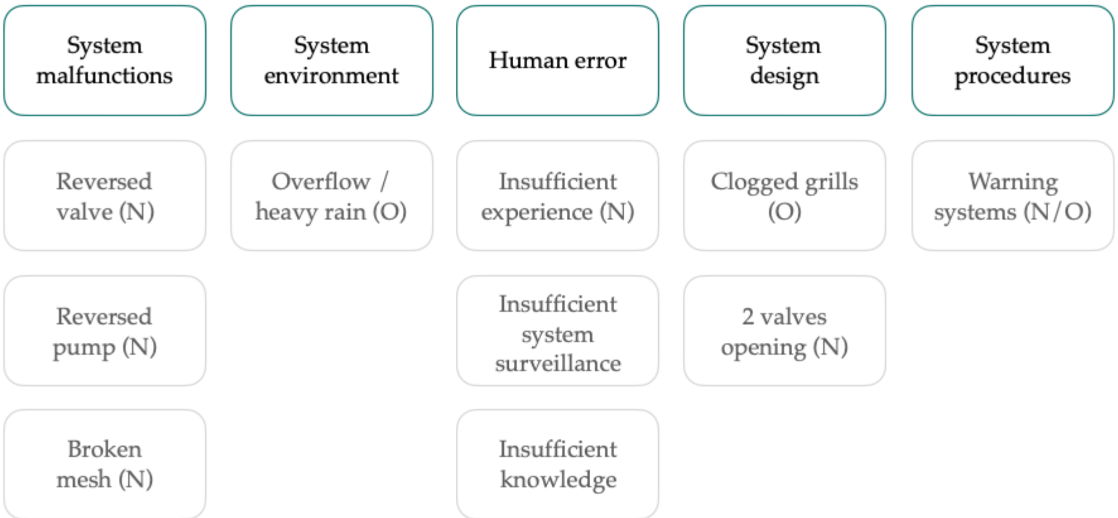


Figure 6.1: Main causes of leakages categorised according to system connection and the outgoing facility route. The parenthesis indicates the escape route (N) for normal route through the pipe outflow or (O) for overflow.

The first two causes mentioned within the system malfunction category is reversed valve and reversed pump, these are both connected to the system installation phase as such error are discovered during test operation. Within the maritime sector, insufficient experience and knowledge was acknowledged as a cause, since the staff at marine vessels have sometimes altered the aeration or rotation in the treatment process, believing that it would fasten the cleaning, but instead disturbing the process and creating more risk for leakage. The danish leak (4.1) had a broken mesh, which is a system malfunction, but that gets connected with insufficient system surveillance as a human error and with clogged grills.

Measures in case of an accident have often been non-existing in the studied incidents. Answering the second research question on what alarm systems and recovery procedures exist proved to involve various actors and not be under specific protocols. Alarm systems for overflow are used in most municipal treatment plants. However, as the case in section 4.3 showed, the thought that a sequence of overflow could generate an escape of biocarriers was not considered.

The systems are designed for managing operation, not managing accidents. Ethical considerations of the surrounding environment do not seem to meet the technology. The responsibility of system impacts on the environment perceives to shift so early that a company is released from the total cost of remediation.

6.2 Actor influences

Operational capacities vary significantly between MMBR systems, and therefore some leaks become more noticeable than others. The municipal wastewater treatment plants have enormous quantities of biocarriers in their operation. However, they also have more complex and extensive regularly supervised installations and are checked for damages and leakages. So if leakage occurs, it is a big one, but the risk of it occurring might be smaller than for other installations. The large leaks that spread biocarriers along several national borders are vital to prevent. The installations of smaller scale may, on the other hand, have continuous leakages from their operation for a longer time without action taken because of ignorance (e.g. the fish ponds in Denmark, section 5.3.5). A lack of professional competence can influence their correct installation capacity and design and lack of operational skills.

Summarising all leakages found gives the operational phase as most prone to leaks (table 6.1). However, answering the third research question of the most influential actor to prevent leakages of biocarriers may not necessarily mean that the actors of the operational phase have the most influence on creating the system change.

While the biocarriers stay in operation for around two decades, it is not strange that more leaks have the time to happen. The system installation phase can be counted as planning, constructing and testing a new installation, which may be a year. That three leakages were found within this phase may still indicate that it is even more sensitive to leakages. Several more accidents and leakages can be assumed to have occurred than the below summarising table suggests.

Table 6.1: Numerical summary of found leakages in the life cycle stages.

phase	production	installation	operation	waste management
no.leaks	0	3	14	0

More than one product chain with biocarriers exists uncoupled from each other. System-wise, the smaller actors dealing with minor reactors and amateur installations for private ponds are in no organisational contact with the large-scale actors. Neither do they pose an environmental risk substantial enough to be put under stricter policies. Yet, this group requires *enhanced knowledge* of the potential risk of leakages and their role to prevent such happenings. Such knowledge is best forwarded on a platform that already grounds the network of such businesses, e.g. the re-sellers of fish pond material.

6.3 Effects and insufficient preparedness

A neglecting attitude of leakage risk and insufficient preparedness for leakage incidents are existing problems. There is an importance of consideration from our society that this impact is severe enough to be acted upon. There are many governmental authorities involved in several life stages of the biocarriers as permissions, approval and surveillance follow both system design, construction and operation of both large and small facilities. In the waste management phase, the responsibilities becomes more unclear as to which authority is to act when during recovery.

The similarities in lacking system surveillance between the Hvide Sand accident mentioned in section 4.1 and the marine vessel repainting example discussed in section 5.3.4 assembles the understanding of needed general knowledge and care. Enhanced knowledge sharing in society to affect policy-makers may thus be an interaction of importance, but more of a long term change. Presenting economic costs connected to the environmental impact can generate the desired engagement, as remediation measures after leakages are work-intensive and more efficient if a recovery is operated immediately before the biocarriers spread further.

Higher governing instances could ensure that technical needs are met by stricter requirements. They could also nurture an industrial culture that cares enough about preventing environmental impacts from their operation. Of those suggestions, only the first seems able to reach. However, the second may be of most excellent and most sustainable importance since it is the only one that can guarantee continuous measures when technologies develop.

Remediation coordination at this sort of acute plastic pollution has lacked protocol, with actions and organisations tentative. Even though some operations have been praised for their efficiency and recovery rate afterwards, the time management can be optimised, and recovery methods simplified if action response is accelerated. This could be further streamlined with relevant protocols on acute plastic pollution accidents. Together with studies on specific plastic pollution like the one of Karlsson et al. (2018) and connecting to evaluations of assessment tools as from Royle et al. (2022) builds the understanding of appropriate actions required. Beach cleaning organisations and environmental NGOs rely on environmental champions and their drive for environmental justice. But to facilitate a voluntary engagement, someone must take responsibility and organise. Engagement is hard to withhold without continuous updates and accurate information, and organisation is difficult to create. The conclusion will thus involve recommendations to increase assessments of risks that could activate further development of strategies for recovery.

Further elaborations of the project results and framework are given in the next chapter, along with considerations to what could have been done different in performing this study.

7
Discussion

To answer the research questions posed for this project has been an exciting detective work involving actors of various backgrounds and businesses. Consideration is given to that not enough actors may have been reached to complete the picture of a detailed product chain organisation, as time has limited the project to discuss some industry sectors merely from document studies. Reaching actors of aquaculture installations and a wider scale of producers could have further established the conclusions and confirm saturation in the interviews. Further, several actors exist inside every organisation who can influence the biocarrier management differently, e.g. a plant manager versus the process engineers.

The mapped product chain clarifies the involved influences and actors to complement the known knowledge within actor organisations and confirms the interconnections and influences amongst the actor networks. The importance of correctly storing, distributing and transporting the biocarriers from production and re-sellers to the point of operation should be further acknowledged, as resemblance can be drawn to the plastic pellet study (Karlsson et al., 2018) mentioned in section 2.3.

Insights from actors' and studied documents have not encircled an individual cause for leakages of biocarriers but rather depicted a variety in accident categories or a combination of reasons as in table 6.1. Most actors addressed have issued the installation phase with its actors as the ones who could have foreseen such incidents. Actors of installation have either agreed with that statement or disagreed. The disagreers have the viewpoint that insufficient knowledge, experience and *care* from the operational unit is what creates the opportunities for leakages. As the opinions depart, the conclusion encircles them both. System malfunctions due to design errors and human errors and relying on warning systems all make up the framework of accidents. A correct installation with adequate design considerations to potential risks is of great importance, as is proper management and operation of the process.

External inspections of wastewater treatment plants are performed regularly. Still, leakages have occurred duplicate times at some plants. Suggestively, the inspection is inadequate at checking leakage sensitive points for biocarriers and should be improved per the given recommendations. If insufficient measures are not caught at visits from authorities, the policy may lack validity. The operating facilities are required to know their potential risks for public health and the environment as stated in Swedish regulations in section 2.2. To pay for a clean-up should thus be more expensive than to add another barrier into the system. *The Polluter Pays* is the standard principle used in national regulations, as consequences of recovery-costs should be expected to spark engagement in improving mitigating measures. But, that is if the responsibility can be assigned where it is effective.

Police reports are rarely filed after plastic pollution incidents, suggesting a general difficulty to assign responsibility. Either that or juridical governmental bodies do not consider the impacts of plastic pollution from these incidents severe enough, reflecting the relationship between impact and response factors in section 6.1.

As stated by Karlsson et al. (2018), frameworks do already exist that could be used to prevent leakages if only enforced adequately. To put direct regulation on a specific type of pollution could clarify the suitable implementation of measures. As the mechanisms of leakages were studied, rather than leakages within a specific geographical area, this allows for up-scaling on appropriate levels for various systems and sectors using biocarriers in their processes. The given compilation of known leakage causes and system mapping of involved actors are applicable information for regulating measures in large-scale product chains likewise individual facilities. Regional or national information on wastewater treatment facilities outflow to specific streams or coastal areas can then merge with the mechanisms to evaluate the risks for those areas.

The overall good intention with the MBBR technology has been considered and mentioned. Thus, the project does not intend to suggest prohibition of the technology, only giving appointed attention to extend the care for its entire life cycle.

Photo by Beth Jnr on Unsplash

8

Conclusions

The wastewater treatment plants have made a massive difference for our intensively expanding population over the last centuries. Society has gone from releasing dirty water straight into the natural environment to filtering away the most unhealthy and dangerous particles in major processes. Nevertheless, technological advancements should not slow down due to considerations of being "good enough" when ecological disturbances still occur.

Primary focus should be on the professional actors and large-scale systems as the interconnections and influence among actors are higher along with the higher risk of failure from the more complex technical systems, as Perrow (1999) mentioned. In these large-scale systems, operators rely on installation companies to receive a resilient system design and the necessary operational knowledge. In return, the installation company relies on the plant personnel to run the system according to their instructions, as publicity from leaks puts the blame and decreases the trust for their product. Both actors are vital for a correct management of biocarriers and are tightly coupled. As authorities govern the gates of these processes, meaning design/implementation permits and effluent discharges, they become the influential governing actor that can steer the necessary efforts for the desired sustainable system change.

8.1 Final recommendations

The fourth question posed for the project asked how further leaks of biocarriers can be prevented. For this, the recommendations for policy implementations and improved management of the biocarrier product chain were formed at three levels.

Company level: Design for and implement physical barriers into the system after the outflow from the biocarrier treatment step and at the inflow of the plant outflow, which is specifically intended for catching potentially escaped biocarriers. Such implementations should reasonably not disturb any other stages of the treatment system, as mechanical filtration of the effluent is expected before the MBBR step. Secondly, include the risk of biocarrier leaks into a risk assessment of the potential environmental impacts from the company operations. Also, conduct continuous system inspections assuring that the biocarrier barriers are intact, which will nurture an ongoing knowledge about leakage risks among operators.

Regional level: The surveillance authorities should require a 2-3 step assurance that biocarriers cannot reach the surrounding waters at the inspections of new or upgraded implementations, both before start-up and at the continuous inspections they already perform. Increase knowledge of prevalent leakages risks and occurrences by informing installations companies.

National and international level: Add into required risk assessments for installing MBBR systems about biocarrier leakage risks, to be applied for the operating business, the contractors, the municipality responsible for the surrounding environment and the authority monitoring the catchment areas. Higher instances of regulators are recommended to regulate this type of marine plastic pollution.

When considering how previous leakages has improved the preventative actions in the day-to-day operation, management and technical implementations for the polluting companies, they have declared added barriers and improved risk assessment as their immediate improvements. Since no further leaks have been made public from the same facilities after those measures, they can be coarsely assumed as functional system improvements.

8.2 Final remarks

The biocarriers have been referred to as *"slippery and just taking every little opportunity they can to escape"* in one of the interviews, and this could seem to be the case. But plastic carriers do not have a will of their own and cannot be blamed in this scenario. The use of IE tools and understanding sociomaterial relations is considered as a feasible approach with similar aims to this projects where input is sought for suitable measures in policy development.

As wastewater treatment will require further innovation to adapt for extended pollutant removal, configurations will be expected in the forthcoming time. What could then be better than for leakage prevention and extended surveillance of system constructions to go side by side with the other interventions.

Hopefully, we can develop a more mindful society that cares about the quality and impact on the marine environment. The cost of the cleanups are present in more value than monetary, but it may be the economic value that spurs the industry engagement.

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A

Appendix 1 - Interview questions

As the interviews were conducted using a semi-structured procedure and different actors have various roles within the biocarrier life cycles, the same questions were not relevant in every interview. This appendix presents the base formula for the interviews and some of the variations for actor relevance.

The questions were formed to consider the specific company case, their leakages, thoughts, and potential development insights.

Table A.1: The interview base formula for all actors.

Question	**Actor relevance**
Describe the company/organisation operations, history, vision and how the company/organisation contribute to mitigated environmental impact from humans.	All
What is your knowledge about leakages of biocarrier? Continuous spill or larger ones?	All
Do you think more educational training is needed for the operational phase than at present moment?	All
Is this technology good enough to be developed for continued use or is a better technology expected to take over?	All
How could the recovery procedure at a leakage be improved?	All
Do you consider your knowledge about this technology and process to be sufficient?	All
As an actor in the life cycle of biocarriers, who do you think have the best influence to prevent leakages and how much influence do you have?	All
Are the leaks more due to technical failures than educational or cultural reasons?	All

Table A.2: Additional interview questions for installation companies and operators.

Question	Actor relevance
Are the installation solutions specific for each new implementation?	Installers
How large are the installations generally and how many biocarriers do they carry?	Installers
Why did you decide to provide solutions of the MBBR technology?	Installers
Is it the most common technology used and what the customers expect?	Installers
What is the supplier and type of biocarrier that you use?	Inst/Oper
What is the level of knowledge of your customers when they hire you?	Installers
Are there procedures in place for remediation after an leakage has been discovered?	Inst/Oper
Have you made adjustments to your technology for preventing spill?	Inst/Oper
How old is the facility and current technology used, was it constructed using the present technology?	Operators
How many biocarriers are in your operation?	Operators
How much and at what frequency do you refill?	Operators
Have you ever had a larger leakage/accident? If so, when, how and how much?	Operators
What is your procedure at an occurrence of leakage into the environment? Who and how do you alert?	Operators

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