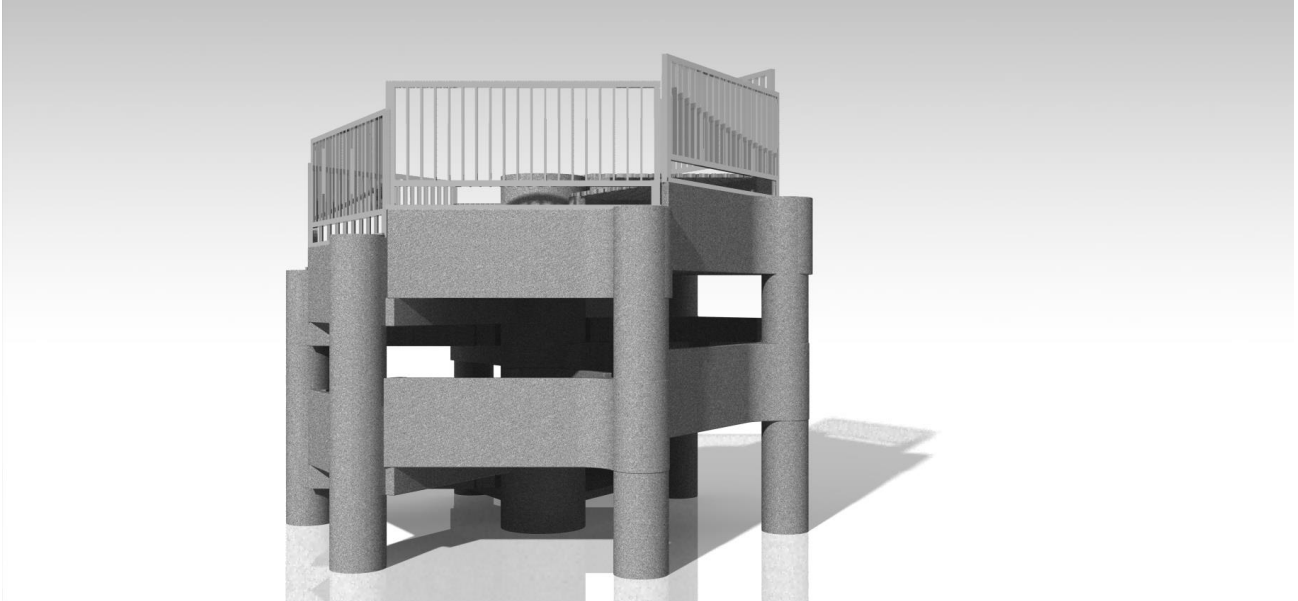




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Modular Fish Ladders for Small-scale Hydropower Plants in Sweden

Investigation of a spiral shaped upstream passage

Master's thesis in Industrial Design Engineering and Product Development

TEA KARPEFORS

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DEPARTMENT OF INDUSTRIAL  
AND MATERIALS SCIENCE

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CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2024

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MASTER'S THESIS 2024

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# **Modular Fish Ladders for Small-scale Hydropower Plants in Sweden**

TEA KARPEFORS  
HANNA QUIST



**CHALMERS**  
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Department of Industrial and Material Science  
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Front page: Rendering of a modular and spiral shaped fish ladder, Tea Karpefors and Hanna Quist

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# Abstract

In this master thesis, new modular principles for upstream fish passages at small-scale hydroelectric power plants in Sweden are investigated. The product development study is conducted at Chalmers University of Technology and carried out in collaboration with The Hydroelectric Environmental Fund (Vattenkraftens Miljöfond Sverige AB). The initial motivation behind the study was the anticipated increase of fish passages that are to be built in the coming years, as a result of modifications to the Environmental Code.

In the initial problem identification, the costs associated with fish passages emerged as the most tangible problem for small-scale hydropower plant owners. Since pre-construction work and customised design based on local conditions were identified as crucial cost parameters, a space efficient solution that was based on a spiral shaped design with mass-produced modules was justified. The study thus aimed to pre-develop these modules with respect to stakeholders' expectations, needs and requirements and in relation to material selection and choice of production technique. Findings from extensive exploration, including site visits, interviews and literature review, could be summarised in a stakeholder analysis. Besides cost-efficiency, and the obvious need of excellent passage efficiency, the importance of maintenance and environmental sustainability emerged as significant factors, guiding further development efforts.

Building upon this foundation, an iterative ideation process was taking place, where multiple ideas were generated using brainstorming, prototyping, and matrices. Three Value Creating Strategies, based on three different scenarios of market outcomes, were created and used for evaluation of the concepts. Concepts, with high expected value in a “one size fits all-with-the-same-needs”-scenario were further developed.

The study resulted in the design of a maintenance platform as well as three design concepts of modules, all with different materials, manufacturing methods, installation and life-cycle approach. The final modules' designs were thereafter evaluated based on cost-efficiency, maintainability, and environmental sustainability criteria. Recommendations for further development followed.

The findings underscore a significant demand and potential for a modular, cost-efficient fish passage. Nonetheless, ensuring successful implementation entails further testing and evaluation.

# Sammanfattning

I denna masteruppsats undersöks nya modulära principer för uppströms fiskpassager vid småskaliga vattenkraftverk i Sverige. Studien genomfördes vid Chalmers tekniska högskola i samarbete med Vattenkraftens Miljöfond Sverige AB. Orsaken till att studien uppkom var det ökade antalet fiskpassager som förväntas byggas under de kommande åren till följd av ändringar i miljöbalken.

Vid den inledande problemidentifieringen framkom kostnaderna förknippade med fiskpassager som det mest påtagliga problemet för ägare av småskaliga vattenkraftverk. Eftersom markarbeten och skraddarsydd design baserat på lokala förhållanden identifierades som kostnadsdrivande, motiverades en platseffektiv lösning baserad på en spiralform och serietillverkade moduler. Studien syftade därför till att designa dessa moduler med avseende på intressenters förväntningar, behov och krav samt undersöka lämpliga materialval och produktionstekniker. Resultaten från omfattande informationsinsamling, platsbesök, intervjuer och litteraturstudier, sammanfattades i en intressentanalys. Förutom behovet av en kostnadseffektiv lösning och en god passageeffektivitet för fisk, framkom vikten av underhåll och miljömässig hållbarhet som viktiga faktorer för vidare utvecklingsinsatser.

Utifrån denna grund genomfördes en iterativ idégenereringsprocess, där flera idéer genererades med hjälp av brainstorming, prototypskapande och matris-metoder. Tre värdeskapande strategier, baserade på tre potentiella framtidsscenario, skapades och användes för utvärdering av koncepten. Koncept med högt förväntat värde i ett "one size fits all-with-the-same-needs"-scenario utvecklades vidare.

Studien resulterade i utformningen av en underhållsplattform och tre designkoncept av moduler, alla med olika material, tillverkningsmetoder, installationssätt och livscykelperspektiv. Modulernas utformning utvärderades därefter utifrån kriterierna kostnadseffektivitet, underhåll och miljömässig hållbarhet. Därefter utformades rekommendationer för fortsatt utveckling.

Resultaten visar att det finns potential för en modulär spiralformad fiskpassage, eftersom det är en platseffektiv design där kostnader kan minskas genom serietillverkning och mindre behov av markarbeten. Att fiskpassagen uppfyller god funktion är avgörande och därför krävs ytterligare testning och utvärdering för att säkerställa funktionen.

# Acknowledgements

This report investigates the potential for developing modular solutions for upstream passages at small-scale hydropower plants in Sweden through a product development process. The study was conducted by Tea Karpefors, a master's student in product development at the Department of Mechanical Engineering, and Hanna Quist, a master's student in Industrial Design Engineering, both at Chalmers University of Technology.

We extend our sincere thanks to our supervisors, Ola Isaksson, professor and researcher at Chalmers University of Technology, and Joakim Thanke Wiberg, project manager at The Hydroelectric Environmental Fund; our examiner, Sophie Isaksson Hallstedt, professor and researcher at Chalmers University of Technology; and expert advisor, Anders Bard, hydropower expert at Sweco. Your knowledge, guidance, and commitment throughout the entire project have been invaluable.

Finally, we would like to extend a big and heartfelt thanks to everyone else who has contributed to the study. The knowledge you have provided has been crucial to its success.

Thank you!

*Tea Karpefors & Hanna Quist, 2024*

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# 1

## Introduction

**Chapter 1.** The following master thesis report is concerning product development of modular fish passages for small-scale hydropower plants in Sweden, especially working towards cost-efficiency, maintainability and environmental sustainability. This opening chapter introduces the background, aim, goal, research questions, demarcations and structure of the report.

# 1.1 Background

Today, there are around 2100 hydropower plants and 10 000 dams in Sweden collectively constituting around 45 percent of Sweden's total energy supply (Swedish Energy Agency, 2023). Hydropower, as a renewable energy source, plays a crucial role in Sweden's efforts to achieve the aim of 100 percent renewable electricity production by 2040 (Regeringskansliet, n.d.). Hydropower is not only renewable, but its adaptable nature and unique ability to store water in reservoirs make it predictable, ensuring the availability of electricity production when needed.

However, hydroelectric power plants pose challenges by blocking fish migration routes and impacting ecosystems, disrupting normal river life (World Wildlife Fund WWF, 2023). The national plan (NAP) was developed in response to the EU's 2000 Water Directive, which mandates that all EU Member States achieve good status for all surface water and groundwater bodies by 2027 (European Environment Agency, 2018). Three authorities— Swedish Agency for Marine and Water Management, Swedish Energy Agency, and Svenska Kraftnät, authored NAP, which suggests a comprehensive national strategy to ensure that hydropower operates under modern environmental standards, coordinated to maximize benefits for aquatic ecosystems while still facilitate efficient national access to hydropower electricity. It includes a joint recommendation to enhance environmental conditions for Sweden's hydropower plants.

In 2019, the Swedish government decided to implement the NAP and introduced changes to the Environmental Code, resulting in all of Sweden's hydropower being tested in Land and Environment Court on whether they need to implement measures to fulfil the new environmental criteria. NAP also includes information along with proposals for plan implementation and follow-up. Additionally, NAP establishes a timetable for hydropower owners to submit their applications to the court (Swedish Agency for Marine and Water Management., Swedish Energy Agency., & Svenska kraftnät.,2019).

Out of around 2100 hydropower plants, 250 contribute to more than 98% of the total installed capacity (Swedish Energy Agency, 2016). This leaves many small-scale hydropower plants that, despite their limited contribution to electricity generation, pose a potential threat to waterways. A requirement in the updated environmental standards mandates that hydropower plants must incorporate effective passage solutions to facilitate the migration of fish (Swedish Agency for Marine and Water Management, 2019). Many hydropower plants are now facing the need to build fish passages that meet court requirements if they wish to continue their operations.

This process requires investigation and involves large investments from hydropower owners, which is why The Hydroelectric Environmental Fund (Vattenkraftens Miljöfond Sverige AB) was established in 2020. The Hydroelectric Environmental Fund's (also referred to as The Fund) primary purpose is to assist hydropower owners in meeting the new environmental requirements. Financed by the nine largest hydropower companies in Sweden, The Fund holds a collective commitment of the finite sum 10 billion SEK (monetary value 2018). The Fund covers 85% of expenses related to investigations, environmental assessments in court, and the implementation of court-mandated measures. The fund can also compensate for any production losses incurred during the process (Vattenkraftens Miljöfond, n.d.-a).

Although The Fund finances 85% of costs related to environmental adaptations, these environmental adaptations are large investments for small hydropower plant owners with limited production revenue. Furthermore, the final cost of the environmental adaptations is difficult to predict.

According to the Environmental Code, measures employing the “best available technology” are also required. Best available technology is often considered as a natural-like bypass (an artificial waterway that mimics a natural watercourse) (Calles et al, 2013). However, this is space-intensive, and it's not possible to install such a type of fish passage at all locations. In some cases, technical fish passages are used instead. However, these too are often space-intensive and require extensive pre-construction work.

The conditions outlined above highlight the necessity for cost efficient fishways specifically tailored for small-scale hydropower plants, that ensure minimal ecological footprint on the local environment. Considering that all hydroelectric power plants are unique with different surrounding conditions, there's a need for fish passages adapted to suit each unique hydropower plant. There are currently ideas about using modular design techniques to achieve scalability and adaptation tailored to the specific characteristics of each individual hydropower plant facility.

To be able to connect the research with an existing location, a case study is reasonable. Hultafors dam and hydropower plant, associated with the Rolfsån river, is one of many hydropower plants that are facing the challenges mentioned above. The hydropower installation comprises Viaredssjön dam, Hultafors dam, and Hultafors power station, all likely dating back to around 1920. In the Rolfsån status report (Länstyrelsen Västra Götaland, 2021), salmon, trout, eel, and river pearl mussel have been identified as target species. The lack of a universal solution for these small-scale hydropower plants has been identified and Hultafors dam has been selected as a case study due to their alignment with the challenges addressed by the modular fishway principle. The location, nestled between a rock wall and a car and train track, also necessitates a space-efficient fishway solution.

## **1.2 Aim and Goal**

The aim of this study is to investigate how a fish passage for small-scale hydropower plants should be designed to meet identified needs and requirements and propose guidelines on how these can be realized and implemented. This master thesis study also addresses several research questions in the area of systems engineering design and sustainable product development, see section 1.3 Research Questions.

The study's goal is to deliver a stakeholder analysis and a list of requirements for an upstream fish passage for small-scale hydropower plants. Additionally, the goal of the study is to propose an upgraded design with a visual representation of the fish ladder's design and a description of intended functions, use and context. Lastly, an assessment of the delivered design will be made, where the goal is to provide equal or better performance in cost efficiency, maintainability, and environmental sustainability in relation to a reference.

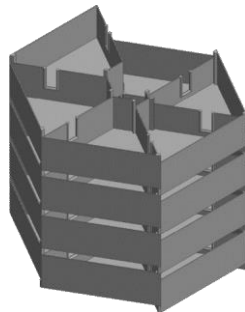
## 1.3 Research Questions

The problem of costly and insufficient fishways for small-scale hydropower plants will be addressed in this report. Thus, the research questions are stated as follows:

1. What problems, opportunities, needs, and expectations are associated with fish passages adapted for small-scale hydroelectric power plants?
2. How can the proposed solution be designed and optimized to align with the stated needs?
3. How can the solution be evaluated in terms of cost-efficiency, maintainability, and environmental sustainability?

## 1.4 Demarcations

The study will be based on an existing, protected design of a spiral shaped and modular fishway, invented by Magnus Danielson and dimensioned by experts at Sweco. The study's focus is the modules in themselves, and their relation to the bearing structure. This emphasizes design, material selection, and manufacturing methods. However, it excludes the dimensioning of the load-bearing structure and strength calculations, as these aspects are addressed in collaborative projects. Expertise on fluid dynamics and fish requirements is provided by Sweco and is considered a prerequisite for this study. Dimensioning of the protected design is based on standards in the DWA Regelwerk (DWA, 2014). Figure 1 represents the idea of shape for the protected design.



*Figure 1. CAD-representation of the spiral shaped fish ladder.*

*Visualisation: Håkan Watson, Sweco.*

The construction of full-scale prototypes will be carried out by individuals external to this study and will be used within the study to enhance understanding. Therefore, the study itself will not deliver a full-scale physical prototype, but a digital visualisation and description of the modules' design.

The scope of the study is to investigate and develop a fish passage tailored for upstream fish migration in small-scale hydropower plants in Sweden. The design aims to accommodate fish species up to 60 cm, and can handle a waterflow of 70 l/s and a step height of 15 cm. This means that the fish passage excludes larger fish as well as bottom-swimming species that are unable to handle a step height of 15 cm.

Delimitations are also that only the vertical transportation of fish has been taken into consideration. Attraction of fish, design of inlet and outlet is not included, but because of their importance for the success of the fish ladder's function, general recommendations are given in Chapter 9.

## **1.5 Structure of the Report**

The report is structured as follows: Chapter 2 describes the method, introducing the four phases of the applied process known as The Double Diamond Process. These four phases are detailed in separate chapters (3, 4, 5, and 6), each concluding with key takeaways. Chapter 7 presents the three resulting design concepts in detail. The report concludes with a discussion, conclusions, and recommendations for further development.

# 2

## Method

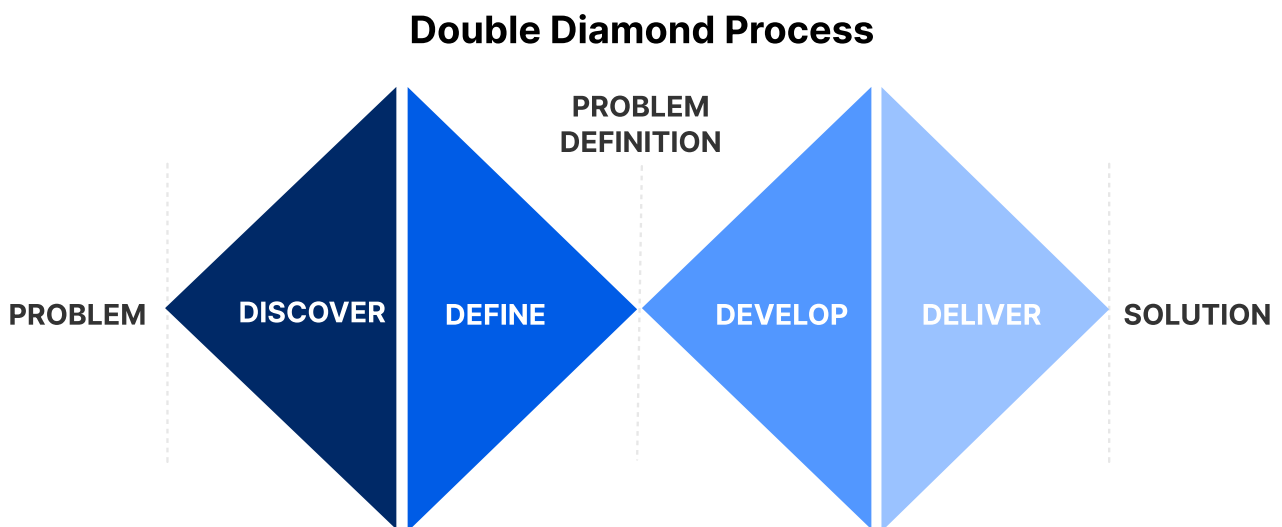
**Chapter 2.** In order to investigate the problem at hand, a structured approach is essential. In this study, The Double Diamond process was chosen to be the framework for problem-solving and design innovation. This method involves exploration and definition of problems before generating and implementing solutions. Particularly beneficial for projects requiring a deep understanding of user needs and iterative refinement of innovative solutions, the Double Diamond process aligns well with the objectives of this study. The following chapter begins by outlining the overall design process, followed by a breakdown of the various project phases, detailing the methods and tools utilized in each phase.

## 2.1 Process Outline

The study has followed The Double Diamond process, a design methodology with origin from the Hungarian American linguist Béla H. Bánáthy in 1996 and was further developed by the British Design Council in 2005 (Design Council, 2024). This process is divided in four phases: Discover, Define, Develop, and Deliver, see Figure 2.

At the initial diamond phases, the process diverges during the Discover phase, when exploring the problem space, and then converges in the Define phase, when establishing clarity, focus, and direction by pinpointing the specific issues and needs at hand. Subsequently, the process diverges again to explore the solution space and generate ideas, during the Develop phase, to thereafter converge once more during the Deliver phase. Here, decisions are made regarding which ideas to pursue and test, effectively narrowing down the possibilities (Design Council, 2024).

It's important to note that The Double Diamond process is not strictly linear; rather, it allows for multiple iterations of divergence and convergence throughout. Nevertheless, it serves as a visual representation of the project's overall process. This chapter will guide the reader through these stages, and the methods and tools that have been used during each phase.



*Figure 2. Four phases of The Double Diamond Process.*

## 2.2 Discover

The Discover phase involves exploring to comprehend the problem. It entails gathering and analysing information, investigating user needs, and understanding the project's context. It is an exploratory phase where insights are sought, and opportunities identified before progressing to the next stage of the design process (Design Council, 2024).

### 2.2.1 Literature Review

A literature review is a qualitative and exploratory method that involves delving into existing research within a specific topic. According to Bashier (2017), literature review is essential to a design process and should be included not only at the beginning but throughout the process. Information can be acquired from academic reports and journals but also from websites, books, and newspapers as long as the source is reliable (Nilsson Wikberg et al., 2015).

The literature study for this project aimed to gather knowledge about the context in which the design will operate, as well as background information on NAP, hydropower, fish needs, biodiversity, current fish passage solutions, and available materials and production methods.

The Fund provided recommendations on relevant literature related to hydropower, NAP, and fish migration. This literature served as a basis for finding additional resources on the subject. The Swedish Agency for Marine and Water Management's comprehensive recommendations and literature links have been a primary source of information.

### 2.2.2 Market and Patent research

An investigation was conducted into the current market landscape regarding fish passages, encompassing their design, materials, strengths, and disadvantages, with the aim of understanding how competitors have solved similar problems. This exploration not only served to gather insights from established practices but also to seek inspiration and ideas. Additionally, a comprehensive patent search was conducted using both PRV, Swedish Intellectual Property Office, and Espacenet, European Patent Office, to identify patents relevant to the proposed design of the fish ladder in this study.

### 2.2.3 Interviews

Interviews serve the purpose of exploring users' opinions, attitudes, experiences, behaviours, and motivations in relation to services and products (Wikberg Nilsson, Ericson Törlind, 2015). Additionally, this method can be employed to gather expert insights within a particular domain.

Interviews are useful in all stages of a design process. At an early stage, interviews can provide insights into users' opinions and experiences and thus increase understanding of how the use is experienced. Interviews can also be done at a later stage of the process, as a mean of evaluation.

Nilsson Wiberg et al. (2015), categories interviews into structured, semi-structured, or unstructured. A structured interview involves pre-prepared questions, and only these specific questions are posed

during the interview. Conversely, an unstructured interview resembles a free-flowing conversation where participants have the possibility to discuss a topic openly. In the case of a semi-structured interview, it falls somewhere in between, with certain prepared questions but allowing flexibility for the conversation to explore new directions.

To ensure that important topics are covered, meanwhile provide the freedom for new directions, this study has consisted mostly of semi-structured interviews. The interviews that arose spontaneously during study visits were of an unstructured format as these interviews were not planned in advance. The majority of the interviews were conducted in the early stages of the project to identify needs and requirements, but interviews were also used later, to evaluate developed concepts. See Table 1 for a list of interviews and their purposes.

**Table 1.** List of interviewees, including purpose and level of structure.

<b>Nr of interviews</b>	<b>Interviewee (Profession)</b>	<b>Purpose of interview</b>	<b>Level of structure</b>
7	Employees at The Fund	Background knowledge and contact recommendations on important stakeholders	Semi-structured
3	Hydropower plant technicians	Gain knowledge of maintenance of hydroelectric power plants and fish passages	Unstructured
1	Consultant in hydraulic engineering	Gain knowledge of fish passage construction	Semi-structured
2	Sport fishermen	Broadening the scope of the problem	Semi-structured
2	Small-scale hydropower plant owners	Identify hydropower plant owners' needs and requirements for a fish passage	Semi-structured
1	Professor in materials engineering	Explore potential materials and manufacturing processes	Semi-structured
1	Biologist and Researcher	Understand needs of fish, surrounding environment and testing of hydropower constructions	Unstructured
2	Biologist	Understand needs of fish and surrounding environment	Semi-structured
5	Environmental representatives from Sweden's largest hydropower companies	Evaluate concepts and get understanding of important needs	Semi-structured
1	Manufacturing company	Explore manufacturing methods and related costs	Semi-structured
1	Consultant SWECO	Discuss cost of different materials and other related expenses	Semi-structured

## **2.2.4 Observations / Site Visits**

Observation relies on the passive witnessing of events, emphasizing the importance of not influencing or interfering with what you see. Conducting observations in real contexts, in the user's environment, is useful to get past what people say, own assumptions and to really understand what they do and feel. Observations involves immersing oneself in the specified context, actively listening, observing, and systematically documenting the experience (Nilsson Wiberg et al., 2015)

Throughout the study, a total of 21 site visits were conducted at dams and hydropower plants located in Halland and Västra Götaland. These visits served several purposes, including observing site conditions such as accessibility, function, dimensions, and overall condition. Additionally, they helped identify latent issues and requirements that could not be discovered through interviews.

Additionally, a study visit was conducted at Vattenfall's test facility to acquire knowledge and understanding of the testing procedures for fish passages, dams, and hydropower structures. Furthermore, a field study was undertaken north of Gävle, Sweden to observe the migration patterns of roach and perch. This was aimed at gaining a deeper understanding of behaviours and requirements of these fish species.

## **2.2.5 Granta EduPack Software**

Granta EduPack is a software designed to facilitate the selection of materials by providing a comprehensive database of material properties and manufacturing methods. It enables users to compare and analyse, for example, the mechanical properties of materials as well as their environmental impact (Ansys, 2024). Granta EduPack has been employed primarily for initial material screening, aiming to identify suitable material groups by comparing parameters such as density, tensile strength, yield strength and price.

# **2.3 Define**

After a broad exploration, the Define phase follows, which is about narrowing the focus and defining identified problems. It revolves around interpreting the findings and understanding the alignment between user needs and the problem at hand (Design Council, 2024).

## **2.3.1 Club Design**

In this project a newly researched and developed tool, named Club Design, has been used to further base the project on methodology that helps to create real value. Club Design, developed at Chalmers University of Technology, aims to effectively manage the diverse and often numerous expectations imposed on a product by various stakeholders. The tool originates from the Value Driven Design methodology (VDD), which focuses on connecting stakeholders' expectations with technical requirements (Isaksson et al., 2013). Initially, the tool establishes a Value Creation Strategy (VCS), which outlines the project's specific context and includes all stakeholders along with their expectations and needs. This process ensures a comprehensive description wherein business aspects, sustainability concerns, and technical parameters are incorporated. Each need is

prioritized according to its significance within the specified VCS. To cover a range of scenarios, multiple VCSs can be generated (Isaksson et al., 2013).

This tool has therefore been used to structure stakeholders and their expressed or latent expectations identified in the Discover phase. These expectations were then transformed into needs, with associated value drivers, which were later used in the ideation phase. Three VCSs were thereafter developed based on different potential market outcomes. This resulted in different ranking of needs, which could be used for evaluation of concepts in a Kesselring Matrix, see section 2.5.2, when ensuring that the final design aligns with the identified expectations and needs.

### **2.3.2 The Pairwise Comparison Matrix**

The pairwise comparison matrix is a valuable tool for systematically comparing criteria or options on a one-to-one basis. Each criterion is compared and judged with every other criterion, receiving a score of "1" when deemed more important than the other one. The final score for each criterion is the sum of each criterion's points. These scores can then inform decision-making regarding which criteria are most important to prioritize further (Masur, Filippo & Salustri, 2007).

In this study, all identified expectations were listed and their importance was ranked in a Pairwise Comparison Matrix. The assessment process relied on an overall judgment from the exploratory phase to determine which criteria were most critical, when comparing one to one. The results were then analysed, visualised in a graph, see section 4.2. The graph was used as a communication tool with stakeholders to get their views on which criteria they think should be prioritised. The design firm (Sweco), financial provider (The Hydroelectric Environmental Fund), and two hydro powerplant owners, members of SVAF (Association of owners of small-scale hydropower plants in Sweden), were asked if they agreed to the overall ranking that was visualised. Input from these discussions provided a basis for the final version of the ranking and was important to ensure alignment with their prioritized criteria, guiding the continued focus of the study.

### **2.3.3 Requirement List**

In the final stages of the Define phase, the findings from the study were compiled into a requirement list, outlining the requests and requirements for the final design. In this study, this list could serve as both a checklist and a guideline for development. Additionally, the requirement list can be valuable on its own, providing guidance for future projects related to fish passages for small-scale hydropower plants, ensuring successful design implementation. See Appendix D for final list of requirements.

### **2.3.4 Size of Series**

The series size in this study is defined as the number of modules to be produced. To estimate the series size, data on the heights of hydropower plants (dam height and head) were analysed. This data was used to summarize the heights of all hinders to estimate the final maximum height of the design. A trade-off was made to include a sufficient proportion of obstacles without incorporating those with excessive heights, to avoid over-dimensioning for only a few cases. All registered

hinders below this height were assessed as potential cases and a calculation of the average height for this group of hinders was calculated.

To also adapt the series' size to later stated scenarios, 103 applications for reassessment to the Environment Court were analysed. This provided information about how many of these hydropower plants were applying for continued operation, fishway implementation and what kind of fishway these applications referred to. Other parameters, such as soil type, target species and accessibility to the site were also considered according to the definition of each scenario.

The combination of the average hinder height of potential cases, and the number of hinders that fulfilled the scenarios' definition allowed the size of series to be calculated for each scenario.

## **2.4 Develop**

Once the problems and needs were defined, the Develop phase follows. Here the process diverges again and is about developing potential solutions. The following section describes the methods used for ideation, decision making and prototyping and how they were utilized in the study.

### **2.4.1 Ideation Techniques**

Creative processes are needed to find new innovative solutions and this process is rarely straight and linear. Brainstorming is an idea generation method developed by Alex F. Osborn in 1953 that aims to generate a large number of ideas where quantity is favoured over quality, the more ideas the better (Nilsson Wiberg et al., 2015).

Brain writing and brain drawing are two variants of brainstorming that are based on the participants writing or sketching down ideas during a limited time that are then passed on to the next participant who builds on the idea (Nilsson Wiberg et al., 2015). Throughout the project, ideation has been conducted both through traditional analogue methods and with the aid of digital tools like Miro, a digital collaboration platform (Miro, n.d.). This ideation process has been ongoing, starting with a broad exploration of technical principles, such as potential methods for moving fish upstream. Subsequently, the focus of idea generation shifted towards addressing identified needs and to find solutions to fulfil sub-functions.

This ideation related to the needs stated in Club Design, resulted in value drivers linked to each stated need. These value drivers were also used in the refinement of the final concepts to further deliver value to the customer.

### **2.4.2 Morphological Chart**

Morphological chart is a method that can be used to explore the solution space and by combining different partial solutions, new combinations can be developed (Nilsson Wiberg et al., 2015).

Sub-functions were ideated on, to create a matrix with a broad range of solutions. In this study, a morphological chart was created from sub-functions and solution proposals addressing transportation, assembly, maintenance, and strength criteria. Material selection and associated

manufacturing techniques were treated separately. The various sub-solutions were later combined by systematically selecting sub-solutions from the morphological chart to create three general module ideas.

After identifying these three general principles for the construction of modules, solutions for different sub-functions were combined with these general principles and with suitable materials in the morphological matrix. These were analysed, and six concepts with the greatest potential were selected for further development and evaluation.

### **2.4.3 Sustainable Product Development Workshop Method**

The Sustainable product development workshop method is developed to be used in the early phases of product development, as it is in the early phases that most of a product's life cycle sustainability impact can be influenced. This method aims to outline the sustainability challenges and opportunities of a product or system at a comprehensive level (Schulte & Hallstedt, 2018).

The method is intended to be conducted in multidisciplinary teams, serving as a framework to address various aspects of sustainability. Initially, it entails creating a vision of what a future sustainable product could entail. Subsequently, the current situation is assessed, followed by a process of reasoning and generating of solutions that bridge the current state with the envisioned future. This approach facilitates the identification of desired goals and pathways toward achieving them (Schulte & Hallstedt, 2018).

The method was implemented during an early stage of this project through a workshop divided into three phases. The outcomes from this workshop have been used as a foundation for generating ideas, exploring potential sustainable materials, circular thinking and identifying the challenges that must be addressed to achieve a holistically sustainable fishway.

### **2.4.4 Prototyping & CAD**

The term prototype can be used to describe a model built to ideate or test a concept (Nilsson Wiberg et al., 2015). Prototyping has been used continuously in the study through simple functional prototypes in cardboard material. The aim of prototyping in this study was to develop a deeper understanding of the product. Also, prototyping was part of the ideation process, as different ideas could be tested and evaluated rapidly.

CAD (Computer Aided Modelling) is the design of structures in 3D using computer software (Nilsson Wiberg et al., 2015). The CAD program CATIA V5 has been used for testing and visualisation of final concepts. As for the physical prototypes, the CAD-prototyping process was used to understand and develop different ideas at a faster speed.

A full-scale and a half-scale prototype has been built out of wood and was built mainly for testing and evaluating the movement of water. This prototype was built by people outside of the project, and more iterations are planned with the intention of testing on a larger scale in a real-life setting.

## 2.5 Deliver

The Deliver phase is the last phase and includes final testing, approval, launch and evaluation (Design Council, 2024). For this study, the phase includes the elimination of solutions, ongoing testing and evaluation with stakeholders and refinement of the final concepts.

### 2.5.1 Elimination Matrix

An elimination matrix is a method where a few crucial questions are posed, and if the idea does not fulfil what is requested, it is eliminated (Johannesson, Persson & Pettersson, 2004).

Ideated solutions were eliminated if not fulfilling basic criteria. In this study the elimination matrix questions were based on basic criteria regarding for example space efficiency and technical complexity. The method was used to systematically filter and compare various ideas to arrive at the most suitable options.

### 2.5.2 Scenarios & Kesselring Matrix

A Kesselring Matrix is a method utilised to identify the most effective solution for a given problem. This involves assigning a numerical rating to each option based on the criteria it must meet, resulting in a total score for each option. The option with the highest total score is deemed to be the most effective solution for solving the problem (Johannesson, Persson & Pettersson, 2004).

As described earlier in this chapter, see section 2.3.1 Club Design, the evaluation of the concepts' value is based on Value Creation Strategies (VCS). Therefore, three VCSs were developed, based on potential future scenarios. Different future scenarios imply different priorities, i.e. different requirements for a fishway. Based on these different priorities, a ranking could be developed for each scenario. This ranking was used to weight the developed concepts in a Kesselring matrix.

The output of the method was a summarised ranking of each concept, for each scenario. After the results was analysed and discussed, each scenario was assigned to the concepts with the highest ranking.

The concepts from the scenario with the highest potential were chosen for further development. The decision on which scenario was most likely to occur was discussed and determined in collaboration with the design firm Sweco. The ranking was decided based on the knowledge gained from the literature review, interviews, and the judgment of the project implementers.

### 2.5.3 Evaluation of Final Concepts

To evaluate the potential and drawbacks of the developed concepts, evaluation has been done through interviews with representatives from five out of the nine largest hydropower companies in Sweden, two biologists working in hydropower, a consultant with experience in design and implementation of fish passages. This provided further understanding of the strengths and weaknesses of each concept. The analyses of these experts also provided the opportunity to formulate informed recommendations for the future development of the product design.

Also, the final concepts were evaluated through a questionnaire answered by 20 persons during a presentation of the project with members of the Swedish Hydropower Association where they were asked to rank the three final concepts on a scale of 1 (bad) -10 (good) based on material, function, and price. This was done to capture the opinions of the potential users of the fish passages, making their feedback crucial to the outcome.

The LiDS Wheel tool has been used to evaluate environmental sustainability, which is an Eco Design tool used to classify and compare the environmental impacts of two different products. With the tool, various parameters throughout a product's life cycle, can be analysed and organised into eight distinct strategies. This tool is typically employed to compare a new product with an existing design, offering a clear guideline on their differences (Wever & Vogtlander, 2014). In this study, the LiDS Wheel was used to evaluate and compare the developed final concepts against a classic vertical slot fishway.

# 3

## Discover Current State & Needs for Fishways

**Chapter 3.** This chapter offers information on important aspects to consider in the development of fishways for small-scale hydropower plants and dams in Sweden. Firstly, information gathered through a literature review is summarized. Thereafter findings and insights gathered from site visits, interviews are presented followed by exploration of existing patents. Figure 3 illustrates a map of interesting areas to explore during the development of a fish passage.



when wind is not blowing, and the sun is not shining. The Swedish Energy Agency (2016) categorize all hydropower plants into three classes based on their contribution: Class 1 plants contribute significantly, Class 2 to some extent, while Class 3 plants contribute the least to balancing Sweden's energy system.

This third class includes about 1,700 small-scale hydropower plants, and environmental measures that reduce their contribution are not considered critical for the overall regulation of the hydropower system, unlike those in Classes 1 and 2 (Swedish Energy Agency, 2016).

### **3.1.2 Consequences of Hydropower**

Even though the benefits are numerous, the consequences of hydropower plants are not all positive. In the Swedish Agency for Marine and Water Management's report on Living Lakes and Rivers (2022) addresses that hydropower plants and their accompanying dams act as barriers to the migration of fish, aquatic animals and organisms. Animals trying to pass can be injured or die, and if the migration route is completely blocked it will, most likely, have an extensive negative affect on biodiversity.

Not only aquatic ecosystems are affected by running water, but also terrestrial ecosystems with direct or indirect dependence on lakes and rivers (Swedish Agency for Marine and Water Management, 2022).

According to SMHI's register of dams, there are over 10 000 dams in Sweden. Most often, these dams are connected to hydropower plants, to enable water storage, i.e., energy storage. The consequence, however, is that not only hydropower plants, but also dams, usually are permanent migration barriers for fish and other aquatic animals (Degerman et al., 2013)

## **3.2 Fish Migration**

Fish migrate for various reasons, such as seeking food, finding shelter during winter, or spawning. These migrations can range from a few meters to hundreds of kilometres. Different fish species have different migration patterns and needs. For more detailed information on fish migration, the needs of strong and weak swimming species, and the time of migration, see Appendix A.

## **3.3 Fishways**

In Oxford English Dictionary, a fishway is defined as a structure designed to facilitate the passage of fish over a waterfall or dam. However, a more modern definition can be found in a common European standard for the evaluation of fishways “prEN17233, Draft European Standard” where both a safe upstream and downstream migration are included. The following section outlines fishways and important aspects associated with them. This report uses several terms, including fish ladder, fish passage, and fishway. A fish ladder refers to a structure with steps, while fishway and fish passage refer to any structure designed to enable fish to pass a migration barrier.

### 3.3.1 Fishways in Sweden

The initial regulations in Sweden, requiring that fish be granted access to a specific percentage of waterways for migration, were introduced in the 18th century. Between the 1930s and 1980s, the majority of hydropower plants in Sweden were constructed, with licenses granted under the old Water Act, introduced in 1918. The old Water Act primarily concerned human health and energy production was replaced in 1983 by the Water Act, which remained until the introduction of the Environmental Code in 1999 (Thorell, 2014).

There are currently fishways at about 10% of all hydropower plants (Calles et al. 2013). Fish passages have not only been constructed at hydropower plants, but also at other types of dams and facilities, such as mills and dams for lake irrigation or regulation.

### 3.3.2 Nature-like Fishways

Nature-like fishways are characterised by being built from natural materials such as rocks and boulders where the aim is to mimic a natural watercourse as much as possible (Calles et al., 2013). Apart from functioning as a passage, these structures also serve as a spawning and nursery area for fish (Fortum, 2024).

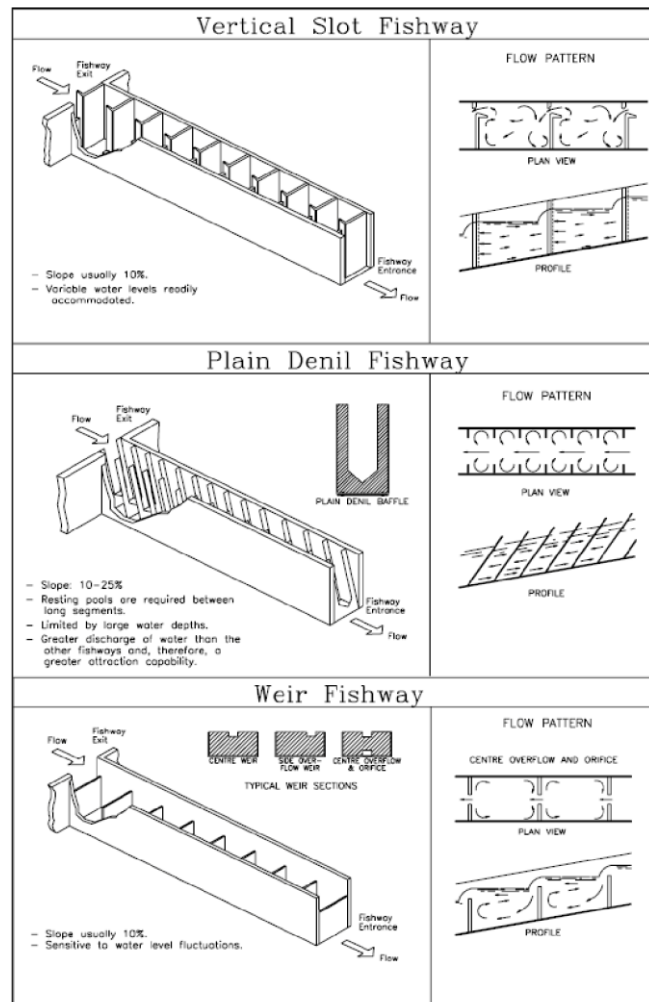


*Figure 4. Nature-like bypass, Strömma kvarn, spring 2024.*

Natural fishways have become increasingly popular due to their many advantages. The low slope and reduced flow favour weak swimming species and, as it operates all year round, it facilitates the dispersal and use of the entire watercourse by all aquatic organisms (Fortum, 2024). Natural passages are well suited where there is a lot of space as they require a large area and sites with a low fall height (Calles et al., 2012).

### 3.3.3 Technical Fishways

A technical fishway is an artificially constructed structure or mechanism designed to enable fish to move safely in an upstream and/or downstream direction past one or more barriers.



**Figure 5.** Three types of technical fishways (Holter, 2017)

There are several different designs of technical fishways, each adapted to the unique conditions at each dam and hydropower plant. The most used fish ladder historically is the pool-and-wire fishway also known as Weir fishway and is a construction of pools connected at different heights providing a staircase-like structure (Clay, 1995). This design is particularly effective for strong swimmers capable of jumping between the pools, see Figure 5 for illustration.

The vertical slot fishway is similar to the pool-and-wire fishway but has an open slot in the cross wall from surface to bottom, See Figure 5. This makes it relatively insensitive to upstream water level variations (Calles et al, 2013).

The vertical slot fishway has been evaluated as suitable for the passage of a diverse range of species, demonstrating the highest passage efficiency among all fishways, including bypasses, according to studies (Nilsson, 2019) (Persson & Leonardsson, 2020). In conclusion, the vertical slot fishway is currently regarded as one of the most efficient technical fishways available (Branco et al., 2023).

Another common technical fishway is the Denil fishway, constructed primarily from wood and sometimes in combination with concrete, specifically designed to decelerate water movement, See Figure 5 for illustration. Within the channel, slats are positioned to gradually diminish water flow, creating a gradient where the velocity is lowest at the bottom and highest at the surface, to facilitate the passage of fish with varying swimming capabilities Denil fishways offer several advantages, including their suitability for narrow spaces (Länsstyrelsen Västra Götaland, 2005).

These represent only a subset of the technical fishways used in Sweden. Traditionally, concrete has been the predominant material used in their construction (Nilsson, 2019) contributing to big carbon dioxide emissions during production (The Swedish Society for Nature Conservation, 2022). Additionally, they require regular maintenance due to the frequent accumulation of dirt and branches in the slats or pools (Calles et al., 2013). Studies show that many of the visited fishways in south of Sweden have insufficient water flows or are completely empty of water, which is a prerequisite for the fish to pass (Nilson, 2019).

### **3.3.4 Passage Efficiency**

Passage efficiency refers to the percentage of fish that successfully navigate through a fishway. Ongoing research aims to develop optimal methods for measuring this efficiency, a task that has proven challenging. One promising approach involves identifying fish intending to use the fishway but ultimately failing to do so, as this can offer insights into passage efficiency. Connectivity is a concept that describes this, implying that individuals can move between habitats. Measuring passage efficiency is typically achieved using cameras equipped with fish counters and occasionally by fitting fish with transmitters (Swedish Agency for Marine and Water Management, 2020).

To achieve passage efficiency, it is crucial to ensure adequate attraction flow and appropriate water velocity for the fish. Attraction flow refers to the flow necessary to attract and guide fish toward the fishway entrance for successful passage. The ability of fish to locate and navigate toward the fish passage is essential. Even a well-designed fishway is ineffective without sufficient attraction flow (Calles et al., 2013). Inside the passage, water velocity is key. Proper water velocity is vital in a fishway to facilitate passage.

Weak-swimming fish species need resting spots with low water velocity, while strong-swimming species require higher water velocity (Degerman, 2008), which influences how a fish passage should be designed to accommodate the target species (Swedish Agency for Marine and Water Management, 2013). For more detailed information on the importance of water velocity and attraction flow for passage efficiency, see Appendix A.

### **3.3.5 Best Available Technology**

The Environmental Code states that the industry must use the best available technology when implementing environmental measures, which means that the fishways that are built must be the best available technology. At present, natural-like fishways are recommended to have the best function and for technical fishways, vertical slot fishways are considered to be the best technical fishway. It should be added, however, that the “best available technology” should be determined on

a case-by-case basis, as the site conditions determine which fishway will be the best available technology (Persson & Leonardsson, 2020).

The Swedish Environmental Protection Agency (n.d.) describes this term, explaining that it encompasses not only the technology employed but also the construction, maintenance, management, and eventual decommissioning and dismantling. For technology to qualify as the best available, it must be commercially accessible and utilised in the industry, rather than merely experimental.

### **3.3.6 Establishment Process**

The Swedish Agency for Marine and Water Management provides a process of establishing a new fish passage solution. However, since each case varies depending on the site's physical conditions and the characteristics of the target species, there is no identical process. Parameters such as local conditions, target species, upstream/downstream alternatives, and costs are highlighted as significant considerations (Persson & Leonardsson, 2021).

Regarding local conditions, dam safety is mentioned as an important aspect when choosing the location of the fish passage. No structure may be placed in front of the spillway as this may risk high flows and thus be considered a weakening of the dam structure (Lundberg et al., 2019). Surrounding infrastructure can also limit the possibilities when constructing a fish passage. If there are cultural-historical values in the area or other structural engineering aspects, these are also important to consider when placing and designing a fishway (Persson & Leonardsson, 2020).

Another aspect that needs to be considered when planning the establishment of a fishway is which target species the passage will be used for. Swimming capacity, time of migration and requirements for water depth and space and flow are examples of parameters that should be considered. Persson & Leonardsson (2020) emphasises the importance of attracting fish into the passage, and that the fish must be given appropriate flow conditions to successfully navigate through it.

The next step involves considering both upstream and downstream passage, as both directions often are critical. Upstream, the emphasis lies on drawing fish towards the passage entrance, while downstream migration focuses on leading fish to the entrance. Additionally, the passage may need to be adjusted for other factors such as the risk of disease transmission or the spread of alien species (Persson & Leonardsson, 2020).

These are some important steps in establishing a fish passage. The full guide can be found on the Swedish Agency for Marine and Water Management website.

### **3.3.7 Cost of Implementing Fishways**

Calculating and estimating costs for building and maintaining fishways has proved difficult. Many construction projects in water overrun schedule and become more expensive than planned, which often can be explained by unpredictable events, such as unforeseen geology, bad weather, project complexity, scope changes, etc. (Flyvbjerg & Budzier, 2019). The study does not specifically focus on small-scale hydropower plants or fishway implementations, but it can provide insights into the factors that increase costs. According to Flyvbjerg and Budzier (2019) a root cause for the

underestimation of cost is also based on political biases and optimism. For fishways specifically, the costs of different solutions can vary widely (Person et al., 2020).

Carlströms (2017) study reveals significant variations in costs for similar fishways, highlighting that the cost of a slot fishway per fall meter, ranges from 250,000 - 5,000,000 SEK. Person & Leonardsson (2020) contributes to this understanding by identifying several factors that can drive costs when building a fishway. Among the mentioned aspects are geological conditions, infrastructure, drainage expenses during the time of construction, materials, production losses, and operation and maintenance costs. Katopodis (1992) believes that costs can be reduced by making full use of the site-specific conditions where fish passages are to be built and also by building the fish passage at the same time as the dam or hydropower plant.

### **3.3.8 Adjustments & Maintenance**

Adjustments and maintenance of constructed fishways are often required over time. According to provisions in The Environmental Code, chapter 22, section 29 (1998:808), every judgment must include a provision regarding the timing of a new relicensing. The legislative history clarify that a review will be required, likely within 40 to 50 years (Government Bill 2017/18:243 s. 216-217).

During an inventory of 175 fish passes in southern Sweden, it was concluded that 77 % of the fishways visited were judged to be well maintained, i.e. no or only minor functional impairments due to maintenance. The 31 fishways with notable issues or that are completely out of function, and 18 of them were completely or partially collapsed. The cause of poor function is considered to be due to age and/or lack of maintenance (Nilsson, 2019).

Nilsson (2019) argues that the lack of regular maintenance stems from uncertainty regarding maintenance responsibilities. An additional reason is that some of the fishways are structures that are difficult to clean but also difficult to access. Branches and twigs that get stuck in slats and steps is common. Continuous checks and maintenance are therefore crucial to maintain a well-functioning fishway (Nilsson, 2019) (Person et al., 2020).

### **3.3.9 Monitoring & Follow-up**

Persson et al. (2020) emphasise the importance of consistently monitoring fishways to guarantee their optimal functionality. Ensuring the construction is intact and free from debris is crucial to facilitate unimpeded water flow through the passage, thereby maintaining the required water depth and current velocity necessary for various target species. Persson et al. (2020) recommend providing straightforward management advice and supervision guidelines in a manual to assist owners in preserving the effectiveness of the fish passage. Additionally, emphasizes the importance of sharing knowledge among those responsible for fishway maintenance to foster ongoing development in this field.

### 3.4 Site Visits

Observations from visits to seven regulating dams and fifteen hydropower plants reveal a number of common issues. Firstly, the roads leading to these sites are often narrow and in poor condition, resulting in limited access, particularly to smaller connecting dams.

During the site visits conducted from February to March 2024, significant accumulations of leaves, branches, and other debris were observed at the grids and fishways of the hydropower plants. The high-water flows observed during the visits likely contributed to the substantial build-up of debris.



*Figure 6. Branches and leaves at the intake gate with automatic cleaner.*



*Figure 7. Rake, commonly used tool for cleaning grids.*

The realization of the immense force of the rushing water made it obvious that a fishway must be engineered to withstand these high forces. Furthermore, ice formation restricts water flow and imposes significant loads on the structure.

Another observation was the automatic cleaners that are frequently employed on larger sites to regularly clean the grids, while manual cleaning using a standard rake of longer length is also prevalent. As no specific equipment was observed for the cleaning and maintenance of fishways during the site visit, it was concluded that these are cleaned and maintained manually.

The presence of algae and moss growth on the passage walkways made of wood and concrete was commonly observed, posing a risk of slipping. The fishways observed were also difficult to access,

limiting the opportunity to inspect or assess their condition, indicating challenges in evaluating their status and need of maintenance.

At several of the visited sites, there were often minimal undeveloped spaces around them. Instead, they were closely surrounded by roads and buildings. Hultafors exemplifies this situation, where the hydroelectric power plant and its supplying dams are situated amidst a rock wall, railway tracks, and a road. Consequently, sites like these have limited space for renovation and thus necessitate fish passages that occupy minimal space.



*Figure 8. Hultafors regulating dam.*

## **3.5 Interviews**

During interviews with experienced staff (n=3) of maintaining hydropower plants and fishways, it became apparent that fishways should ideally require minimal maintenance and supervision. This is partly due to their often remote locations and the challenges due to difficulties accessing them during high water flows. Concrete fishways typically necessitate extensive cleaning every 8-10 years to remove moss growth, preventing it from infiltrating the concrete and causing frost damage during winter.

Addressing the management of leaves and branches is a crucial aspect that requires a well-defined strategy and designated locations. The interviewee highlighted the lack of strategy for managing this waste.



**"It's important to not only think about the well-being of the fish, but those who have to manage everything as well."**

*- Interviewee, working as a hydropower technician (translated quote)*

**Figure 9.** Guided tour of a hydropower plant, spring 2024.

In terms of fishway design, the interviewee with experience in building a fishway emphasized the importance of effective sealing during assembly. They recounted an experience where a poorly sealed fishway resulted in leaks, necessitating a complete rebuild. This incident led to production losses, highlighting the economic significance of ensuring proper sealing to hinder leakage.

Interviews with people in the industry revealed that numerous owners of small hydropower plants exhibit significant interest in effective and cost-efficient fish passage solutions that meet environmental standards. Owners are concerned that decisions made in Environment Courts could lead to the necessity of demolishing their hydropower plants. These decisions may render their businesses unprofitable, ultimately forcing them into decommissioning.

Moreover, repeated in interviews is also the importance of that the designed fish passage undergoes rigorous testing to ensure functionality. This testing is essential for approval of the design as the best available technology, facilitating its implementation at hydropower plants and dams throughout Sweden.

## 3.6 Existing Patents

A search of existing patents has been done to explore similar existing solutions related to a helical modular fish ladder. The most frequently used IPC category in the patent research was IPC E02B8/08, which classifies patents for "Fish passes or other means providing for the migration of fish; Passages for rafts or boats."

To find European patents, the patent search site Espacenet (European Patent Office) was used. A search within IPC E02B8/08, including the terms "spiral," "helix," or "module" in the title, yielded 30 results.

In the Swedish patent register PRV, IPC E02B8/08 also resulted in 30 findings, with eight of them currently in force. However, searches using the terms "modul OCH (fiskpassage ELLER fiskväg ELLER fisktrappa ELLER laxtrappa)" and "IPC E02B8/08 spiral OR helix AND modul" returned 0 results in the PRV register.

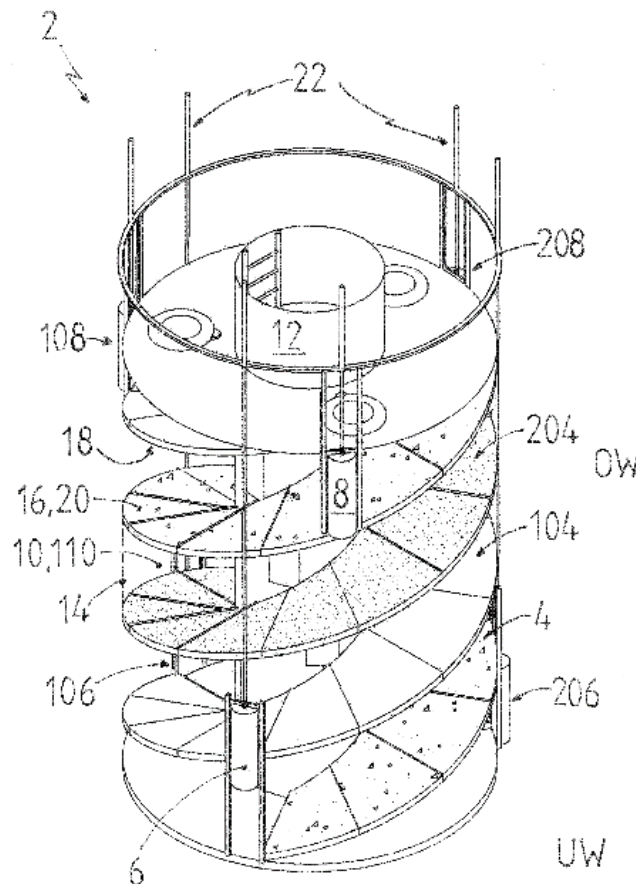
In summary, the concept of a spiral-formed fish ladder appears to have significant potential to address the problem this master thesis focuses on. Many patents describe helix solutions as cost- and space-efficient, providing easy and fast installation. However, the only similar patent found in the PRV database, shown in Figure 10, is not of a modular design. Therefore, further development of this design is considered motivated. For a complete summary of the most interesting patents, see Appendix B.

### EP 3231942A1 Fish Ladder

**Applicants:** Vandezande Aquatem GmbH

**Inventors:** Zeiler Georg; Flach Bernd

A devise for upstream and downstream passage through a three dimensional spiral. In the description it is mentioned as space-efficient, cost-effective, and technically simple. This patent can also be found on the PRV database and is therefore specifically important to consider. (Zeiler G., Flach B., 2017)



**Figure 10.** Spiral fish ladder for upstream and downstream passage (Zeiler & Flach B, 2017)

## 3.7 Summary Discover

Hydropower plants and their associated dams pose barriers to migrating fish. Different fish species have different migratory patterns and place different requirements on a fishway. Historically, most fishways are made of concrete and to some extent wood and stone. Many of the existing fishways in Sweden are considered to maintain incomplete function partly because they are neglected in maintenance and partly because they are old. All fishway require a unique design adapted to the specific site.

The natural bypass is the type of fishway considered by many to be the best functioning fish passage and therefore the “best available technology”, as it allows many fish species to pass and can also provide habitat for other animal species. The vertical slot fishway is considered to be the best performing technical fish ladder, as the slot allows weak swimmers to pass as they can rest on the bottom where the water velocity is lower. However, both of these fishways require a gentle slope and a large accessible area and are therefore not suitable for sites with limited space.

When establishing a fishway, numerous considerations must be taken into account. The Swedish Agency for Marine and Water Management offers guidance on the necessary steps for establishing a fishway. Construction projects often incur significant costs, emphasizing the importance of ongoing monitoring to ensure the functionality of fishways through maintenance, monitoring and counting fish passing.

Key findings from site visits revealed challenges such as limited accessibility, large accumulations of debris, and space constraints. Interviews emphasised the necessity for new fish passage solutions in areas with limited available space and highlighted the importance of easy maintenance. Furthermore, extensive testing was emphasized as essential for the successful implementation of a fishway.

A patent investigation revealed several fish passage solutions in spiral shape and based on modular principles, though they are not deemed to surpass the protection afforded by the developed design.

# 4

## Define Expectations, Needs & Requirements

**Chapter 4.** This chapter defines and summarizes the identified problems and needs from the Discover phase. After analysing the collected material, all stakeholders were listed with their diverse expectations, needs, and requirements. Following this, all expectations were ranked using a Pairwise Matrix. This process aimed to pinpoint the central aspects of the study in order to generate the highest possible value. This was followed by including associated key needs. Subsequently, a comprehensive list of requirements that the designed fish passage must meet is provided. Finally, the chapter presents calculations determining the optimal height of design and the projected production capacity of modules, providing insight into the expected size of series.

## 4.1 Stakeholder Expectations and Needs

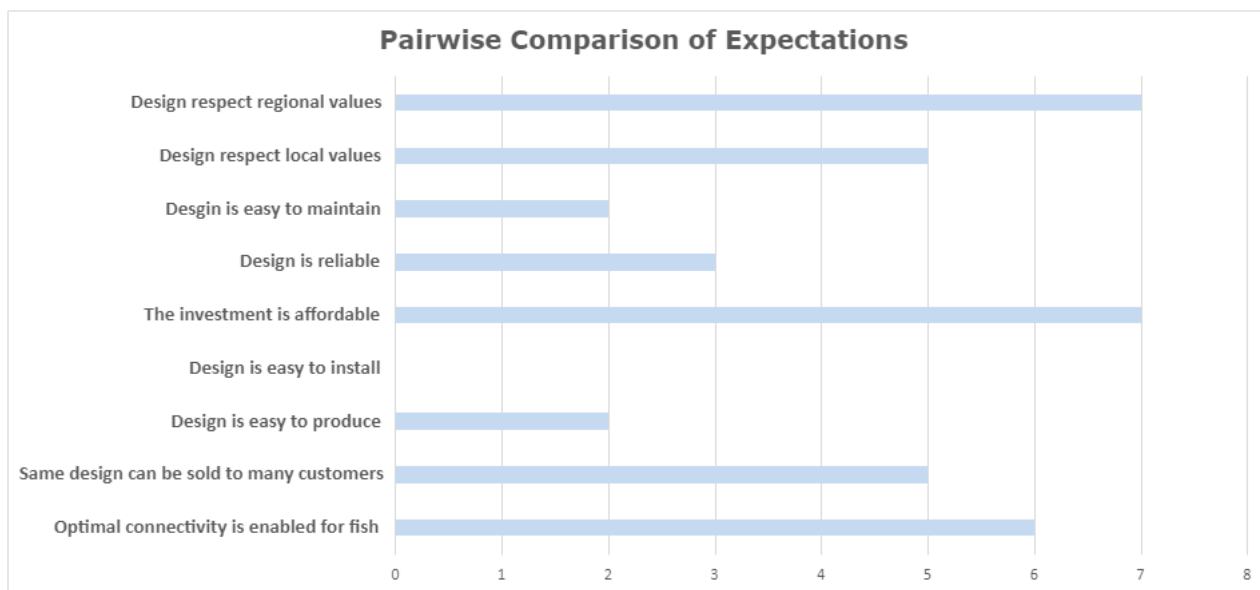
The following table is a summary of the identified stakeholders, their expectations, and needs.

**Table 2.** *Compilation of Stakeholders and their related expectations and needs.*

Stakeholder	Stakeholder Expectations	Stakeholder Needs
Biologist	Optimal connectivity is enabled for fish	Enable targeted species to pass
		Avoid harm to fish
		Possible to count fish
Design Firm	Same design can be sold to many customers	Adaptable to different hinder heights
		Possible to install in varying site conditions
Manufacturing Firm	Design is easy to produce	Reliable resources for production
		Scalable production method
Constructing Firm	Design is easy to install	Efficient installation process
		Ergonomic assembly and installation
Financial provider (Powerplant Owner and The Fund)	The investment is affordable	Low long-term costs
		Low short-term costs
		Predictable final costs
Powerplant Owner	Design is reliable	Well dimensioned design
		Design's functional status is communicated
Maintainer	Design is easy to maintain	Easy and efficient maintenance
		Ergonomic accessibility during maintenance
		Provide status and feedback of maintenance
Local society	Design respect local values	Not destroying historical sites and important infrastructure
Regulative authorities	Design respect regional values	Low emissions and environmental impact
		Avoid production-loss

## 4.2 The Pairwise Comparison Matrix

In the following section, the results of the ranking conducted using the Pairwise Comparison Matrix are presented. The final ranking is illustrated in a bar chart; see Figure 11. The expectations with the highest ranking are *Design respecting regional values*, *Optimal connectivity is enabled for fish* followed by *The investment is affordable*. See Appendix C for the complete Pairwise Comparison Matrix.



**Figure 11.** Summarised ranking of prioritised expectations.

*Design respect regional values* encompass environmental sustainability and the avoidance of production losses and due to Sweden's high demand for all available electricity generation, earning it a high ranking as a fundamental aspect of the new environmental conditions.

*Optimal connectivity is enabled for fish*, is fundamental, as an ineffective design renders the project unnecessary. As the project was based on an existing design with calculated dimensions based on standards presented in DWA (2014), further calculations of these dimensions have not been included in the scope of this study. However, expertise on fluid dynamics and fish biology has been sourced from external experts, to understand the design, to be able to give recommendations for continued development.

*The investment is affordable* was deemed the highest priority for hydropower plant owners, design firms, and financiers. This is critical for small-scale hydropower owners to afford, and it is also a priority for The Hydroelectric Environmental Fund, as they co-finance and aim for The Fund's resources to cover as many environmental measures as possible.

In relation to other basic expectations, such as those presented above, maintenance ranks slightly lower. However, the lack of maintenance may lead to the degradation or elimination of fish connectivity and a short lifetime of the design. A short lifetime can be linked to other parameters,

such as price and environmental sustainability. With this reasoning, maintenance itself is important, although the possibility of easy maintenance for maintenance staff is not ranked as highly.

In conclusion, stakeholders prioritize regional values (including low production loss and environmental sustainability), connectivity for fish and cost-efficiency. As different expectations overlap each other to some extent, this prioritizing is only considered as an introductory guide, to ensure a well-directed focus.

## 4.3 Project Scope and Important Criteria

After conducting research and holding ranking discussions with stakeholders, the study can be further refined to maximize value creation. The ongoing priorities for the study are outlined as follows:

- **Affordable investment** - Deemed important by all parties involved.
- **Maintenance** - Simplified and infrequent maintenance is crucial for preserving functionality.
- **Environmental sustainability** - In addition to sustainability efforts aimed at promoting fish migration, environmental sustainability is considered a fundamental requirement for the design of new products and therefore crucial to consider.

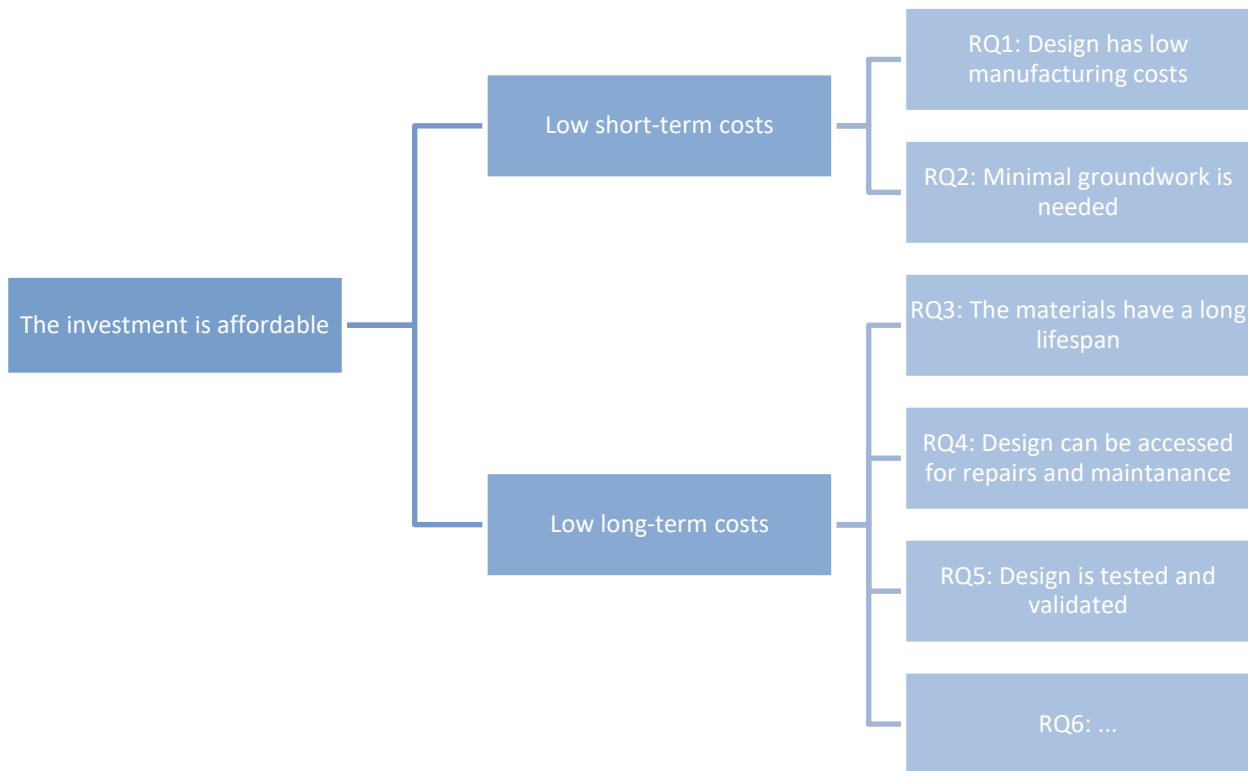
Table 3 consists of key aspects essential for achieving an affordable investment, ensuring good maintenance, and establishing an environmentally sustainable fishway. These aspects were developed during the Discover phase and have provided a guiding framework for the subsequent stages of the project.

**Table 3.** Summary of key aspects to be considered and influenced by design in further development.

<p><b>AFFORDABLE INVESTMENT</b></p>	<p><b>Low Short-term Costs:</b></p> <ul style="list-style-type: none"> <li>✓ Purchase price</li> <li>✓ Transportation cost</li> <li>✓ Planning costs</li> <li>✓ Groundwork needs</li> <li>✓ Installation cost</li> </ul>	<p><b>Low Long-term Costs:</b></p> <ul style="list-style-type: none"> <li>✓ Quantity of leakage</li> <li>✓ Frequency of maintenance</li> <li>✓ Repairability</li> <li>✓ Lifespan of design</li> <li>✓ Need of expensive tools</li> <li>✓ Maintenance cost per event</li> </ul>	<p><b>Predictability:</b></p> <ul style="list-style-type: none"> <li>✓ Standardised production process</li> <li>✓ Tried and tested materials</li> <li>✓ Standardised installation process</li> <li>✓ Predictable maintenance need</li> </ul>
<p><b>MAINTANANCE</b></p>	<p><b>Easy and Efficient Maintenance:</b></p> <ul style="list-style-type: none"> <li>✓ Need of assisting tools/machines</li> <li>✓ Frequency of maintenance</li> <li>✓ Maintenance time</li> </ul>	<p><b>Ergonomic Accessibility:</b></p> <ul style="list-style-type: none"> <li>✓ Degree of physically heavy work</li> <li>✓ Level of safety</li> </ul>	<p><b>Provide Status &amp; Feedback:</b></p> <ul style="list-style-type: none"> <li>✓ Access to feedback</li> <li>✓ Clarity of feedback</li> </ul>
<p><b>ENVIRONMENTAL SUSTAINABILITY</b></p>	<p><b>Low Emissions and Environmental Impact:</b></p> <ul style="list-style-type: none"> <li>✓ Environmental impact of raw material</li> <li>✓ Environmental impact of production</li> <li>✓ Environmental impact of transportation</li> <li>✓ Environmental impact of installation</li> <li>✓ Environmental impact of maintenance</li> </ul>		<p><b>Lifespan &amp; End of life:</b></p> <ul style="list-style-type: none"> <li>✓ Repairability</li> <li>✓ Recyclability</li> </ul>

## 4.4 List of Requirements

A total of 60 requirements and 49 requests were identified, detailing the 19 needs that emerged from the stakeholder analysis, see section 4.1. Figure 12 shows the stakeholders' expectation for an affordable investment, with corresponding need for low long- and short-term costs and related requirements. This example is provided to demonstrate the structure, while the complete list of requirements and requests can be found in Appendix D. For a design, all requirements need to be satisfied while requests are treated as “wishes”, i.e. can be negotiated.



*Figure 12. An example of how stakeholder expectations are linked to needs, which in turn are linked to requirements.*

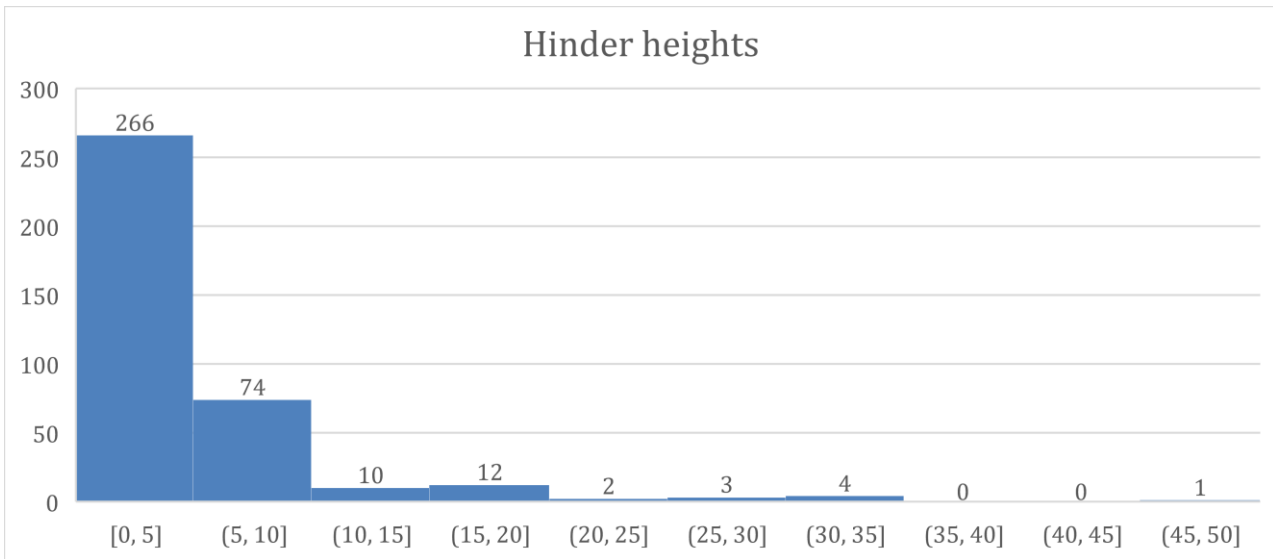
## 4.5 Optimum for Design’s Maximum Height

The maximum height of the spiral shaped fish ladder is an important parameter for mechanical calculations and design. This specific study aims for a balance between the height of hinders for which the solution could be used, and the design’s dimension due to mechanical strength. If the design is made for all possible heights, it could be sold to many customers. However, if it should be dimensioned for all heights, the risk is that the design gets over dimensioned and less cost-efficient.

In the subsequent section, a calculation determining the optimal maximum height for the design is provided. The results are based on data from hydropower plants registered in “Bubblan”, The Fund’s support system, which manages all the facilities admitted to the Fund (Vattenkraftens Miljöfond, n.d.-b). The data was extracted from Bubblan March 25, 2024. Due to the lack of validated data for all hydropower plants and dams in Sweden, these calculations serve only as an approximation.

Data from 488 dams and hydropower stations were collected, with 372 locations reporting values for head and/or dam height of the neighbouring dams. Head is the vertical distance between the upstream surface level and the downstream surface level of where the water leaves the hydropower system. In cases where only one value (head *or* dam height) was reported, that value was used, and in cases where both values were reported (head *and* dam height), the lowest value was used. This was to estimate the minimum vertical distance that fish must traverse to bypass the hinder, called

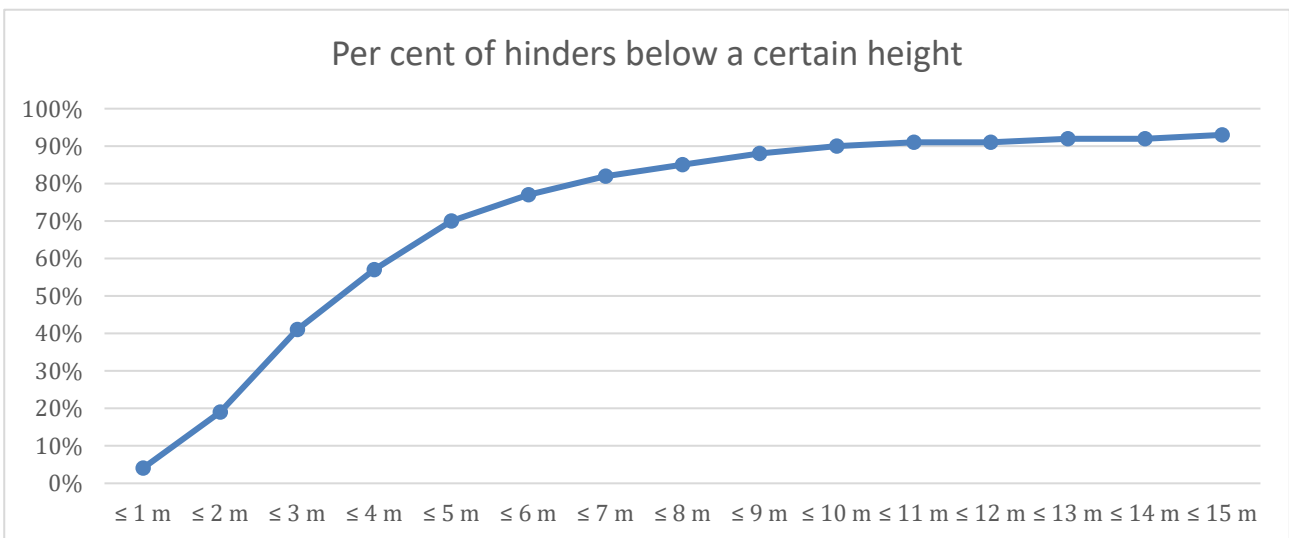
“hinder height” in this study. Using this data, a summary of number of hinders and their height could be visualised, see Figure 13.



**Figure 13.** 340 out of 372 hinders are  $\leq 10$  m.

As shown in Figure 13, most hinder heights are lower than 10 meters. This value is consistent with Kling (2020) figures indicating that 71% of the hydropower stations and regulating dams are less than 5 meters in height with an average height of 4.6 meters.

Analysing this data set further, the values can be divided in percent of barriers that are under a specific height, which also can be visualised in a graph, see Figure 14.



**Figure 14.** Per cent of hinders below a certain height

The curve gets flatter after around 6 meters. It could therefore be argued that the design should be made to work for hinders under this height, to cover as many cases as possible without the need for over dimensioned design. To facilitate calculations, the limitations will be described in full turns

(360 degrees). 7 full turns result in 6.3 meters height of the fish ladder. A maximum height of 6.3 meters in height covers 78% of all hinders in the dataset.

## 4.6 Calculation of Potential Series Size

Potential series size plays a crucial role in determining the choice of materials and the suitable manufacturing method. To estimate the series size of modules, documentation has been compiled concerning factors such as the number of potential cases and the average head height at potential cases.

Potential cases are places where the spiral formed fishway could be used, i.e., mainly places where a technical fishway is considered to be the best option. Data for analysing these potential cases is sourced from applications for relicensing, supported by The Fund and submitted to the Environment Court in 2022. In total, there are 103 submissions, that can be derived as follows:

*Table 4. Distribution of applications to the Environment Court*

Applications	Continued operation	Fishway	Technical fishway	Vertical slot fishway
103	78	39	13	11

From this, a statistical estimation of potential cases can be made. In Table 5, the number of cases are divided into hydropower plant cases and cases including all dams in Sweden:

*Table 5. Calculation of potential cases, i.e., technical fishways that will be needed in Sweden.*

Category	Hydropower plants	All dams included	Explanation
<b>Number of hinders</b>	2100	10000	(Swedish Energy Agency, 2023, 2014),
<b>Have no fishway</b>	1890	9790	10% of 2100 hydropower plants already have fishway (Calles et al., 2013)
<b>Less than 6.3 meters</b>	1474	7636	78% are less than 6.3 meters (according to estimations in section 4.5)
<b>Continued operation</b>	1088	5634	76% submitted applications are asking for continued operation
<b>Fishway</b>	558	2891	Of them, 50% are applying for a fishway
<b>Technical fishway</b>	186	964	1/3 of all fishway applications concern technical fishways

The result is an interval of approximately 186-964 potential cases.

To convert potential cases to series size, an average number of modules needs to be calculated. Focusing on dams with a height below 6.3 meters, as detailed in section 4.5, 295 reported hinders remain. These hinders have an average height of 3.3 meters. The result is therefore as follows:

**Table 6.** Data of the design and the average number of units per hinder.

Step height (m)	0.15
Modules per lap (units)	6
Height of one lap (m)	0.9
Average hinder height (m)	3.3
Average number of modules per hinder (units)	22

**Table 7.** General size of series, i.e., modules to be produced.

<b>General size of series:</b> (i.e., estimated number of cases multiplied with average number of modules)		
<b>Size of series - only counting hydropower plants (units)</b>	4093	<i>modules that are to be produced</i>
<b>Size of series - counting all dams (units)</b>	21203	<i>modules that are to be produced</i>

If all hinders below 6.3 meters that require a technical solution implement a helical fishway, 4000 – 21 000 modules need to be produced. The number is depending on how many dams that are relevant to consider. However, further calculation of series size, including additional limitations with respect to scenarios, can be found in section 6.1.

## 4.7 Summary Define

In this chapter stakeholders have been identified and their expectations and needs have been defined in a stakeholder analysis. Through a Pairwise ranking, cost-efficiency, maintainability and environmental sustainability were confirmed to be the continued focus, as these parameters affected customer value and were in accordance with the scope of the study. However, all expectations were important to concretize to needs, to assure a holistic understanding of value creation in relation to identified stakeholders. As a supporting guideline for the upcoming development phase, and as an overall guide for future design processes of fishways for small-scale hydropower plants, a requirement list was delivered, see Appendix D.

The chapter concludes with defining the optimal maximum height of the design to be 6.3 meters, as an effort to address as many sites as possible, meanwhile not over dimensioning the bearing structure. Considering cases with less than or equal to 6.3 meters in height, an average of 22 modules per fishway could be determined. By combining this with a statistical estimation of potential cases, a final estimate of the potential series size was established. Without additional constraints, the estimated production size was 22,000 modules. Further analysis of the production size will be discussed in section 6.1.

# 5

## Development of Ideas & Concepts

**Chapter 5.** This chapter explores possible designs for modules in a spiral formed fish passage. Design parameters considered include material and shape, based on the defined functions and needs. Initially, the chapter presents information about materials with potential application in this context. Subsequently, it presents results from various ideation methods utilized throughout the study.

These findings lead to three general principles for the construction of modules, accompanied by descriptions of maintenance, installation, and repair processes. These general principles are then combined with materials identified as most promising for each design idea. Consequently, the chapter yields six combinations of shape and material. These six concepts are subsequently advanced to the final Deliver phase, where those offering the highest value to the customer undergo further development.

## 5.1 Identified Potential Materials

This section provides a review of the materials examined in this study for potential use in constructing a modular fish ladder. The materials considered include concrete, metal, polymer composite, plastic, and glass as these have been identified through interviews and rough filtering processes in Granta EduPack. These materials are later in the development phase combined with different general principles for construction of modules.

### 5.1.1 Concrete

Concrete is widely utilised as a building material in the construction of various infrastructure projects, houses, and other structures (SGU, 2023). The main reason why concrete is commonly used can be explained by the fact that it is a material that is durable and has proven suitable for the construction of pool and weir fishways, a commonly used fishway in Sweden (Nilsson, 2019) (Calles et al., 2013). Concrete has a density of 2300-2400 kg/m<sup>3</sup> and is characterised by high compressive strength but low tensile strength. Concrete offers numerous advantages, including high strength, longevity, resilience to harsh climates, and the ability to form intricate shapes (SGU, 2023).

A study commissioned by Energiforsk (2023) presents a construction cost price index of expenses associated with the construction of hydropower from 1993 to 2023. Recent years have seen notable price hikes in concrete and reinforcement, with cement rising by 42% and reinforcing steel by 86% between 2020 and 2023. While future price trends remain uncertain, these numbers give an indication.

Additionally, concrete is being questioned due to its environmental impact, particularly stemming from cement production, a key ingredient in concrete (Sabado Manansala et al., 2022). Currently, cement production contributes to approximately 8 % of the world's total carbon dioxide emissions (Cooke, et al., 2020). Green concrete is concrete where 35-65% of the cement is replaced by residual waste such as fly ash, which means a major reduction in carbon dioxide emissions (Skanska, 2019). The material is already being tested and used today for similar applications and is a possible material for the construction of fishways.

### 5.1.2 Metals & Alloys

Metals are typically categorized into ferrous and non-ferrous types. They are stiff, ductile, malleable, and serve as excellent conductors of heat and electricity. Through alloying and heat treatments, metals can significantly enhance their strength while reducing ductility. Their malleability enables a wide array of manufacturing processes, including casting, pressing, and rolling. Metal has in general a high density and has usually a long lifespan.

However, a notable drawback of metals is their low resistance to corrosion. Stainless steel and aluminium stand out for their high corrosion resistance, making them a potential choice when designing outdoor applications. However, aluminium, being a soft metal, is unsuitable for products requiring resilience against severe climates and impacts. Stainless steel is therefore a more suitable

option for the construction of fishways and is an alloy primarily composed of iron and a small amount of carbon, with a density of  $7850 \text{ kg/m}^3$  (Ashby et al., 2019).

Few fish ladders are constructed of steel today, except when utilized as reinforcement in concrete fish ladders. Given the exposure to water in a fish ladder, a steel variant with high corrosion resistance is essential. There are currently steel variants with an oxidized layer created through chemical processes, offering natural rust protection. One such material available on the market is SSAB weathering steel, which operates on this principle (SSAB, n.d.).

### **5.1.3 Wood**

Wood is a strong, light, and durable material with little environmental impact when extracted (Svenskt Trä & Skogsindustrierna, 2020). Historically, wood has been used as a material in fishways in Sweden. However, its limited resistance to moisture is known to result in a relatively short lifespan. In an inspection of fish ladders carried out in 2016, built around 1993-1995, all the examined fish ladders made of wood were stated to have poor function, which indicates that the service life of a wooden fishways does not exceed about 15 years (Nilsson, 2019).

The structure of wood significantly influences its strength and resistance to moisture and degradation, with core wood being notably stronger and more resistant. Certain wood types, such as alder, ash, birch, beech, maple, spruce, and pine, are classified as having high natural resistance to degradation (Svenskt Trä & Skogsindustrierna, 2020).

Wood that is constantly under water lasts longer than wood that alternates between getting wet and drying. Apart from enhanced resistance to rot, the fluctuation between swelling and shrinking in the wood leads to cracks, which can result in undesired leakage.

Wood utilised can undergo treatment to enhance its resistance to decay and moisture. Various surface treatments, such as pressure impregnation with anti-rotting agents or saturation with ample amounts of oil, are available options for long-term moisture protection. Regular maintenance is necessary for both methods to ensure the preservation of optimal protection (Svenskt Trä & Skogsindustrierna, 2020).

In addition to solid wood, there are many different wood-based board materials, which allow for greater freedom of shape but come with the disadvantage of containing adhesives that may release harmful substances into the environment. Wood can be shaped through cutting and joined mechanically or with adhesives. Solid wood such as pine and spruce have a dry density of around  $400 \text{ kg/m}^3$  (Svenskt Trä & Skogsindustrierna, 2020).

### **5.1.4 Polymer Composites**

Composites are combinations of materials where two or more have different properties but together form a structural material with completely new properties. Composite materials typically consist of a reinforcing material, typically glass fibre or carbon fibre, and a bonding component, usually epoxy resin. The benefit of composite materials lies in their inherent strength and lightweight nature, surpassing those of single-material alternatives. This makes them particularly suitable for the construction industry, where both durability and weight play crucial roles (Chawla, 2019).

Polymer composite is not commonly used as a construction material for fish ladders today, but there are cases where it has been employed. For example, in Piteå, a fishway has been constructed using glass fibre composite in a sandwich structure (Composite Service Europe AB, 2022). There are various types of glass fibre with different chemical compositions, often containing silicon as a common component. Glass fibre composites have a density of 255 kg/m<sup>3</sup> and possess a high strength-to-weight ratio. It is water-resistant and can be processed using several different methods, allowing freedom of shape in design. However, glass fibre composite has drawbacks, such as difficulty in recycling, brittleness, and poor abrasion resistance (Chawla, 2019).

A study conducted by RISE (Research Institute of Sweden) in 2019 indicates that microplastics may be released into the environment from composite materials, particularly those based on polyester. Therefore, careful consideration of composition is crucial, and further investigation is warranted to mitigate the dispersion of microplastics in nature (RISE, 2019).

### **5.1.5 Plastic**

There exists a wide variety of plastics, each possessing different properties. Plastic serves as an umbrella term for a broad category of semi-synthetic or synthetic materials adaptable to numerous applications. Typically, plastics comprise one or more polymers blended with additives (Ashby et al., 2019). When utilized as a construction material for a fishway, plastic must endure harsh outdoor climates without releasing toxins. Plastics suitable for outdoor environments include Acrylonitrile Butadiene Styrene (ABS) and High-Density Polyethylene (HDPE), both known for their durability, lightweight, and recyclability (Ashby et al., 2019).

Injection moulding, suitable for larger series (5000+ parts), entails a significant initial cost for moulding tools. Conversely, 3D printing, with rapidly evolving technology, is suitable for smaller series (<1000 parts). Compression moulding presents an additional alternative for large series requiring high precision, with minimal material waste, but it incurs a high initial cost and is restricted to applicable plastics (Formlabs, n.d.).

However, microplastics result from the degradation of plastics due to wear and tear as well as sunlight exposure. Microplastics are considered harmful to fish health, highlighting one of the downsides of plastics (Wenfeng et al, 2019).

### **5.1.6 Glass**

Glass, a non-crystalline solid typically composed of quartz sand, soda ash, lime, and potassium carbonate, is an ancient construction material with diverse applications. Modern advancements include construction glass with enhanced properties achieved through lamination and hardening, allowing for the construction of large buildings with advantages such as high strength and transparency. Additionally, it is 100% recyclable and corrosion resistant (Ashby et al., 2019).

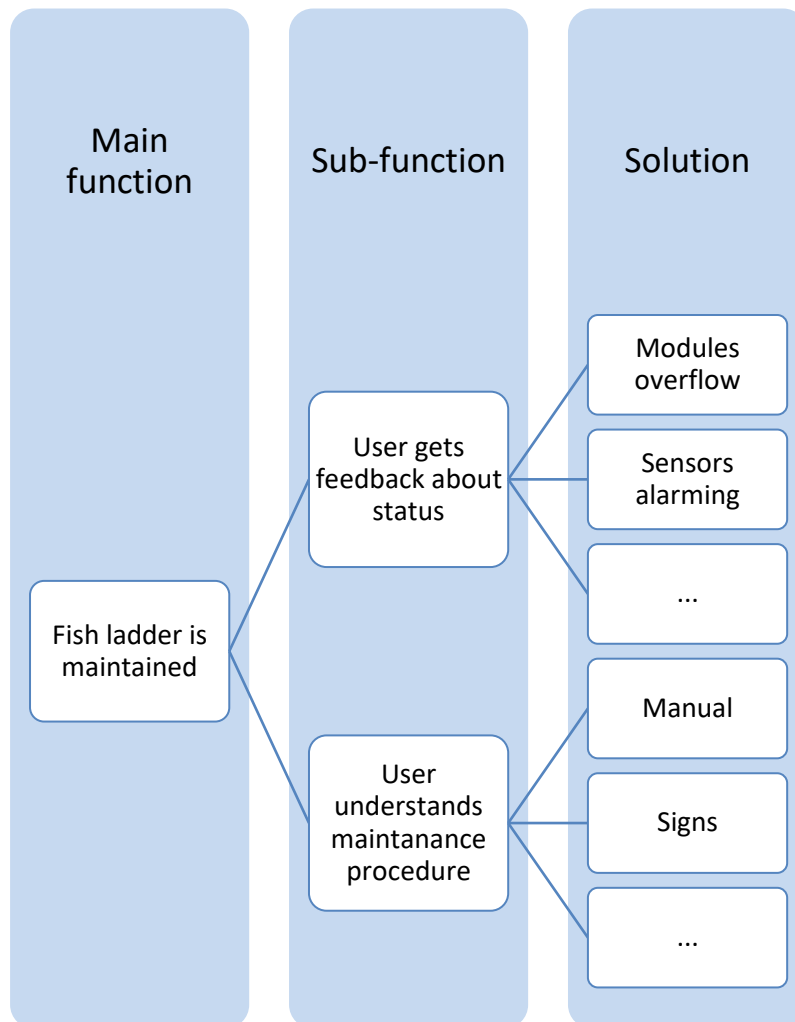
However, glass is inherently brittle, sensitive to stress concentrations, and necessitating significant energy inputs for production (Ashby et al., 2019). Its fragility and the need for supporting structures contribute to the complexity of construction, likely explaining the absence of glass fish ladders in the market.

## 5.2 Ideation

Ideation continued throughout the study, and various forms of brainstorming were utilised in all following sections. First, the structure of the morphological chart is presented, including an example of a main function, subfunctions, and generated solutions for each subfunction. This is followed by descriptions of developed prototypes and lastly a summary of developed concepts.

### 5.2.1 Morphological Chart

Figure 15 illustrates an example from the morphological chart, showing the main function, subfunctions, and a solution for each subfunctions. For the complete morphological chart, see Appendix F. Solutions for different subfunctions were combined resulted in three conceptual ideas that are developed in section 5.3.



*Figure 15. An illustration of the structure of the morphological chart with an example.*

## 5.2.2 Sustainable Product Development Workshop-method

Derived from the Sustainable Product Development Workshop-method were the materials and processes that could be relevant from a sustainability perspective, and how the design could be adapted early on to align with sustainable values. The workshop resulted in many new thoughts, and the following insights had the most significant impact on the result:

### Raw material and production insights:

- The material in a design can be from recycled material. Glass, plastic, and metal are alternative materials that can be obtained from recycled materials.
- Local resources and local manufacturing allow for shorter transportation and thus lower emissions.
- Materials manufactured locally include for example glass, wood and concrete.
- There is extensive knowledge of wood production throughout Sweden, and the material is easy to adapt as production is done manually.

### Lifespan insights:

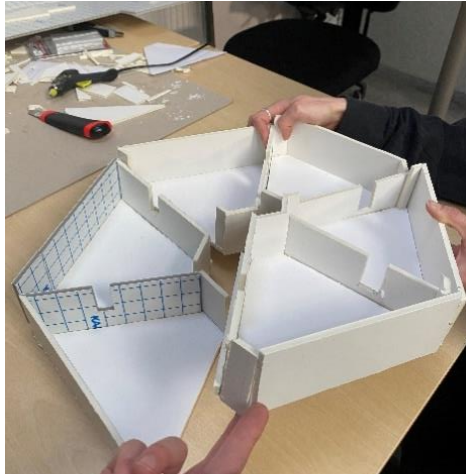
- Creating a design adapted to the products' whole life cycle can provide both environmental and cost benefits.
- Longevity and repairability reduce environmental impact in the long run, as the number of newly manufactured products may decrease.
- The continued function of the product, i.e., efficient and correct maintenance and good quality of parts, affect the product's lifespan.
- The environmental impact of the usage and maintenance of the product needs to be taken into consideration. For example, no toxic cleaning substances should be needed.

### End of life insights:

- If parts of different materials are easy to separate, they are also easier to recycle.
- Designs that are adaptable in many locations are more probable to be reused.

## 5.2.3 Prototyping & CAD

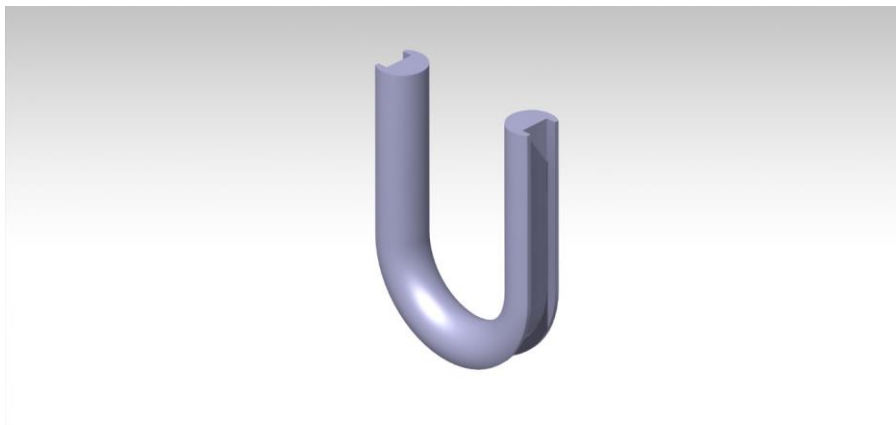
Prototypes in kapa (scale 1:10) were made to understand limitations of the design better and ideate about solution of those problems. One problem found was the fact that the bearing structure hindered dismantling of separate modules, as the pillars were locking them from movement in the horizontal direction (see Figure 18 for illustration of bearing structure). Therefore, prototypes with cut corners were made, to avoid this problem, see Figure 16.



**Figure 16.** *Module with cut of corners for easier dismantling.*

However, the dismantling problem remained as each module supported the next modules side. This made it impossible to slide out one module without affecting neighbouring modules, and possible solutions were explored with CAD. It was found that the modules could be shaped as tubs and thereafter be connected to the bearing structure separately, not supporting each other. To keep the separate modules tight together, they could be connected to each other with sealants around the slot openings.

This led to an additional idea, since a round slot-opening, instead of a rectangular, resulted in an easier production of the sealant profile. This was because a round sealant strip can be made through bending an extruded profile, and no corners of the strip need to be considered, see Figure 17.



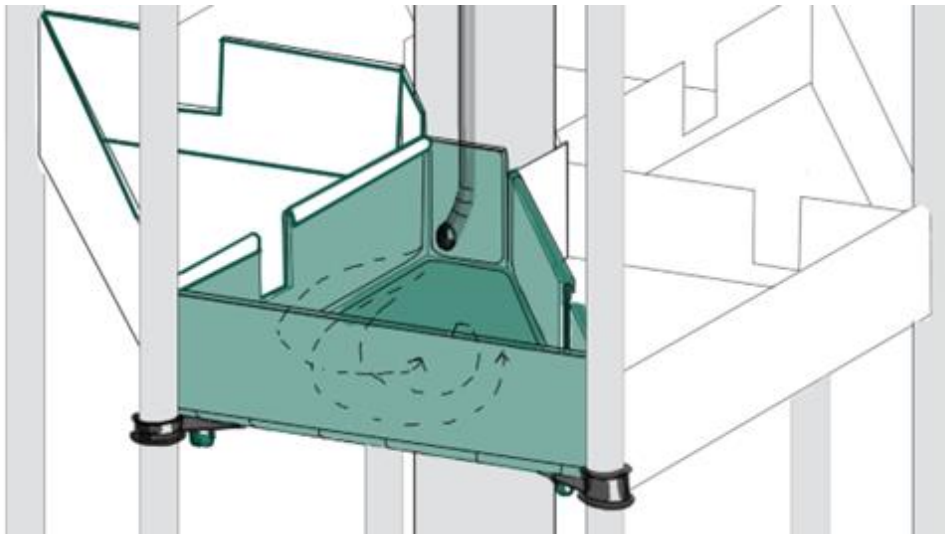
**Figure 17.** *Sealing profile for a round design of slot-openings.*

These ideas, combined, not only results in an easier dismantling of separate modules but could also result in less leakage.

## 5.3 Resulting Conceptual Ideas

This section presents three general ideas for constructing a module, derived from the morphological chart, along with an overall description and considerations for maintenance and repair. Subsequently, potential materials for each construction idea are combined, resulting in six final concepts, which are presented at the end of the section.

### 5.3.1 Pool-concepts



*Figure 18. Illustration of concept Pool with high pressure flushing as maintenance system.*

The first general design suggestion is based on a seamless shape that is casted or form pressed in one piece. This design approach not only provides flexibility in shape but also reduces the necessity for joints, as the shape can allow built-in assembly-system.

The pool-shaped concepts clean their modules by generating turbulence within each module using a high-pressure waterjet. The pressure washer can be connected with each module from a platform on top of the fish ladder. For further explanation of the assembly, maintenance and repair of the pool-concepts, see Appendix G.



*Figure 19. Assembled pool-modules with platform on top.*

**Table 8.** Possible materials for pool-concepts

Possible material	Main weakness for this concept	Potential for concept?
Polymer	UV resistance Mechanical strength	No
Glass fibre composite	Recyclability	Yes
Wood	Water resilience	No
Metal	Weight Price	No
Concrete	Weight	Yes
Glass/ceramics	Difficult production Brittleness	No

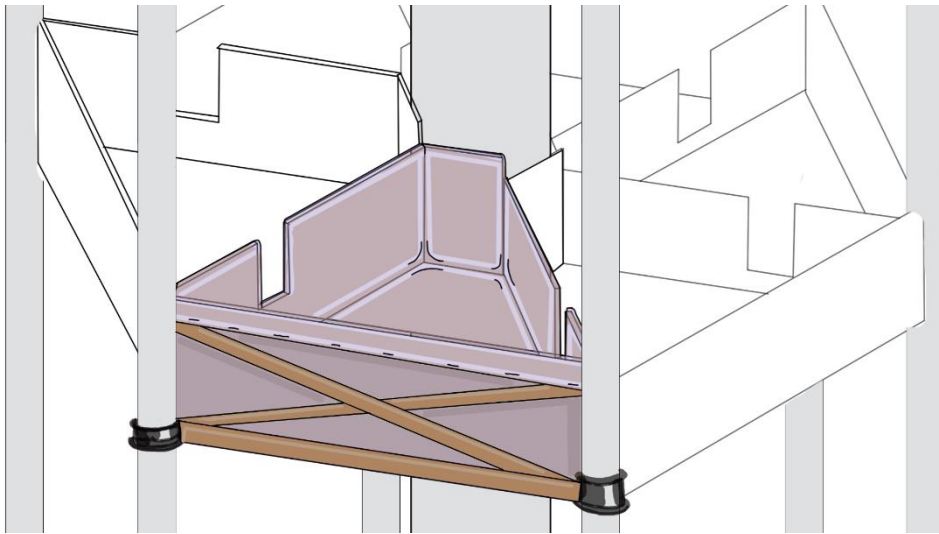
**Concept 1 - Glass fibre composite pool:** Glass fibre composite in a sandwich structure is possible option because it meets the above-mentioned requirements and has undergone testing for a similar application. This provides a significant advantage, as it suggests compatibility with this type of modular fishway principle. The sandwich structure can also provide a lighter, but still strong, module.

The disadvantages of glass fibre composite are that there are no well-developed methods for recycling the material, it requires a lot of energy during production, and it is a chemically developed material. The investment can be costly, depending on size of series.

**Concept 2 - Concrete pool:** Concrete is well-suited for this approach since moulding enables constructing modules in a single piece. Most of today's fishways are made of concrete, and this material is therefore proven to be a feasible material. Concrete has lower price and environmental impact than glass fibre composite materials.

However, concrete's drawbacks include for example high density, affecting transportation, environmental impact, installation, and dimensions of bearing structure. The recycling of the concrete modules could be a struggle, as they also consist of reinforcing bars, to strengthen the structure. The production of moulding these pieces is relatively simple, but concrete does not provide the same design flexibility as glass fibre composite.

### 5.3.2 Skeleton-concepts



*Figure 20. Illustration of concept Skeleton, one module.*

**Description:** This conceptual design comprises two distinct components: the skeleton and the tub. The skeleton bears the inner tub and transfers loads to the supporting structure, while the tub contains water and shields the skeleton from water damage.

This design affords the fish ladder owner flexibility in style and expression, as external panelling can be added to the wooden skeleton. This customization option grants the owner greater influence over the final visual outcome.

The modules can either be prefabricated or assembled on site. On the top of the fish ladder, there is a platform from which the six upper modules can be cleaned. The underlying principle of the concept is that if dirt passes through all six upper modules, it is likely to traverse the entire fish ladder. The modules are possible to dismantle separately for repair. For further explanation of the assembly, maintenance, and repair of the skeleton-concepts, see Appendix G.



*Figure 21. Assembled skeleton-modules with platform on top.*

**Table 9.** Possible materials for the skeleton of the skeleton-concepts

Skeleton		
Possible material	Main weakness for this concept	Potential for concept?
Polymer	Mechanical strength	No
Glass fibre composite	Mechanical strength	No
Wood	Water resilience	Yes
Metal	Environmental impact	Maybe
Concrete	Shape limitations	No
Glass/ceramics	Brittleness	No

The material most suitable for the skeleton is wood. To be able to handle rain and humidity, it could either be impregnated, painted or heat-treated to last longer. Suitable wood types can be pine or spruce due to price and the fact that these varieties are common in Sweden.

**Table 10.** Possible materials for the tub of the skeleton-concepts

Tub		
Possible material	Main weakness for this concept	Potential for concept?
Polymer	Microplastics	Yes
Glass fibre composite	Environmental impact	No
Wood	Water resilience	Maybe
Metal	Environmental impact and Corrosion	Yes
Concrete	Malleability	No
Glass/ceramics	Brittleness	Maybe

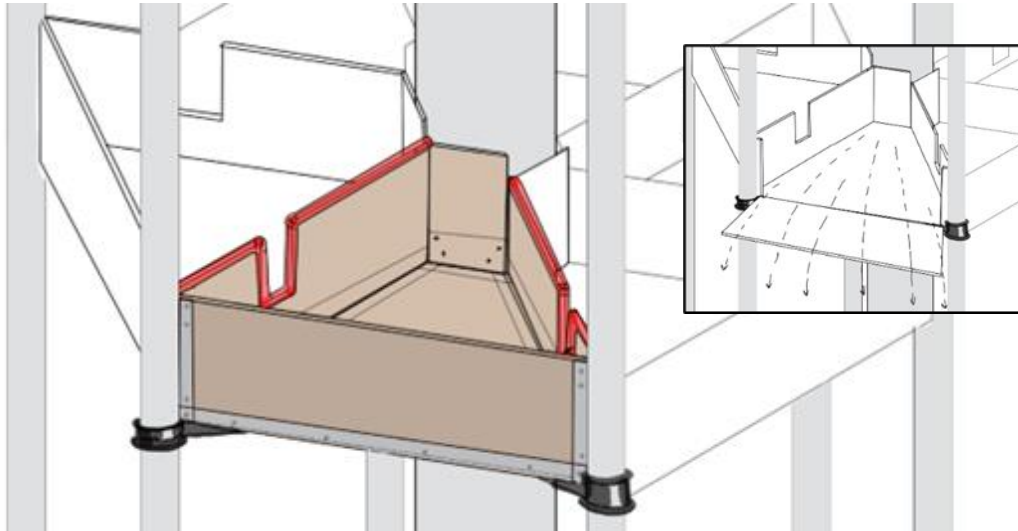
**Concept 3 – Wooden skeleton with plastic tub:** In the third concept, the skeleton is made of wood, while the tub is constructed from polymer material, typically known for its low cost and flexibility in shaping. This material has demonstrated ease of production on a scalable level. Transportation could be optimized by slightly cone-shaping the tubs to facilitate stacking.

However, not all polymers are suitable for this application. Parameters that must be considered include the risk of microplastic contamination, UV resistance, and recyclability.

**Concept 4 – Wooden skeleton with metal tub:** The fourth concept also consists of a wooden skeleton, but with a tub of metal. The production of such metal tubs could either be done with pressing, as for kitchen sinks, or with bending and welding of laser cut metal sheets. Metal has been used for similar applications, especially in downstream passages.

Drawbacks with metal materials are that some of them react with water, and therefore need a protective layer or other treatment. Metals are often expensive and energy consuming to produce.

### 5.3.3 Board-concepts



*Figure 22. Illustration of board concepts, and how to open the module for maintenance.*

**Description:** The board concepts is designed for easy and cheap transportation and assembly, drawing inspiration from IKEA's packaging approach. Each module is constructed from sheets and delivered in flat packages, facilitating installation onto the supporting structure with an easy-to-follow manual.

All components are designed to be easily lifted, handled, and assembled by one or two individuals. Consequently, professional assistance is only necessary for installing the supporting structure, which comprises columns with supports allowing each wooden board to be attached with screws and sealant.

For the Board concepts, each module can be accessed with a ladder from the outside. The outer wall of each module can be opened to access cleaning of the inside. For further explanation of the assembly, maintenance, and repair of the board-concepts, see Appendix G.



*Figure 23. Assembled board-modules with roof*

**Table 11.** Possible materials for board-concepts

Possible material	Main weakness for this concept	Potential for concept?
Polymer	Mechanical strength Not reasonable to use as sheets	No
Glass fibre composite	Not reasonable to use as sheets	No
Wood	Water resilience	Yes
Metal	Environmental impact Weight	No
Concrete	Weight	No
Glass/ceramics	Brittleness Weight	Yes

**Concept 5 – Wooden boards:** In this first material alternative, the Board-concept is comprised entirely of wooden boards, formed by merging planks of pure wood and cut to suitable dimensions for easy installation. However, due to wood's limited resilience to water, the concept is restricted to a lifespan of up to 15 years, emphasizing the need for a design that prioritizes reparability, low short-term costs, and ease of installation.

To extend the lifespan, a substantial roof construction is essential to shield the structure from the sun, maintaining constant moisture during summer, and protecting it from rain and freezing during winter. This is crucial because wooden constructions are prone to damage when exposed to alternating wet and dry conditions.

Consideration could also be given to employing of surface treatment. If opting for surface treatment, it's imperative to mitigate any adverse effects on the surrounding environment and fish. Options include saturating affected surfaces with oil or treating them with impregnation to prolong their lifespan. Another possibility is exploring sustainable boat coatings, as they are used in similar environments to protect wood from decay.

**Concept 6 – Glass boards:** The final alternative for the IKEA concept is glass, as this is a local resource that is water resistant and strong. The edges of the glass boards are covered with rubber strip to avoid leakage, but also to prevent cracking, as the rubber list can take some of the force during compression.

The downside with glass is its weight as it needs to be of a certain thickness to handle the loads from the water in the module. Even though the modules are not assembled from the start, a lifting crane could be necessary if the parts are too heavy.

## 5.4 Summary Develop

Combining various ideation methods with literature studies, workshops, and previously identified needs and requirements, the Development phase resulted a material study and three general principles for construction of the module including shape, assembly, maintenance, and repair. Combining materials and general principle resulted in six concepts with deemed having the highest potential, and are the following:

1. Glass fibre composite pool
2. Concrete pool
3. Wooden skeleton with plastic tub
4. Wooden skeleton with metal tub
5. Wooden boards
6. Glass boards

These concepts underwent further evaluation, testing and refinement.

# 6

## Deliver Concepts with High Customer Value

**Chapter 6.** Building upon the ideas and concepts outlined in Chapter 5, the focus now shifts towards elimination and refinement to deliver solutions that best align with identified needs and requirements. This chapter takes a systematic approach by initially presenting three potential scenarios, along with their projected series size of modules. This is followed by an elimination of concepts through the Kesselring matrix, where the concepts are analysed and matched with the scenario that offers the highest expected value. Subsequent analysis and development can then be done accordingly.

## 6.1 Value Creation Strategies

The number of cases where this type of fishway would be appropriate has a major impact on how the fishway should be designed and which materials and manufacturing methods would be the most suitable. Therefore, three potential scenarios have been developed to investigate which concepts and scenarios are most likely. The developed are based on various potential outcomes regarding how the spiral-shaped fish passage principle is expected to be applied in the future. These are also linked to distribution area, deadline for when the design should be operational, and how customer value is created in each scenario.

### 6.1.1 VCS 1 – Space Efficiency is a Requirement

**Scenario:** In this scenario, the spiral formed fishway is just an addition to the already existing solutions of fishways. It fills the gap where space efficiency is crucial or when a solution is needed for a limited time, for example in the delay of another solution or to test principles and quickly adjust the solution based on what provides the best functionality for the fish passing through.

**Distribution area:** The design should be able to distribute to all of Sweden.

**Deadline:** The first implementation should be in less than 1 year.

**Value creation:** In this scenario, value creation could be done through low short-term costs as well as easy installation and dismantling. The time aspect in the concept reinforces the importance of that the concept can be produced locally, with local materials, to reduce transportation time and costs.

The limited production probably leads to a higher purchase price, which results in that repairability, and recyclability are crucial. Therefore, replacing parts would be prioritised over installing new ones. The shorter expected lifetime of the product further strengthens the argument for a recyclable solution.

### 6.1.2 VCS 2 – One size fit all-with-same-needs

**Scenario:** In Scenario 2, the solution aims to replace the need of technical fishways with similar dimensions/target species as the design is adapted for.

**Distribution area:** The design should be able to distribute to all of Sweden. Export potential.

**Deadline:** The first implementation should be in 2-3 years.

**Value creation:** In Scenario 2, the solution aims to replace other technical fishway solutions, in cases where similar dimensions are required.

As a result of the fact that most hydropower plants are small-scaled, the cost-efficiency is of great importance to create value to the customers. Large-scale production with a concept of the principle of “one size fits all-with-same-needs” would result in a low financial investment as well as possibility to predict the final cost of implementation.

However, not only the short time cost would be important in this scenario, but also the long-time perspective needs to be taken into consideration. This includes leakage, maintenance need/cost and lifespan. Long lifespan, including repairability, makes the installation cost less crucial.

### 6.1.3 VCS 3 - Most Cases Covered

**Scenario:** Lastly, in Scenario 3, the design not only aim to cover cases with specific conditions and target species but replace the need of most technical fishways.

**Distribution area:** The design should be able to distribute to all of Sweden. Export potential.

**Deadline:** The first implementation should be in 5 years.

**Value creation:** In Scenario 3, the design not only aim to replace cases with specific conditions and target species, but most fish migration hinders. To attract this big market segment with a broad range of customers, a modular and parametrised design where it is possible to customise to site conditions and target species is desirable. This requires a design that can be constructed at different ground conditions and which dimensions, such as step-heights, volume and flow, can be adjusted to the meet needs of migratory fish. In this scenario, value is also created through other kind of customisation – as adding optional features.

A parametrised design could result in a higher purchase price and therefore primarily be an option to hydropower plant owners where such an investment could be motivated. Long-term investment, including leakage, maintenance, and lifespan, is therefore of great importance. Also, environmental sustainability gets increasingly important as the series size is bigger.

### 6.1.4 Size of Series for Each Scenario

In Chapter 4, an estimation of the potential series size was provided, concerning if all installations of technical fishways (not exceeding 6.3m in height) from now on will adopt a spiral shape. This resulted in approximately 4000 produced modules, if only considering hydropower plants, and 21 000 produced modules, if including all dams. As it, in this state, is difficult to predict how many dams that are relevant to consider, the following calculations will be presenting an interval between “all hydropower plants applicable” and “all dams applicable”.

Additionally, as it is unrealistic to expect that every possible case will utilize this specific solution, previously described scenarios will serve as a guiding framework for further approximation. Each scenario includes additional parameters that may be relevant to consider.

Ten pending applications for the implementation of technical fishways, currently under review by the Environment Court, have been thoroughly analysed. A matrix with more information of each specific case can be found in Appendix H. After discussions with experts at Sweco the estimation is as follows:

**Table 12.** Percent of different criteria observed in 10 applications.

Limited construction area	Similar target species	Good or rel. good vehicle accessibility	Rock as soil type
30%	77%*	60%	60%

*\* Many reports did not include information about target species. “Similar target species” were estimated to be most cases where a vertical fish ladder could be used, as the low water flow of the design (70 l/s) is probable to allow similar species to pass, especially if there is a ramp for bottom-oriented species. 11 of 13 applications (i.e., 85%) of technical fishways in 2022, were applications for vertical slot fishways. Also considering the limitations in space, 1 of 10 of the analysed applications stated that large fish needed to pass (dimensions of 3 meters long pool were needed). In 90% of the cases there were no such indications. It is reasonable to assume that in small watercourses (often the case for small-scale hydropower plants) there are not as big fish. Combining these numbers (0.85 \* 0.9), 77% are assumed to be similar target species, as a rough estimation.*

In section 4.6, the estimated series size was calculated to be 4093 modules for cases involving only hydropower plants and 21203 modules for cases incorporating dams. The estimated values above make it possible to calculate an interval of production size for each scenario, divided into “all hydropower plants applicable” and “all dams applicable”.

**Table 13.** Size of series, depending on different scenarios

Scenario 1			
Criteria	Limited construction area	30%	
	Geology - rock as soil type	60%	
	Similar target species/dimensions	77%	
	Percentage meeting the above criteria	14%	567 (Modules for hydropower plant) 2939 (Modules for all dams)
Scenario 2			
Criteria	Good or rel. good vehicle accessibility	60%	
	Geology - rock as soil type	60%	
	Similar target species/dimensions	77%	
	Percentage meeting the above criteria	28%	1135 (Modules for hydropower plant) 5878 (Modules for all dams)
Scenario 3			
Criteria	Good or rel. good vehicle accessibility	60%	
	Geology - rock as soil type	60%	
	Percentage meeting the above criteria	36%	1474 (Modules for hydropower plant) 7633 (Modules for all dams)

To summarize, these various scenarios lead to different potential series sizes, which significantly affect the choice of material and production process. This, in turn, influences decisions regarding transport, centralized or regional manufacturing, and other related factors. These considerations have been incorporated into the analysis of the Kesselring matrix, see section 6.3.

## 6.3 Kesselring Matrix

Based on the various presented scenarios, the different needs can be ranked according to their value creation. The following six concepts are arranged in a Kesselring matrix and ranked according to identified needs:

1. Glass fibre composite pool
2. Concrete pool
3. Wooden skeleton with plastic tub
4. Wooden skeleton with metal tub
5. Wooden boards
6. Glass boards

For the complete Kesselring matrix, see Appendix I. Together with the ranking, each VCS is matched with the concepts that provide the highest value. The results were as follows:

**Table 14.** Kesselring matrix with ranking corresponding to VCS 1.

VCS 1							
Need	Weight	1	2	3	4	5	6
Possible to count fish	4%	0.12	0.12	0.12	0.08	0.08	0.12
Possible to install in varying site conditions	15%	0.3	0.3	0.6	0.6	0.75	0.6
Scalable production method	5%	0.25	0.2	0.15	0.1	0.15	0.15
Efficient installation process	8%	0.4	0.4	0.24	0.24	0.32	0.32
Ergonomic assembly and installation	0%	0	0	0	0	0	0
Low long-term costs	10%	0.3	0.3	0.3	0.3	0.2	0.3
Low short-term costs	20%	0.4	0.6	0.8	0.4	1	0.8
Predictable final costs	5%	0.2	0.2	0.15	0.15	0.15	0.15
Design's functional status is communicated	10%	0.3	0.2	0.3	0.3	0.3	0.5
Easy and efficient maintenance	7%	0.35	0.35	0.35	0.35	0.07	0.07
Ergonomic accessibility during maintenance	2%	0.08	0.08	0.08	0.08	0.02	0.02
Provide status and feedback of maintenance	5%	0.1	0.1	0.2	0.2	0.1	0.1
Low emissions and environmental impact	9%	0.18	0.27	0.45	0.09	0.36	0.18
<b>Sum:</b>		<b>2.98</b>	<b>3.12</b>	<b>3.74</b>	<b>2.89</b>	<b>3.5</b>	<b>3.31</b>

**Concepts with highest value creation in Scenario 1:** Wooden skeleton with plastic tub, Wooden boards, Glass boards

**Motivation:** Low short-term cost is a priority here, which value drivers are for example cost for transportation, production, material and installation. Concepts that can be made locally with cheap materials are therefore rewarded with higher scores.

Additionally, it is important in this concept to be able to install the concept in various site conditions. That means for example less accessible places, where heavy vehicles cannot reach. A light solution that can, for example, be divided into many elements can therefore be motivated.

**Table 15. Kesselring matrix with ranking corresponding to VCS 2.**

<b>VCS 2</b>							
<b>Need</b>	<b>Weight</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
Possible to count fish	5%	0.15	0.15	0.15	0.1	0.1	0.15
Possible to install in varying site conditions	5%	0.1	0.1	0.2	0.2	0.25	0.2
Scalable production method	15%	0.75	0.6	0.45	0.3	0.45	0.45
Efficient installation process	1%	0.05	0.05	0.03	0.03	0.04	0.04
Ergonomic assembly and installation	0%	0	0	0	0	0	0
Low long-term costs	12%	0.36	0.36	0.36	0.36	0.24	0.36
Low short-term costs	17%	0.34	0.51	0.68	0.34	0.85	0.68
Predictable final costs	5%	0.2	0.2	0.15	0.15	0.15	0.15
Design's functional status is communicated	10%	0.3	0.2	0.3	0.3	0.3	0.5
Easy and efficient maintenance	13%	0.65	0.65	0.65	0.65	0.13	0.13
Ergonomic accessibility during maintenance	3%	0.12	0.12	0.12	0.12	0.03	0.03
Provide status and feedback of maintenance	7%	0.14	0.14	0.28	0.28	0.14	0.14
Low emissions and environmental impact	7%	0.14	0.21	0.35	0.07	0.28	0.14
<b>Sum:</b>		<b>3.3</b>	<b>3.29</b>	<b>3.72</b>	<b>2.9</b>	<b>2.96</b>	<b>2.97</b>

**Concepts with highest value creation in Scenario 2:** Glass fibre composite pool, Concrete pool, Wooden skeleton with plastic tub

**Motivation:** In Scenario 2, the cost on both short and long term is the most crucial factor. Modules with the same dimensions enables mass production. Therefore, materials and shapes that can be easily mass-produced in large volumes are advantageous. Simple and efficient maintenance is also an important parameter.

The Pool concepts could have an even higher value in this scenario if they had used another maintenance principle. The turbulence creating principle was in this scenario considered too expensive and with a risk of breaking.

**Table 16.** Kesselring matrix with ranking corresponding to VCS 3.

VCS 3							
Need	Weight	1	2	3	4	5	6
Possible to count fish	5%	0.15	0.15	0.15	0.1	0.1	0.15
Possible to install in varying site conditions	16%	0.32	0.32	0.64	0.64	0.8	0.64
Scalable production method	13%	0.65	0.52	0.39	0.26	0.39	0.39
Efficient installation process	3%	0.15	0.15	0.09	0.09	0.12	0.12
Ergonomic assembly and installation	0%	0	0	0	0	0	0
Low long-term costs	15%	0.45	0.45	0.45	0.45	0.3	0.45
Low short-term costs	10%	0.2	0.3	0.4	0.2	0.5	0.4
Predictable final costs	5%	0.2	0.2	0.15	0.15	0.15	0.15
Design's functional status is communicated	8%	0.24	0.16	0.24	0.24	0.24	0.4
Easy and efficient maintenance	10%	0.5	0.5	0.5	0.5	0.1	0.1
Ergonomic accessibility during maintenance	3%	0.12	0.12	0.12	0.12	0.03	0.03
Provide status and feedback of maintenance	5%	0.1	0.1	0.2	0.2	0.1	0.1
Low emissions and environmental impact	7%	0.14	0.21	0.35	0.07	0.28	0.14
<b>Sum:</b>		<b>3.22</b>	<b>3.18</b>	<b>3.68</b>	<b>3.02</b>	<b>3.11</b>	<b>3.07</b>

**Concepts with highest value creation in Scenario 3:** Glass fibre composite pool, Concrete pool, Skeleton with plastic tub

**Motivation:** In Scenario 3, adaptability is one of the most important parameters. It is also crucial to have a production where many modules can be created, as the series size is high. Materials and production processes with high flexibility are of great value.

Here, the long-term investment is particularly important, as customizations are more expensive and therefore it is even more important to ensure longevity. Longevity encompasses both qualitative materials, effective feedback, easy maintenance, minimal leakage, and high repairability.

It is also important that this concept can be installed in various environments, which means that concepts with lower weight are favoured. Additionally, adaptability in appearance to local environments can be valuable.

## 6.4 Choice of Value Creation Strategy

The analysis of the Value Creation Strategies, related to a certain scenario, was based on the study's findings. Discussions and choice of VCS were thereafter conducted in collaboration with the design agency Sweco.

During the study, it has been shown that there is a high demand for cost-effective and space-efficient fishways. Consequently, Scenario 1 is not considered the most likely future scenario, as this scenario describes a situation where the spiral formed fish ladder is only considered as an option where there is limited construction area, or a temporary solution is needed. Scenario 3 does not meet the crucial need of cost efficiency, as the production of a parameterized design is expensive. The high demand of cost efficiency justifies a standardised design that can be mass-produced, to reduce costs.

Furthermore, the study has identified that testing has proven crucial to achieving good functionality. A parameterized design entails unique solutions requiring extensive testing, as each fish ladder's dimensions differ. Therefore, Scenario 2 "One size fits all-with-the-same-needs", with its standardized design, reduce the need for testing (for every separate design) as all fishways with the same dimension will provide similar function.

However, there is a need for more temporary fish passages, as described in Scenario 1, but this is argued feasible also with Scenario 2.

All abovementioned reasons are pointing towards the fact that the Value Creation Strategy 2, related to Scenario 2, is favourable.

## 6.5 Refinement

After selecting the most likely scenario (Scenario 2) and ranking the options using the Kesselring matrix, the three most value-creating concepts for Scenario 2 were chosen for further development and refinement. Sub-solutions with good potential were included and combined with selected final concepts. Decisions made during the refinement of the concepts were based on findings of the study and dialogues with Sweco. Adjustments included maintenance principles, weight optimization, assembly methods, and the design of openings for fish passage. This final refinement led to the three final designs, presented in Chapter 7.

## 6.6 Summary Deliver

From the Development phase, six concepts remained, which in the Deliver phase have been evaluated and refined. Starting with three Value Creation Strategies, based on scenarios with different market segments, the concepts were evaluated with a Kesselring Matrix ranked according to each VCS. This resulted in different potential concepts for depending on which strategy to apply. In dialog with Sweco, the market scenario was that the design should be sold only to customers with the same dimension needs. This, to enable serial production and therethrough cost-efficiency. The concepts with highest potential for this VCS were therefore the Glass fibre composite pool, the Concrete pool, and the Wooden skeleton with plastic tub. However, through analyses of the evaluation it was found that the maintenance solution associated with the skeleton concepts, were considered more value creating than the solution associated with the pool concept. All sub-solutions were analysed and those with the most potential were selected and formed the basis of three final concepts to be further developed and refined.

# 7

## Final Design & Evaluation

**Chapter 7.** Since the aim of this study is to contribute to a feasible design, it was argued that one in-depth and detailed concept may not provide as much value as three concepts designed at a more general level, which can serve as a basis for further research and development. This is because of the uncertainties that still have the potential to alter the parameters. Therefore, having three possible alternatives offers a lower risk and hopefully results in a feasible outcome in the end.

Through analyses conducted during concept evaluation, prototyping, and modelling, the solutions were developed with consideration given to material selection, production, assembly, durability, maintenance, repair, and life cycle. In this chapter, the overarching idea of the spiral-shaped fish ladder will be presented first. Subsequently, the three concepts for modules will be explained, aiming to pass on our acquired knowledge to future designers, researchers, and engineers.

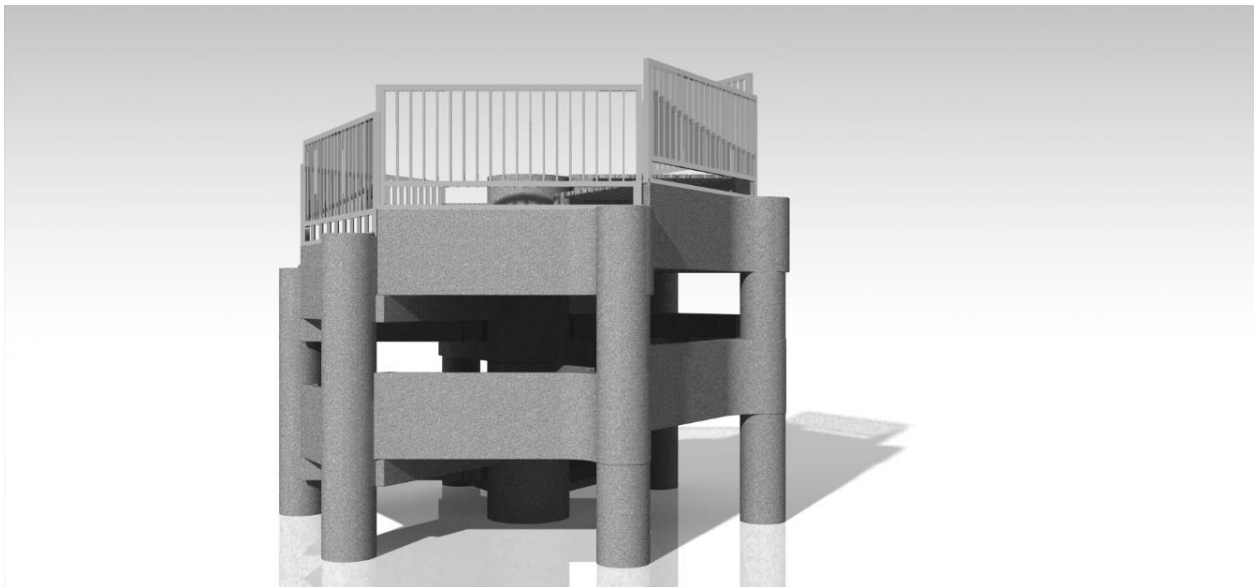
# 7.1 General Idea

Previously, in Chapter 6, various scenarios were considered. This led to the conclusion that this study would be further developed in accordance with the “one size fits all-with-the-same-needs”-scenario, and be designed for implementation where there is a need for a technical fish passage, and the following parameters are fulfilled:

*Table 17. Limitations for the design.*

<b>Target species</b>	Fish under 60 cm, capable of navigating a step height of 15 cm and a flow of 70 l/s.
<b>Ground conditions</b>	A surface area of 12 m <sup>2</sup> , where 7 anchorages in rock can be made.
<b>Maximum hinder height</b>	6.3 m in vertical distance

**Shape:** As a starting point, the fish passage has a spiral shape with 6 modules/steps per turns, with set dimensions calculated based on standards in DWA (2014). The bearing structure for each concept is a central column and 6 outer columns, to which the modules can be connected. Common for the three concepts below is that they require a foundation where these 7 columns can be attached.

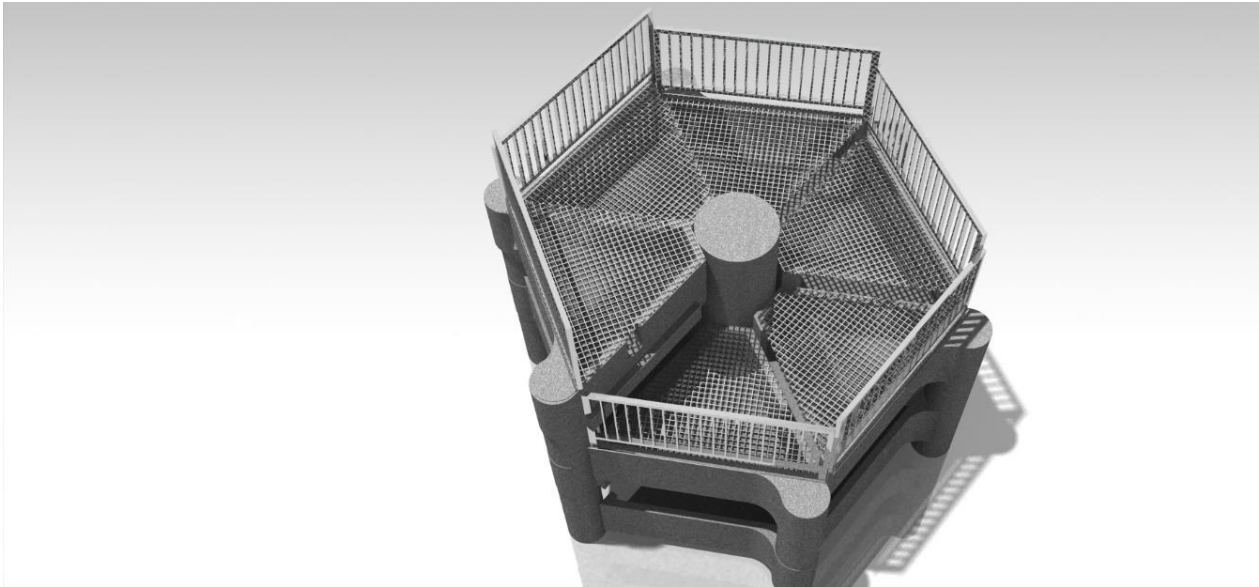


*Figure 24. General concept with 12 modules, i.e., two laps.*

The spiral principle revolves around moving fish vertically while minimizing the need for extensive pre-construction work. As the fish ladder is assumed to be placed next to the watercourse, a natural bypass or other engineered channel guide the fish to and from the fish ladder. Design of inlet and outlet is addressed in Chapter 9, regarding recommendations for further development, as they are outside the scope of the study, but their design is crucial for a successful outcome.

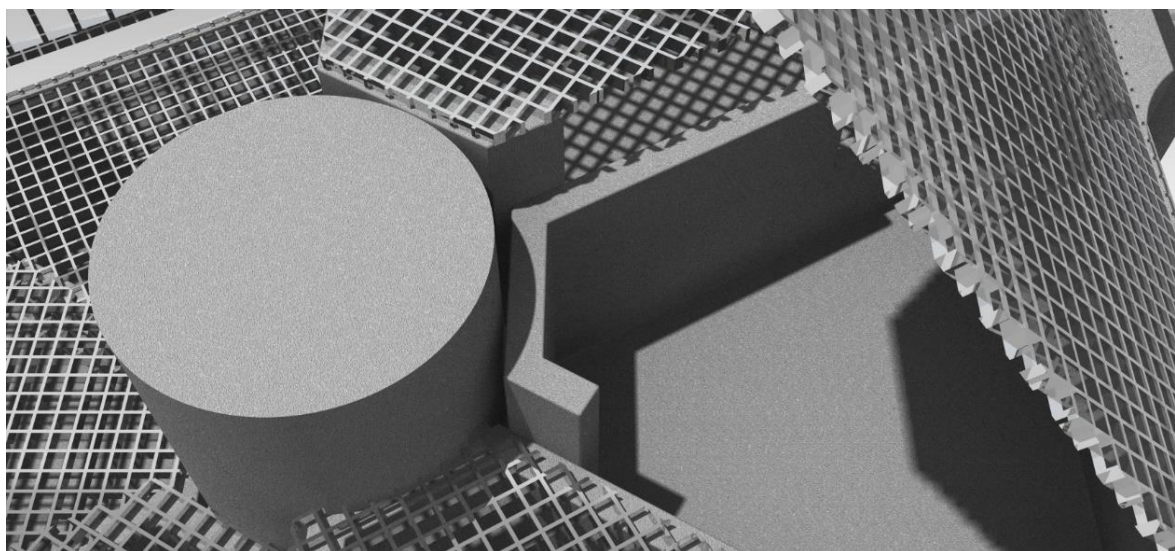
**Maintenance:** The maintenance principle is similar for all three concepts, as it mainly occurs from a platform on top of the fish passage, see Figure 25. The reasoning is that most accumulation of

debris will be in the first lap, and therefore the top six modules are most critical to consider. Debris that succeed to pass all the first six modules are probable to pass the other modules as well, and the most frequent maintenance will be made from this platform. The fact that the person maintaining the fish passage can stand above the water surface level, allows for higher safety.



*Figure 25. Maintenance platform with opening grids and protective fence.*

The person maintaining can access this platform either by ladder or with a footbridge, depending on site conditions. The platform comprises a grating roof for each module, which maintenance personnel can lift to access and clean the modules, see Figure 26. The hole of the grate allows for quick feedback on cleaning status for maintenance personnel. From a maintenance perspective, light colours are optimal for easily identifying where debris has accumulated. However, this may be less favourable for the fish, which are accustomed to a darker bottom. The primary concern in this case is that the fish should be encouraged to pass through the fish passage.

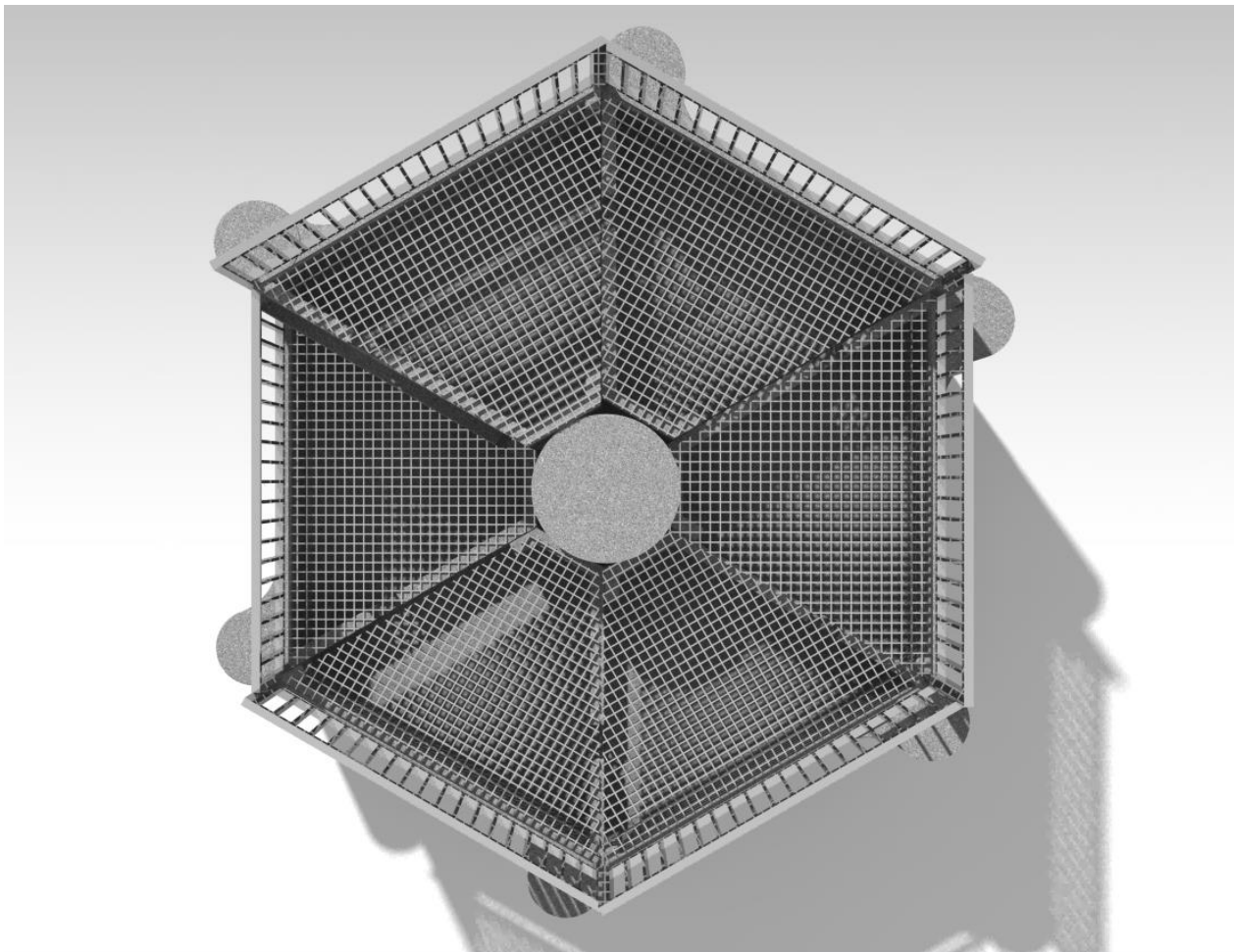


*Figure 26. Close-up of opened grating on maintenance platform.*

Also, having some kind of surface water grate at the outlet (where the water flows into the fishway, and the fish swims out) is crucial. The grate collects and diverts the floating debris while allowing passage for fish, which can swim under the grate. Similar grate-principles have already been developed, and separate design proposals for the outlet has not been included in this study.

The other modules, located at lower levels, can be accessed by users by placing a ladder on each side of the fish passage. The solution is designed to ensure the secure attachment of the ladders. In passages with a height exceeding five meters, hooks for attaching a harness should also be available. During maintenance with a ladder, which is intended to occur less frequently, the water needs to be shut off to avoid the risk of the maintainer getting wet or injured. The inside of the modules can be reached with a rack or similar tool.

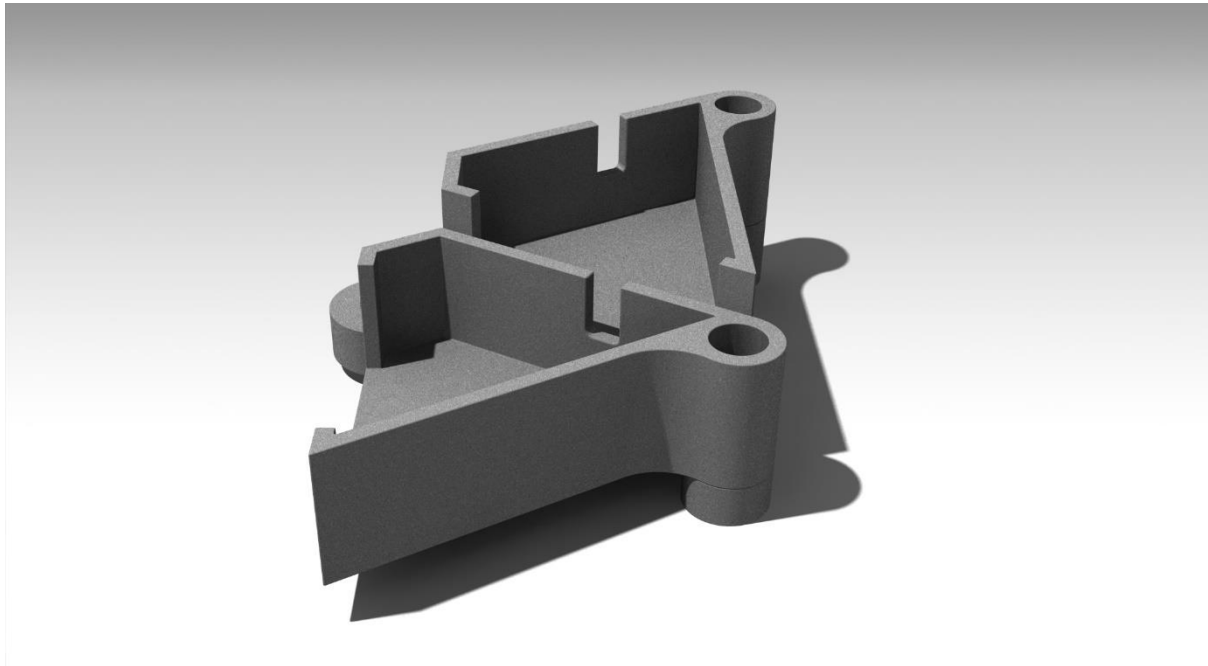
Feedback when maintenance is needed in the lower modules occurs automatically through flooding of the modules. If there is an excessive build-up of organic debris, the affected module will receive more water than it can accommodate, leading to overflow.



*Figure 27. Top view of the design*

## 7.2 Concept Valkyria

The Valkyria concept is based on prefabricated concrete elements that, when assembled, create voids where the pillars can be casted. Valkyria stands for security, stability, and durability. In the following section, an description of Valkyria is provided.



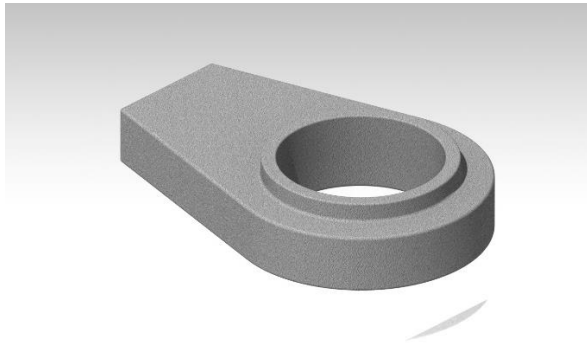
*Figure 28. Two modules assembled of concept Valkyria.*

**Material and production:** The Valkyria concept relies on the reliability of material choice, as most technical fish passages existing in Sweden today are made of concrete. There is a lot of knowledge and experience about concrete construction and production in Sweden which is favourable for finding local skilled suppliers. The difference from an on-site cast solution is that this concept consists of prefabricated concrete elements casted in reusable moulds.

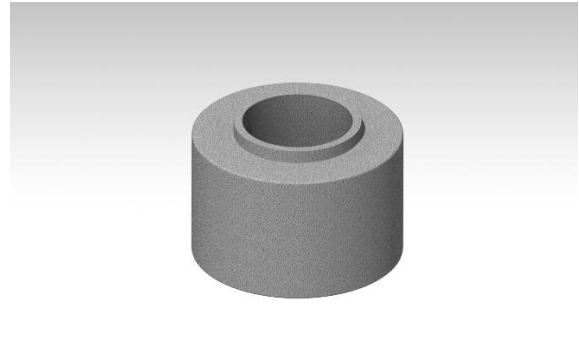
Green concrete is used because it is both stronger and better from a sustainability perspective. However, the concrete pool consists of two separate materials since the concrete needs to be stabilized with reinforcement mech to strengthen the modules' resistance to tensile stress. An alternative type of concrete is fibre-reinforced concrete to avoid the need for reinforcement and allow for a neater construction. However, it has proved difficult to calculate the strength of a fibre-reinforced concrete structure, but it remains a possible alternative if it proves suitable for this type of application.

After the moulding has hardened, each module is placed in a crane truck, like “Toblerone-packaging”, and transported to the designated location. Since concrete and metals are heavy materials, it's important to consider that this truck needs to be able to access the required location. This concept could be challenging to transport to hard-to-reach places with roads that do not allow heavy vehicles.

**Assembly and disassembly:** The prefabricated concrete elements, including the main module and two spacer columns (see Figure 29 and 30), are delivered by a crane truck with trailer.



*Figure 29. Spacer column for creating inner pillar and support module.*

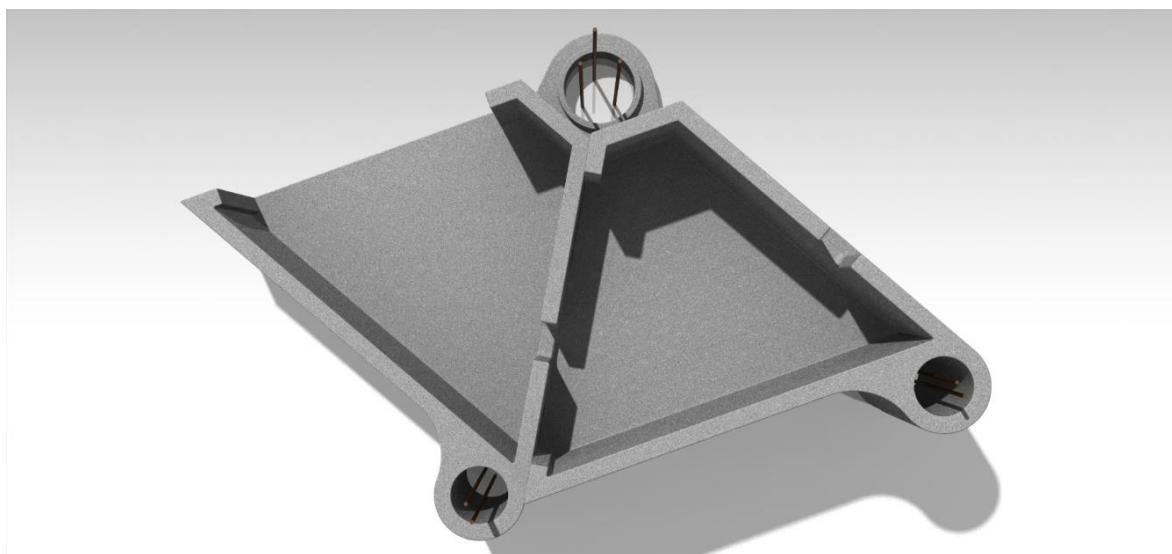


*Figure 30: Spacer column for creating outer pillar and support module.*

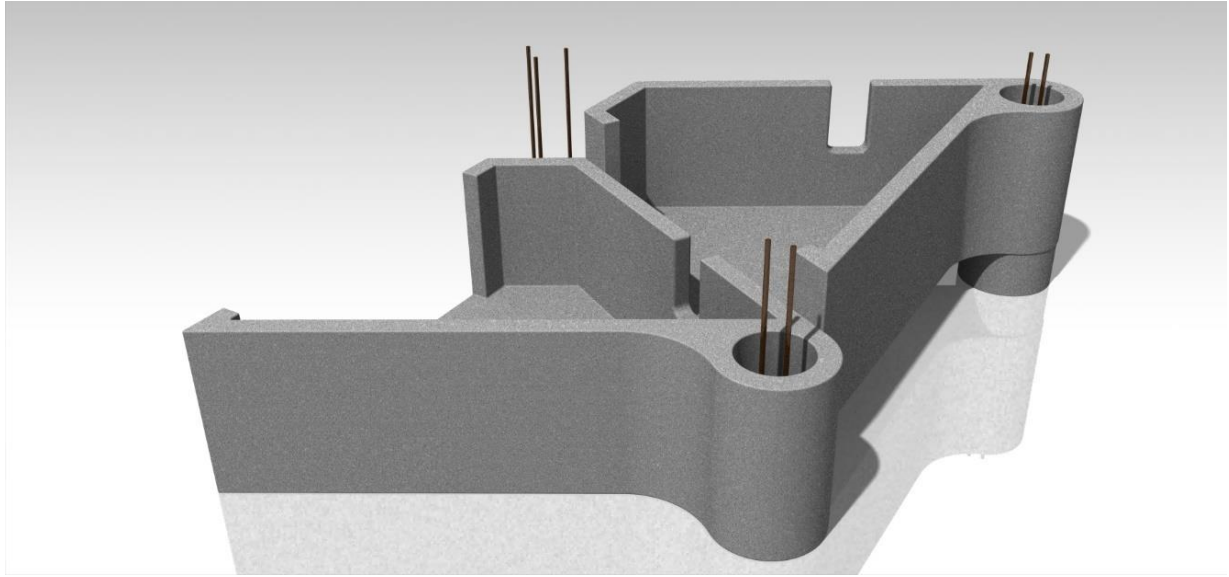
A concrete foundation, with protruding reinforcing bars for each pillar, is prepared on site. Thereafter, the concrete modules are lifted off, one by one, and placed so that the holes of the prefabricated modules are threaded onto the reinforcing bars. The inner corner of the module is supported by the inner spacer column, see Figure 29, one outer corner of the module is supported by the outer spacer column, see Figure 30, and the other outer corner of the module is supported by an edge on the neighbouring module.

The holes, of the modules and the spacer columns, create cavities acting as moulds for casting the pillars, see Figure 31 and 32. Once all modules are assembled, the voids are filled with concrete to create a sturdy load-bearing structure. The structure is thereafter difficult to dismantle, as it is casted in place.

A possible sealant, between the pool-modules, could be the Sikadur combiflex with epoxy glue Sikadur 31 DW. This has been used in another prefabricated concrete fishway, with promising results. Important to consider is that this sealant is applied during suitable conditions.



*Figure 31. Top view of concept Valkyria, ready for casting the pillars.*



*Figure 32. Side view of concept Valkyria, ready for casting the pillars.*

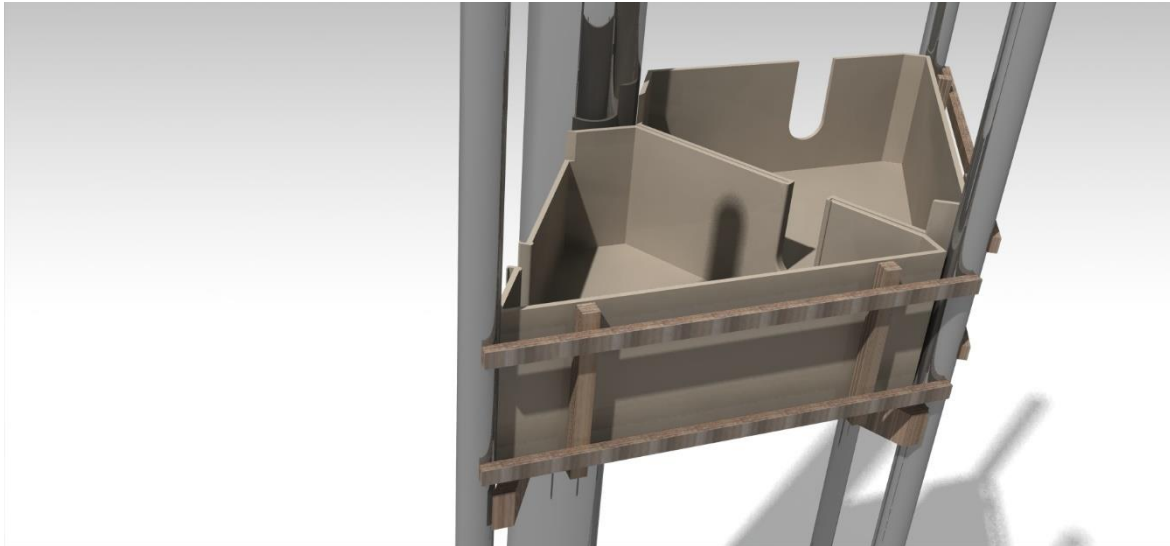
**Maintenance and repair:** The fish passage is maintained by standing on a platform on top, as described in section 7.1. From there, one can reach all the top modules. It is also possible to reach other modules, by placing a ladder on the outside of the construction.

Valkyria is designed for long lifespan rather than reparability. Therefore, it is of utmost importance that the preparatory work, including strength calculations, dimensioning, and testing for relevant target species, is well executed. Once in place, major adjustments cannot be made. Minor repairs, such as touching up surfaces with wear, can be done through manual application of materials. However, this may be difficult to do on all parts of the modules, as the inner parts may be hard to access.

**Life cycle:** Valkyria utilises green concrete in its manufacturing process and is designed to last for at least 50 years. Because it is partially casted on-site, the potential for dismantling and reusing modules is reduced. This also limits the design's adaptability if adjustments or changes are required. However, dismantling would have been challenging regardless, as the roughly shaped modules would still need to be joined together with sealant. This drawback is partially offset by the concrete's long durability. Nonetheless, it is advisable to explore recycling options for concrete to determine if the material can be reused.

## 7.3 Concept Balder

Balder is a concept consisting of a structural wooden framework for each module, within which rests a plastic tub. Balder stands for repairability, customisation, and low investment cost.

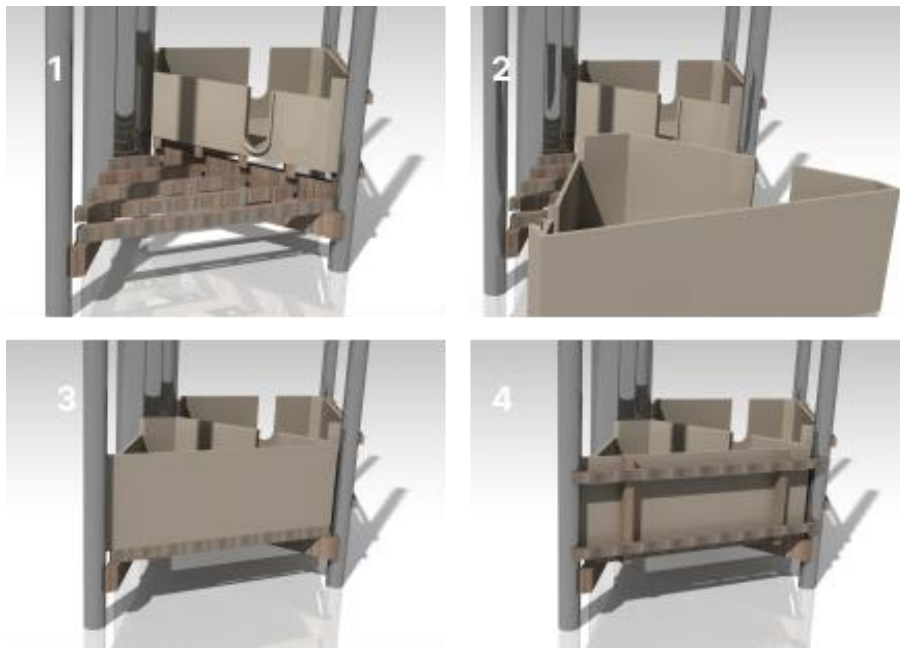


*Figure 33. Concept Balder.*

**Material and production:** The Balder concept is a solution that is taking advantage of the inherent strengths of wood, such as mechanical robustness, lightweight, environmental sustainability and low cost. However, woods' drawback is the limited water resistance, and to address this issue, each wooden module is equipped with a protective water-resistant interior tub. The tub is made of recyclable plastic, adapted for water environments and prevents direct contact between the wood and the flowing water, extending the service life. This concept necessitates a type of plastic that is appropriate for moulding, resistant to harsh weather conditions, and is recyclable, making plastics such as ABS and HDPE suitable options.

The material wood is a local resource that is easy to obtain locally in Sweden. There are also many companies with great expertise in the field, which enables local production and even shorter transportation distances. The wooden parts, which supports the plastic basins from underneath and from the outside, is constructed using wooden frames that are screwed together. The plastic basins are formed by pressing them into shape, and the openings for the fish are cut out. The fact that these are cut out separately, makes it possible to adjust the step height, if needed.

Wood and plastic are relatively lightweight materials, and in this concept each module is divided into three separate parts, making each part easier to carry. This means that the transportation and installation could be done without heavy vehicles, such as crane trucks, which makes it possible to reach places with limited accessibility. A consequence of this is lower transportation costs, not only because of lower vehicle costs, but especially because of less preparatory work. Preparatory work, including for example strengthening of roads to provide accessibility, is related to unpredictable and high costs.



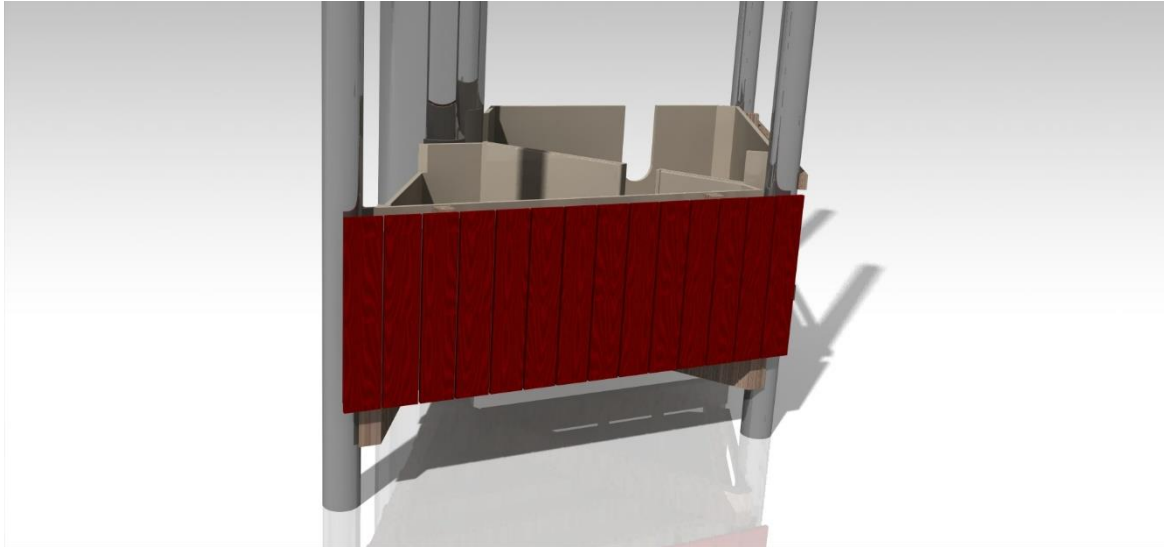
*Figure 34. Assembly of Balder, step by step.*

**Assembly and disassembly:** Each module of the Balder concept is assembled in four steps, that are as follows:

1. Firstly, the supporting wooden bottom-structure is mounted to the inner column and the outer columns with screws.
2. Then, the plastic tub can be placed on top of the wooden bottom-structure.
3. To create a design with detachable modules while also preventing leakage, a rounded sealing strip has been developed, see section 5.2.3 Prototyping & CAD. This sealing strip is slid on from above, securing that the neighbouring modules are kept tight together, making it challenging for water to penetrate the space between the plastic walls. The strip can be constructed from rubber or plastic. However, there remains a risk of minor leakage, so the fish passage should primarily be used during warmer seasons to avoid damage from ice formation.
4. Finally, the wooden frame is mounted on the outside of the structure to provide support for the outer wall of the plastic tub. The inner wall is supported by the inner column, and the side walls are supported by each other because their water volume creates pressure that keeps the side walls stable.

All parts are designed to be attached from one direction, i.e., the outside of the spiral fish ladder. This allows for easy assembly and disassembly of each module.

The appearance of the balder concept can also be customized, as a panel can be added on the outer frame. To match the visual design of the fish passage with the surrounding environment and buildings can be beneficial for example in cultural and historical environments.



*Figure 35. Balder with wooden panelling.*

**Maintenance and repair:** During the cleaning process of the modules, as in the previous design, one can stand atop the structure to clean the upper modules. Access to the remaining modules is facilitated by a ladder. However, a key distinction of this concept lies in the disassembly nature of the system. The modules are designed for individual removal and can be extracted like slices of a cake. This facilitates maintenance tasks such as cleaning with high-pressure washers and conducting repairs.

To remove a module, the water flow is first shut off, and then the outer wooden frame is unscrewed. Subsequently, the plastic basin can be manually lifted out or removed with the assistance of a tractor equipped with forks. If required, the supporting floor can also be disassembled. In the event of damage to wooden components or the plastic basin, these parts can be reordered and replaced without necessitating the dismantling or destruction of the entire structure.

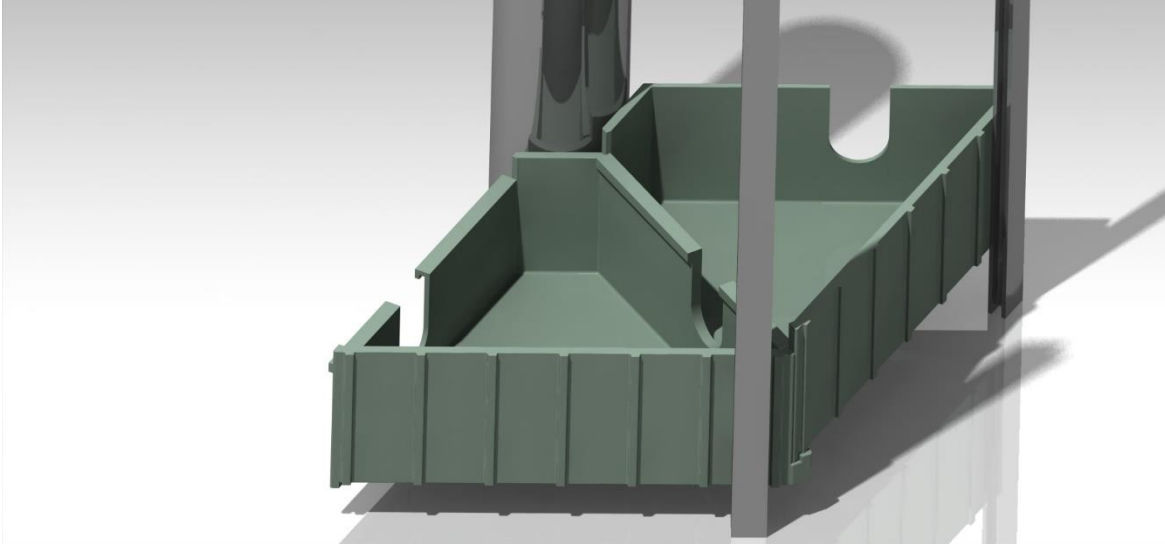
To protect the framework of wood from rain, and the plastic tubs from UV-radiation, a panel on the outside is recommended. If some kind of surface treatment is made to protect the panel, as painting, maintenance is needed according to instructions provided.

**Life cycle:** Since the Balder concept consists of wood and polymer materials, its estimated lifespan is slightly lower than that of the other two concepts. Therefore, repairability and recyclability are crucial in this concept. The parts that require replacement should be recyclable and replaceable to ensure that the overall lifespan of the fish passage can reach 50 years. It is estimated that most parts will be replaced once or twice during this time.

However, the advantage lies in increased adaptability, as this solution is not as enduring as the others. If adjustments are needed, they can be made even after implementation, which can be a positive aspect in terms of lifespan.

## 7.4 Concept Kållerado

In the Kållerado concept, the modules are made from glass fibre composite material, offering the freedom to create more intricate shapes that can seamlessly interlock with each other and with the supporting structure. Kållerado is the concept of great flexibility, light weight and long lifespan.



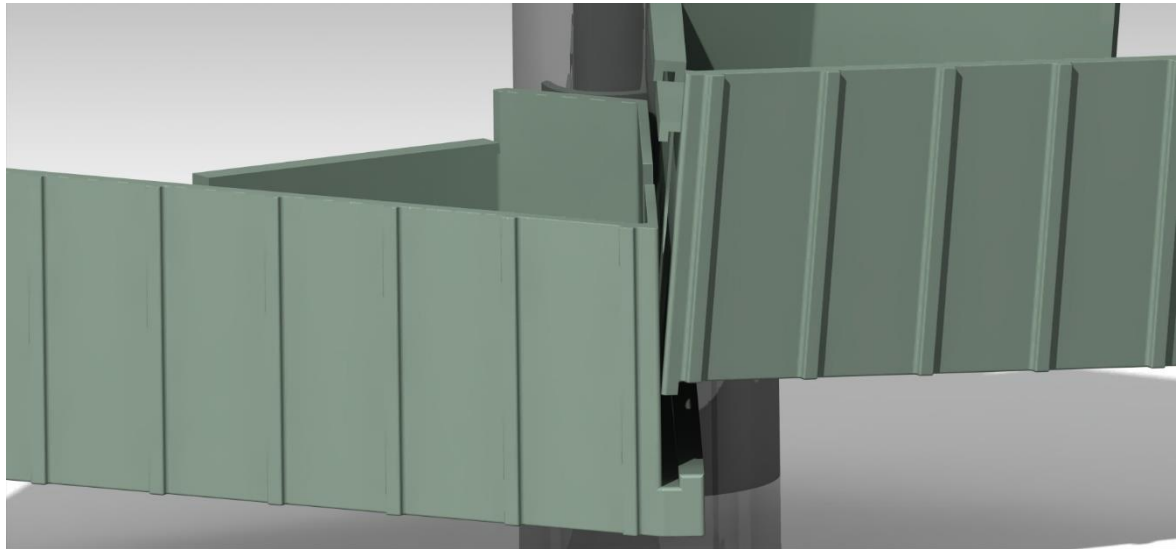
*Figure 36. Two assembled modules with inner and outer columns.*

**Material and production:** Concept Kållerado is made of glass fibre composite in sandwich structure, which gives it good mechanical properties meanwhile reducing weight. However, the sandwich structure complicates the production, and could be reconsidered if proven too expensive. The glass fibre composite material has been tested for the construction of a modular fishway in Piteå, indicating that the material works for this type of application.

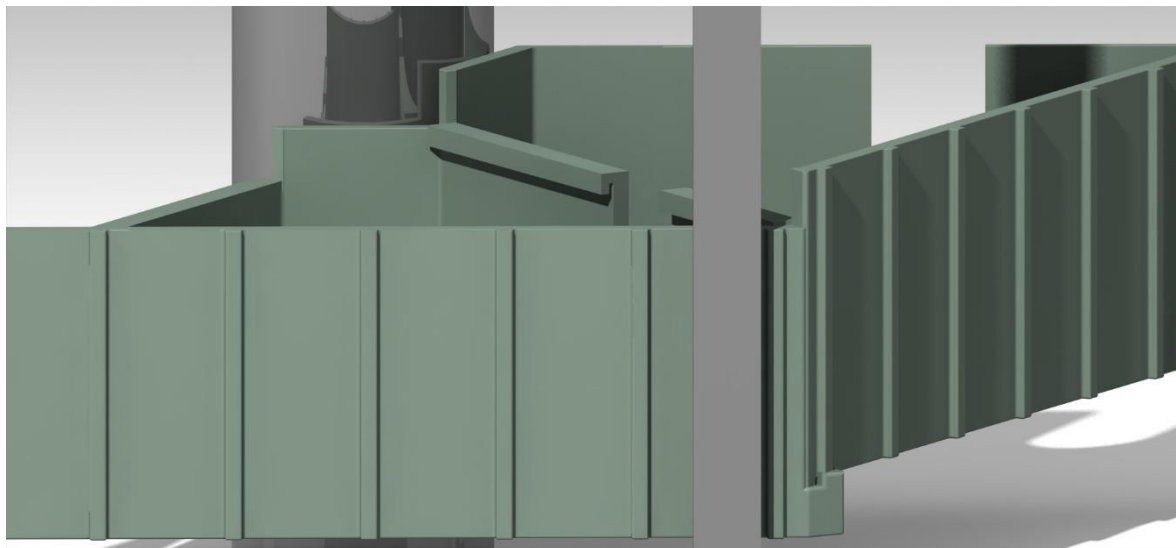
The modules are produced through vacuum injection, advantageously through large production volumes so that the same mould can be used to produce exact replicas. However, unlike wood and concrete, there are fewer suppliers in Sweden capable of manufacturing these types of elements, leading to longer lead times and higher prices. Additionally, the material itself is expensive and the guarantee of a sufficiently large production volume is recommended before developing advanced tools for production.

Nevertheless, if successful, the production method can provide exact replicas with a strong and light structure. The investment for the production tools is probable to be refunded if many modules are sold.

**Assembly and disassembly:** The modules are assembled with a crane and the modules are designed to interlock with the supporting structure and the adjacent module. Each module rests with one outer corner on the outer supporting column and the other outer corner on an edge of the neighbouring module. The inner part of the module rests on the inner column. Together, this creates a load-bearing system where the modules partially support each other, and the supporting structure distributes forces into the ground.



*Figure 37. Assembly of modules.*



*Figure 38. Assembled modules.*

If it turns out that there is a leakage between the modules, sealant will be added onto the edge of each rounded opening. This sealing should be done with aquarium silicone, as this is a sealant made for application in similar environment and does not create harm to fish.

When dismantling the modules, the process begins with dismantling the top module and thereafter a repetitive process proceeds downwards. Bolts and fastenings are loosened, and the modules are lifted off one by one. The dismantling is needed to be done in this order, as each module is carrying its neighbouring module.

**Maintenance and repair:** Maintenance of Kållerado follows the same process as described the general idea. As for Valkyria, it may sometimes be challenging to access the innermost parts of the modules on the lower levels since they cannot be removed and rinsed off at ground level.

The design is crafted to minimize the need for repairs. Since all modules are created using the same tooling and identical assembly of materials, the hope is that wear and tear on the fish passage will

be uniform, making it justified to take down and repair all modules simultaneously. This contrasts with other materials where there is an increased risk of localized weakening, resulting in less uniform wear. If repairs are necessary, however, manual application of glass fibre can be done in accessible areas.

**Life cycle:** The idea behind Kållerado is that the modules should operate in a circular loop. When they need repair or are no longer needed at a specific location, they are dismantled if needed and repaired manually applying new glass fibre composite utilising hand lay-up method. This is estimated to occur multiple times, allowing a module's lifespan, including repairs, to reach at least 50 years. However, damaged modules that cannot be salvaged through repair will be removed from this cycle and be disposed. This is a consequence of the difficulty in recycling glass fibre composite. Research in this area is ongoing, with the hope that too damage modules for reuse, will be possible to recycle in the future. However, the current recycling process is energy-intensive and is not considered feasible at present.

## 7.5 Stakeholder Evaluation

To be able to evaluate the customer value, stakeholders have been asked to provide the study with feedback of the solutions.

### 7.5.1 Survey Hydropower Plant Owners

Twenty owners of small-scale hydropower plants were asked to rank all the concepts on a 1-10 scale in terms of material, function, and price, where findings indicate a diversity of opinions among respondents. See Appendix J for layout and see Appendix K for complete summary of answers.

Regarding the Valkyria concept, proponents highlight its concrete construction, emphasising its stability and long-term reliability. Approximately 50% of respondents rank it above 7 out of 10 in terms of function, but it receives lower ratings for price and material, with environmental concerns being a significant factor. Some suggest that using green concrete could mitigate environmental impacts, although others criticize its aesthetics and compatibility with cultural heritage.

Balder receives mixed reviews, with many respondents appreciating its use of wood but expressing reservations about the plastic components due to concerns about aging, maintenance requirements, and durability. While perceived as initially cheaper, there are concerns that ongoing maintenance costs could outweigh any initial savings.

Kållerado emerges as the highest-rated concept in terms of overall function, attributed to its easy handling and long lifespan. However, the fact that the material cannot be recycled, and the associated manufacturing costs contribute to lower rankings for material and price among certain respondents.

Feedback from respondents regarding all concepts are that several respondents expressed the desire for accessibility and maintenance of individual modules. Opinions were also expressed about

concerns over the strength of the structure and that they would like to see tests to show that the fishway actually works.

In summary, all concepts received a similar ranking and no concept stood out significantly. However, the verbal feedback during discussions provided valuable insights.

### **7.5.2 Evaluation with Industry Representatives**

To gain further understanding, interviews were held with industry representatives. A majority of the industry respondents were in favour for the use of prefabricated concrete modules for the concept Valkyria, agreeing that they should be cheaper than casting on site and that concrete is a well-proven material in fishway contexts. Green concrete was suggested as a sustainable alternative, but concerns were raised about concrete's static nature and difficulty for adjustment if needed. The potential difficulty in accessing modules on lower levels for maintenance was also noted as a potential issue.

Balder was considered to offer a cheaper initial cost but potentially becoming more expensive in the long run due to its shorter lifespan compared to other options. Wood was mentioned favourably but recommended for components that can easily be replaced.

Kållerado was evaluated to have good potential, but with the drawbacks of higher initial cost due to the expensive manufacturing of modules in glass fibre composite.

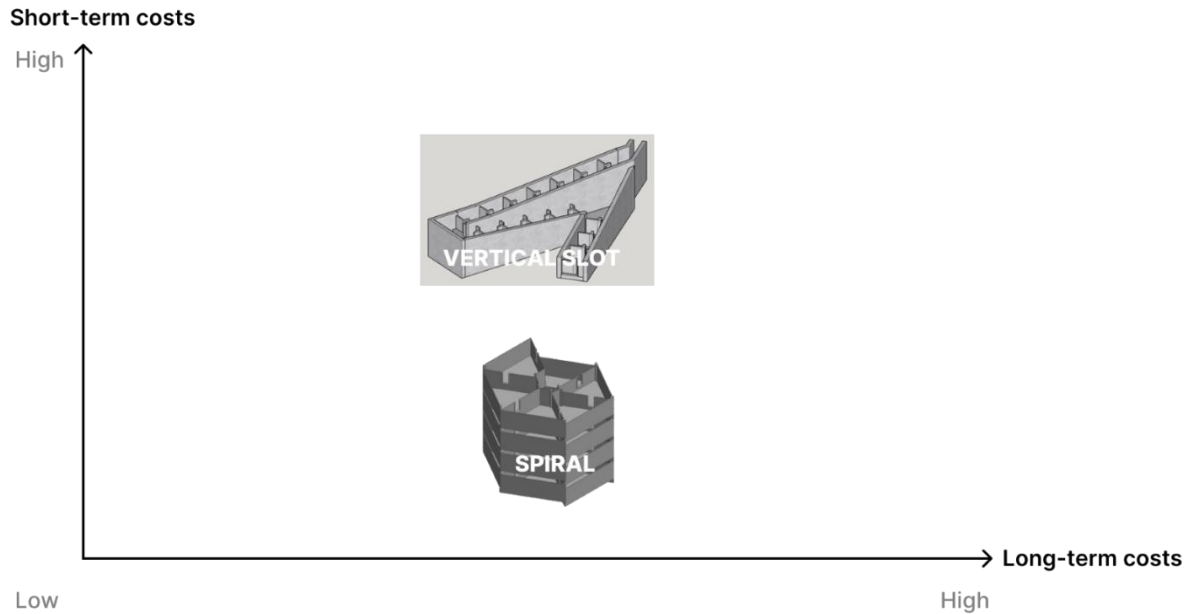
Opinions regarding all concepts emphasize the importance of testing and follow-up. Sufficient data must justify that the solution can be considered as the "best available technology". All representatives mention that the pre-construction cost of the fish passages is a major cost driver. Therefore, minimizing the need for pre-construction work, such as avoiding rock blasting and large foundations, is crucial for keeping costs low. The fact that the fish ladder requires little space is therefore seen as positive in this respect.

All representatives consider a water flow of 70 l/s as low, and some mentioned that at least 5% of the total water flow is necessary to attract fish. While the issue of attraction and the importance of functioning inlets and outlets are acknowledged as crucial, they are deemed beyond the study's scope. However, they are recognized as significant points for future discussion and development.

The consideration of sustainability in such projects often revolves around connectivity and biodiversity. Participants appreciate that environmental sustainability aspects related to manufacturing and materials are considered. Moreover, all agree that the maintenance solution shows promise. They appreciate its design allowing for work from above, which enhances the working environment and safety measures.

## **7.6 Cost Evaluation**

The following section first presents a cost comparison of a modular fish ladder in modular principle compared to a vertical slot fish ladder through short- and long-term costs followed by a cost comparison of developed concepts.

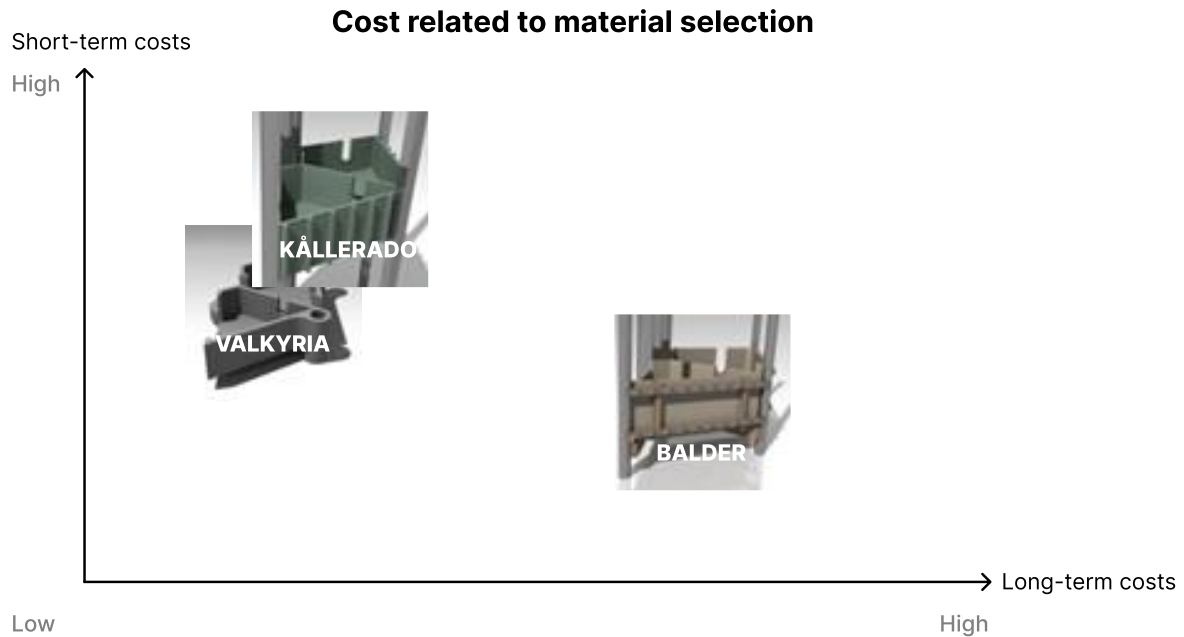


**Figure 39.** Long and short-term cost comparison spiral shaped fishway and a vertical slot fishway.

An exact assessment of costs is not feasible at this stage, as it necessitates a more developed design to calculate material usage and subsequent manufacturing expenses. By employing material price indices and drawing insights from past projects, rough estimates can provide an indication of the cost scenario for a modular spiral fish ladder.

Pre-construction costs have been identified as a significant cost driver, indicating that the pre-construction expenses for a spiral fish ladder are likely to be lower compared to those requiring more space, which typically entail more blasting and casting work. The inherent space-efficiency of the spiral fish ladder design minimizes the need for extensive groundwork, thereby substantially reducing these costs. With fixed pricing per module and supporting columns, predicting initial costs is easier compared to constructing a fish ladder tailored to specific site conditions.

Regarding long-term costs, these assumptions primarily rely on estimated lifespans, with material quality playing a crucial role in assessing expected durability. Since it's not feasible to determine on a general level how the long-term costs differ, they are assigned an equivalent.



**Figure 40.** Long and short-term cost comparison of developed concepts.

Figure 40 concerns evaluation related to materials as it is too early to make a more precise evaluation of the total cost of each concept. It is not possible to take into account site-specific conditions such as accessibility, soil conditions and the need for preconstruction work.

When comparing the costs associated with the developed concepts, it appears probable that Kållerado and Valkyria will incur higher short-term expenses than Balder. This is because of higher costs related to materials, production and accessibility need for heavy vehicles. Balder has a shorter lifespan and entails costs for repair and replacement of modules in the long run. Kållerado, with the option of repairing modules through hand lay-up, resulting in slightly higher long-term costs than Valkyria. However, both Valkyria and Kållerado have a long-life expectancy and can therefore be considered a better long-term investment.

Concrete offers a cost advantage over glass fibre composite; however, it necessitates larger module dimensions, resulting in increased material volume. Moreover, reinforcement is essential for strength, adding to both cost and weight. What can be said is that Valkyria involves heavier and larger modules, which entails more expensive additional costs of foundation work and transport. Heavier modules require heavier cranes and larger work routes. It is therefore difficult to estimate which of these will be cheapest in purchase price, but after dimensioning and quotation from the supplier it can be estimated with better accuracy.

The material and manufacturing costs of modules are influenced by series size, as prices per module can be lowered for larger production volumes. The perception of glass fibre composites having a high initial cost primarily stems from past projects where glass fibre was not selected due to pricing considerations.

Wood and plastic have a lower purchase price than concrete and composite can therefore result in a cheaper fish ladder initially. It should be noted, however, that the manufacture of wooden structures and plastic modules can be manual and time-consuming, which affects the short-term cost.

Another influencing factor is the competition among manufacturers. When there are numerous potential manufacturers, prices can be driven down. Additionally, finding local suppliers can help reduce transportation costs.

To summarise, it can be concluded that there is potential for a spiral-shaped modular fish ladder to entail a lower investment cost compared with the alternatives on the market. Of the three concepts developed, Balder is a cheaper short-term investment but is likely to be more expensive in the long run compared to Valkyria and Kållerado. The total cost will vary depending on specific site conditions, and the most cost-effective concepts developed may vary accordingly. To obtain more accurate cost estimates, it is necessary to dimension the respective designs and then discuss manufacturing, obtaining quotes from manufacturers.

## **7.7 Maintainability & Reparability Evaluation**

To evaluate maintenance, real scale testing is required. Constructing a prototype at full scale allows for evaluating accessibility, particularly in terms of module cleaning. Feedback from experienced maintenance personnel underscores the necessity of individual module accessibility for maintenance and inspection purposes. They noted that the 30 cm distance between each floor might hinder access to clear modules of accumulated debris, suggesting a need for testing and potential adjustment.

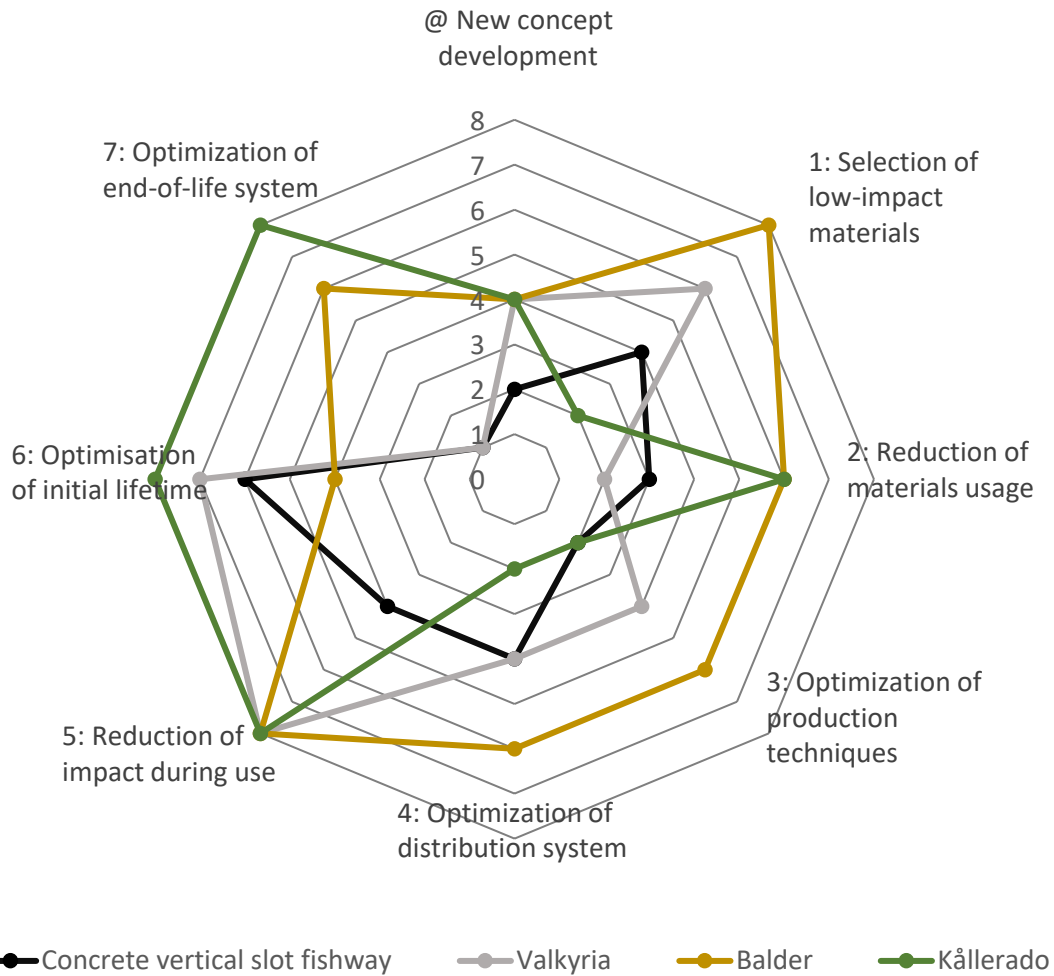
The proposed maintenance solution for all concepts has garnered positive feedback from the industry, as it facilitates safe and accessible clearance of the most exposed modules. Balder, designed to permit removal of all modules, offers a significantly more flexible design, thereby enhancing maintenance and repair capabilities compared to the relatively static designs of Valkyria and Kållerado.

Compared to a traditional notch weir, regular maintenance is assessed as simpler and safer, as maintenance personnel can stand on a platform above the water level when performing maintenance. It becomes easier to access when there is a flat surface to stand on, and it is straightforward to get an overview of maintenance needs when looking down into each module from above. However, maintenance becomes significantly more challenging with the spiral-shaped principle, as it is more complicated to reach, and there is a safety risk associated with performing cleaning work from a ladder.

## **7.8 Environmental Sustainability Evaluation**

The tool used to facilitate the comparison of both concepts was the LiDs Eco Design Strategy Wheel. This not only compared the concepts to each other but were also to a traditional concrete vertical slot fishway. Below is a graph of the LiDs Wheel for this study, followed by comments for each category in the evaluation. The template for the tool can be found in Appendix L.

## LiDs Ecodesign Strategy Wheel



**Figure 41.** Comparison of the environmental sustainability of developed concepts versus a concrete vertical slot fishway.

**1. Selection of low-impact materials:** Since Valkyria is made of green concrete, it has a lower environmental impact than an ordinary concrete fishway. Balder is constructed from wood, a clean and local material, as well as recyclable polymer. Kållerado, on the other hand, is made from high-impact materials that are difficult to recycle and require a lot of energy.

**2. Reduction of materials usage:** As Valkyria is prefabricated the weight is lower than wet concrete (as it consists of less water) but needs bigger dimensions than the other concepts need to carry the load and give place for reinforcement net. Balder is light, and the bearing structure of wood is not solid, which lowers its volume. Kållerado is probably the lightest concept with the smallest volume.

**3. Optimization of production techniques:** A drawback of the traditional technical fishway is the extensive pre-construction work required. In contrast to Valkyria, which utilizes the same mould for each casting, new moulds need to be created for each moulding. Additionally, Balder's use of two separate materials necessitates more production steps. The production of the plastic tub is

particularly critical for production optimization, as the wood skeleton can be produced with "clean production" methods. Kållerado consumes energy during the manufacturing process, but the same tools and moulds can be utilized for every module.

**4. Optimization of distribution system:** Concrete is heavy, and Valkyria requires a large transportation volume, exceeding that of a traditional concrete fishway made on-site, as the prefab elements contain cavities inside each module. Balder comprises two separately produced parts, which might lead to less efficient transportation. However, this may not be an issue, as the tub parts can be designed for stacking, and the wood skeleton parts can be delivered in flat packages. In contrast, the Valkyria cannot be stacked and is produced at one or a few locations in Sweden, resulting in long transportation distances.

**5. Reduction of impact during use:** The spiral formed fishway is designed for a waterflow of 70 l/s, which is very low in relation to traditional fish passages. If the concepts' function succeeds, with such low flow, that would be a great success for the energy consumption, as the water then can produce energy in the hydropower station instead.

**6. Optimisation of initial lifetime:** The vertical slot fishway is a classic design, but even if considered tried and tested, it is always adjusted for local conditions, which makes it difficult to guarantee its function in advance. The modular fishway however has the same dimensions for every case, which makes it easy to evaluate its function in advance, if the direction and amount of entering water is correct. The three concepts are achieving long lifespan in different ways: Valkyria focuses on long lifespan, Balder focuses on reparability, and Kållerado focuses on long lifespan and reuse of modules.

**7. Optimization of end-of-life system:** The concrete designs are not optimised for their end-of-life system since they are difficult to both reuse and recycle. Balder is made for recycling and Valkyria is made for reuse, which is valued higher than recycling.

**@ New concept development:** This includes dematerialisation, shared use and functional optimisation. The new design could be integrating a system for fish detection/counting and other measurement systems and could be optimised for water use and optimisation of fluid dynamics, to create low turbulence areas for the fish to rest.

# 8

## Discussion

**Chapter 8.** This chapter discusses the various aspects of the study, focusing on the stated research questions and results. It is divided into two parts: the first phase, Discover and Define, and the subsequent phases, Develop and Deliver.

## 8.1 Discover & Define

Numerous challenges, opportunities, expectations, and needs concerning fishways for small-scale hydropower plants have been identified, revealing a multifaceted problem landscape. Through broad examination, interviews, and analysis, the problem space was discovered and defined.

However, it's important to note that our site visits were limited to sites within Västra Götaland and Halland during early spring, which may not fully represent the conditions across Sweden and throughout different seasons. This limitation could have influenced our understanding of the prevailing conditions.

Furthermore, the rarity of sites equipped with fishways underscores the importance of visiting more locations for a comprehensive evaluation. This would enable us to draw more definitive conclusions, including insights into the accumulation of debris. Although relatively few fishways were visited in comparison to the number of hydropower plants and dams there are, we believe the conclusion regarding that accumulation of debris as an important issue to address, is justified. Previous studies and interviews confirm that the accumulation of debris is common in both fishways and gratings.

During the Define Phase, weighting expectations at a high level in the Pairwise Matrix against each other, was proven challenging. It was discovered that certain expectations, such as respecting regional values and enable connectivity for fish, were fundamental and therefore difficult to weight against each other. Therefore, when ranking needs with respect to different scenarios, basic needs were not weighted but considered as requirements, not possible to de-prioritise. The tool used for this was Club Design. Unfortunately, this tool was implemented in a later state of the study, when the process was already outlined. This affected the use of Club Design and limited its strength of creating value by systematically following the problem from stakeholders' expectations to a simulation of the value creating strategy in relation to each design. Instead, this study used the rankings in each Value Creating Strategy to compare the design suggestions in a Kesselring Matrix. Even though this was not resulting in a simulation, the study followed the problem from the stakeholders' expectations to a ranking of the concept. The use of Club Design was still of great value.

Another part of the Define Phase was the size of series-estimation, where calculations and assumptions needed to be made. The first part of the calculations was based on 378 reported values for waterfall height and/or dam height of the neighbouring dam. As the dataset consisted of many data points, conclusions drawn from this calculation are considered credible. However, the second part, based on reviews supported by The Fund and submitted to the Environment Court in 2022, only 10 cases were analysed in detail. Additionally, some of the documents lacked information on target species. The statistical estimations made for calculations of series size with respect to each scenario are therefore consisting of big uncertainties. Before using these values, they were discussed with experts at Sweco. The series size for temporary solutions was not calculated at all, as it was considered that no justification for conclusions existed.

The Discover and Define phases of the study aimed to address research question 1 “What problems, opportunities, needs and expectations are associated with fish ladders adapted for small-scale hydroelectric power plants?”. While acknowledging the existence of additional layers of challenges,

opportunities, expectations, and needs, this study has identified many of them. The results from the Discover phase, compiled in Define phase, have been repeatedly confirmed through interviews and literature review, which enhances the credibility of the findings. Therefore, we believe that Research Question 1 has been addressed in this study.

## 8.2 Develop & Deliver

The Develop phase of the study consisted of many ideation methods with a broad range of resulting ideas, on different levels. To concretise this, conceptual ideas that are a combination of several sub-solutions were presented in section 5.3. However, this method resulted in a difficult comparison and assessment of the concepts, where the impression of many sub-solutions resulted in an overall rating. To not neglect good sub-solutions, the motivation of the ranking was analysed. During redesign and refinement of the final concepts, solutions for sub-functions with high potential could be combined to provide a more optimal design.

The developed design has not been further developed with regards to the needs of the fish, as this was addressed by Sweco. Opinions related to the function of the fishway, especially the design of the inlet, outlet and step height, varied widely during the evaluation, which underscores the need for further iterations and test of the design to ensure that the needs of target species are met.

Initially, the goal was to develop one final concept in detail. However, as the development is at such an early stage, it was deemed more value-adding to generate additional concepts with lower levels of detail to enable multiple choices. This could for example be valuable when new parameters and test results are added as the project progresses, or if future outlook brings changes in scenarios. For example, we envision a potential scenario where a spiral-shaped fishway could be combined with a natural-like fishway, thus increasing the expected series size. Nevertheless, such conjectures need to be further analysed.

To summarise, the stakeholder needs have been a common thread throughout the whole project. The Value Creating Strategies were used to further assure that the delivered designs were in accordance with these needs. Research Question 2 “How can the proposed solution be designed and optimized to align with the stated needs?” is therefore considered addressed in the study.

Testing, as well as monitoring and follow-up, is vital for a fair evaluation of cost-effectiveness, maintenance, and environmental sustainability. While the evaluation has been conducted at a general level, providing an indication, supplementation is necessary for a more equitable evaluation.

For environmental sustainability, an in-depth life cycle analysis (LCA) would have been beneficial. An LCA was not conducted, as a reliable execution demands considerable expertise and time. Although the maintenance solution has received positive feedback, evaluating the effectiveness of the maintenance solution remains uncertain. In cases where branches or similar items become lodged in other modules, accessing and cleaning all modules, despite the chosen material and design, may prove challenging due to their spiral configuration. User test with maintenance process would also have been beneficial, if such recourses would have been accessible during the period of the study. This monitoring should span over at least one year, preferably longer, to account for varying levels of organic material accumulation over different seasons. Finally, to evaluate costs, cost

quotations would need to be obtained from different companies based on dimensions and estimated series size.

Even though all above-mentioned in-depth evaluation methods would have been beneficial, evaluation has still been made in relation to cost-efficiency, maintainability and environmental sustainability. The results of this evaluation, presented in Chapter 7, is a result of literature studies and discussions with experts, making the findings both relevant and interesting for future development.

To summarise, there are needs outside the scope of the study, that cannot be guaranteed fulfilled, as they have not been further investigated. Also needs within the scope are considered insufficient tested, as in-depth studies and long-term follow-up is needed to fully evaluate these terms. However, as Research Question 3 is stated “How can the solution be evaluated in terms of cost-efficiency, maintainability, and environmental sustainability?” this research question is considered addressed, as the study involves both a basic evaluation and further evaluation recommendations.

# 9

## Conclusion & Recommendations

**Chapter 9.** The upcoming chapter will provide conclusions and recommendations for future development. It will begin with recommendations for the design firm, followed by recommendations for implementation in Hultafors. Next, it will present general recommendations for the County Administrative Boards, and finally, our recommendations to The Hydroelectric Environmental Fund.

## 9.1 Conclusion

This study concludes that there's a significant demand in Sweden for cost-effective and efficient fish passage solutions for small-scale hydroelectric power plants. The main cost factors identified are pre-construction work and custom design for each plant. The study focuses on a spiral-shaped principle, thus occupying a limited area, which has been assessed as both cost-effective and desirable in space-constrained locations. Additionally, modular design can aid mass production, further reducing costs.

Design functionality relies on well-dimensioned structures and efficient maintenance, favouring debris diversion before reaching the passage as well as easy cleaning of the top modules, considered most critical. Sustainability considerations highlight the importance of lifecycle-based design, with three final design concepts addressing either long lifespan, recyclable and low-impact materials, or repairable designs.

Extensive testing and design iterations, including inlet and outlet configurations, are necessary to attain the status of best available technology in intended contexts. However, if this type of fish passage is proven effective, it has great potential to create cheaper and less space-consuming passages for future hydropower plant owners. Complemented by the most promising concept of modular units in this study, customized to meet stakeholder needs, the resulting solution is likely to offer increased value to customers.

## 9.2 Recommendations for Further Development

Further development is necessary to enable implementation in Hultafors and other locations where the spiral-shaped fish passage is deemed a suitable option. Recommendations to achieve this are described in the following section.

### Recommendations to Design Firms, such as Sweco:

1. **Test Fluid Dynamics and Turbulence:** Develop a prototype to ensure that the flow is adapted to fulfil the needs of the target species, that turbulence does not prevent fish from passing and that there are resting places for fish during their migration through the fishway.
2. **Bottom Structure Enhancement:** Further develop the bottom structure of the modules, potentially creating ramps, to allow passage for weaker-swimming and bottom-oriented species.
3. **Field Testing with Full-Scale Prototype:** Test the prototype and associated measuring equipment in the field. Design the prototype with a structure and materials, such as wood, that allow for easy redesign and adjustments if needed.
4. **Development of a Surface Water Grid:** Further develop a surface water grid for collecting and redirecting surface debris to prevent it from entering the fish passage. Test maintenance accessibility and ergonomics from platform and ladder.
5. **Manufacturing Methods and Quotes:** Investigate appropriate manufacturing methods and gather quotes from potential suppliers based on estimated production volume.

6. **Site-Specific Adaptations:** Adapt the inlet and outlet for each specific site based on the conditions and the amount of water needed to attract fish.
7. **Pilot Projects Implementation:** Implement pilot projects with measuring equipment to evaluate the solution's long-term functionality. Collect data about maintenance need and follow up the maintaining persons' experience of the solution.

### **Recommendations to Intea/Sweco Regarding Hultafors in Particular:**

1. **Target Species Needs Analysis:** Investigate if the test results from the laboratory align with the needs of the target species in Hultafors.
2. **Groundwork Assessment:** Investigate the site's groundwork requirements.
3. **Transportation and Installation:** Accessibility at the site is crucial for the choice of transport and installation process.
4. **Adjustable design:** The full-scale prototype should be built in a material that can be adjusted, preferably wood, so that customisation can be done to ensure that the design works optimally.
5. **Solution Implementation:** After testing and adjusting the design, a decision should be made on which material the final design should be built in. The design firm makes a final drawing which is sent to the supplier for production.
6. **Follow-up and measurement:** Install measurement equipment at the same time as the fish ladder is instrumented to monitor passage efficiency.

### **Recommendations to the County Administrative Boards:**

1. **Innovation and Testing:** Utilize new knowledge and embrace innovations, while not underestimating the importance of testing solutions in the lab and on-site, as well as following up on the solution's success.
2. **Define "Best Available Technology":** Clearly define "best available technology" and consider parameters such as passage-efficiency, cost-efficiency, maintainability, and environmental sustainability of the solution.
3. **Economic Considerations:** Consider the size of the hydropower plant when proposing a solution, to ensure that both the short- and long-term investment is affordable. Also consider the importance of that The Hydroelectric Environmental Funds capital should last for as many environmental adaptations as possible.
4. **Data Recording and Analysis:** Systematically record data from fishway implementation and follow-up, making it possible to analyse this data and draw valuable conclusions.

### **Recommendations to The Hydroelectric Environmental Fund:**

1. **Further Development Funding:** Allocate economic resources to investigate the further development of cost-efficient and sustainable solutions, ensuring the funds' capital lasts for more environmental adaptations.
2. **Utilize Network Expertise:** Use expertise within the network to inform the design process of new solutions.
3. **Promote and Communicate Promising Ideas:** Utilize the existing network to communicate promising ideas, thereby spreading knowledge. If more hydropower plants and dams can utilize the same design, producing more modules will reduce the price per unit for larger volumes.

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# Appendix

## Appendix A – Fish Migration

### Migrating Fish

Connectivity implies that individuals can transport themselves between habitats. Fish migrate both within a river or from a main river or lake to a tributary or vice versa. For fish, connectivity is mainly longitudinal, which without natural migration barriers means they can move freely upstream and downstream. 23 of 46 known Swedish freshwater fish species in Sweden 2013, were defined as migratory (Swedish Agency for Marine and Water Management, 2020)

The Swedish Agency for Marine and Water Management (2013) states in their report about fish migration that many species of fish, including salmon and trout, are dependent on habitats in streams. Improved food supply, reproduction, and physical conditions are examples of the driving forces that result in fish migration. A common life cycle pattern for these fish are the following: the fry comes to life at its birth habitat in the river, the fish undergoes its first growing phase in another habitat, the fish migrate to lake, sea or lentic environment, and finally, when the fish is sexual mature it returns to its birthplace to reproduce. However, the migration is not limited to the spawning periods, but occurs at other times of the year as well. (Swedish Agency for Marine and Water Management, 2013)

There is a geographical variety of what kind of fish species that are expected to migrate in a specific water. Fish species, also vary in many ways such as time of migration, and direction of migration (Näslund et al., 2013).

### Strong and Weak Swimming Species

The swimming speed of fish depends mainly on species and size and can be defined with different measurements. The speed of fish is often defined by how long the fish can maintain a certain speed, e.g., sustainable, critical and burst speed, before it becomes exhausted (Brett, 1967).

In general, species with a salmon or roach-like shape have a better swimming capacity than species with a slightly flattened body. High motivation and swimming capacity makes salmon pass many fish passages (Bunt et al., 2012), but to pass efficiently salmon needs 2-2,4 m/s in water speed and sufficient space (Larinier, 2002). Katopodis & Gervais (2016) study reveals that the critical swimming speed can also be influenced by water temperature as a fish has a stronger swimming capacity at warmer water.

Eel needs to be given extra consideration as it utilises freshwater as a breeding ground and is listed as critically endangered in the Swedish Red List. Regarding requirements for passage solutions, the eel differs from most other species. For example, eel migrate upstream as juveniles, grow in freshwater, and then migrate downstream as adults. The juvenile eel travels upstream using the structure and low speed of the bottom, as its swimming capacity is low. (Calles et al., 2021)

With many target species, this can be a challenge because some species are strong swimmers and are attracted to strong currents, while other species that are weak swimmers may have problems travelling in such environments.

### **Needs and Requirements of Fish**

For the migrating fish to feel safe and be able to manoeuvre, the space requirements for different species, in terms of depth, width and length, need to be considered. Following measures could be used as a general guiding rule:

- Depth should not be less than 2.5 times the height of the fish.
- Width should be at least 9 times the width of the fish.
- Length at least 3 times the length of the fish.

These are sourced from the Marine and Water Agency's annex on fish information and target species (2020).

### **Time of Upstream Migration**

The Swedish Agency for Marine and Water Management's guidance for fish and wildlife passages on fish information/target species states that time of migration depends, not only on species, but also the life stages of that particular specie. Most species of cyprinids, perch, grayling, and roach migrate upstream in the spring and most salmonid spawn in October to November but can start their upstream migration in connection with the spring flood.

The need of this non-traditional migration time is unclear and is likely to differ between populations. However, migration times for species that are dependent on migration to complete their life cycle, are often synchronized. Because metabolism and swimming capacity are affected by water temperature, fish are generally less likely to migrate in winter, with a few exceptions (Katopodis, 2016).

The time of migration is important to consider, as winter conditions involves requirements of ice loads and bursting forces due to ice formation.

### **Water Velocity**

Creating the right water velocity is important in a fishway to make passage possible. The water velocity is naturally lower at the bottom and near the edges, and the more structure, the more the water is slowed down. In order to enable passage for even the smallest and weakest swimming species, there must be continuous sections with lower velocities, maximum 0.2 m/s. One single section where the velocity is then too high for weakly swimming species, is sufficient for the whole passage to remain a migration barrier (Degerman, 2008).

To accommodate both weak and strong swimming species, areas of low water velocity and water velocity are needed. Examples of modifications made to enable passage of small fish, eels, and insects in fishways include adding structure to the bottom, reducing the difference in level between pools, and reducing the size of the pool which reduces the size of swirls (Larinier, 2008).

### **Attraction Water**

Attraction water refers to the flow of water necessary to attract and guide fish towards the entrance of the fishway for successful passage. The ability of fish to locate and navigate towards the fish passage is crucial; even with a functional fishway, insufficient attraction water renders it ineffective. At large and wide hydropower plants, this presents a significant challenge, as the flow within the fish passage constitutes only a fraction of the total flow, making it challenging for fish to locate it. Calles et al. (2013) suggest as a guideline that the attraction water should be at least 5 percent of the total water flow and should increase proportionally with periodically increased flows. Furthermore, research is dedicated to investigating additional factors influencing attractiveness, such as sound, scent, and turbulence (Swedish Agency for Marine and Water Management, 2020).

# Appendix B – Existing Patents

In this section presents a summary of the most interesting patents, in relation to a spiral formed, modular fish ladders. Most used IPC-category in the patent research were IPC E02B8/08, which is an international patent classification for “Fish passes or other means providing for migration of fish; Passages for rafts or boats”.

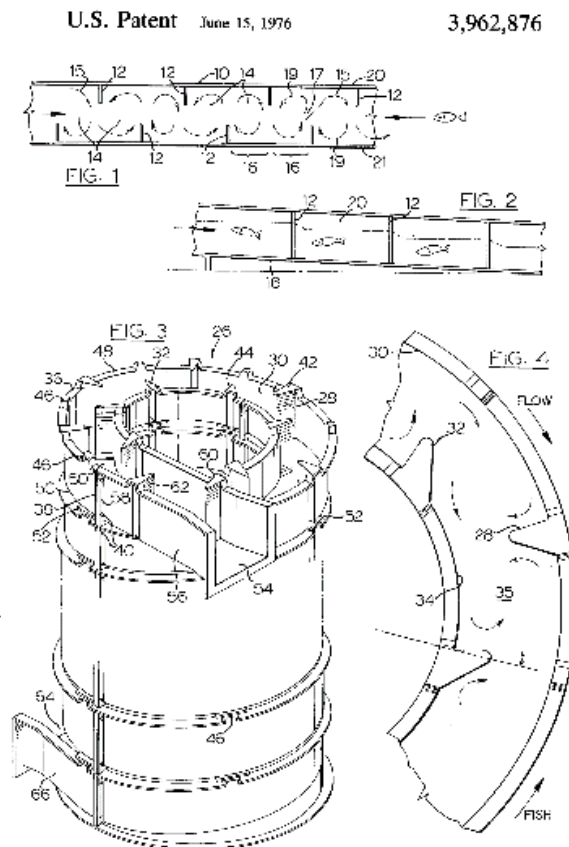
To find European patents, the patent search site Espacenet (European patent office) was used. The patent search within IPC E02B8/08 and inclusion of the words “spiral” OR “helix” OR “module” in title, gave 30 results, whereas the following patents were considered most interesting:

## US 3962876A Fishway

**Applicants:** Aeroceanics Fishways Corp

**Inventor:** Phillips Adrian

A fishway consisting of a channel for upstream migration of fish. Could be straight or formed as for example a helix. (Phillips A., 1976)



*Figure B1. Fishway (Phillips A., 1976)*

**EP 3231942A1 Fish Ladder (PRV-published as SE 3231942T3)**

**Applicants:** Vandezande Aquatem GmbH

**Inventors:** Zeiler Georg; Flach Bernd

A devise for upstream and downstream passage through a three dimensional spiral. In the description it is mentioned as space-efficient, cost-effective, and technically simple. This patent can also be found on the PRV database and is therefore specifically important to consider. (Zeiler & Flach B, 2017)

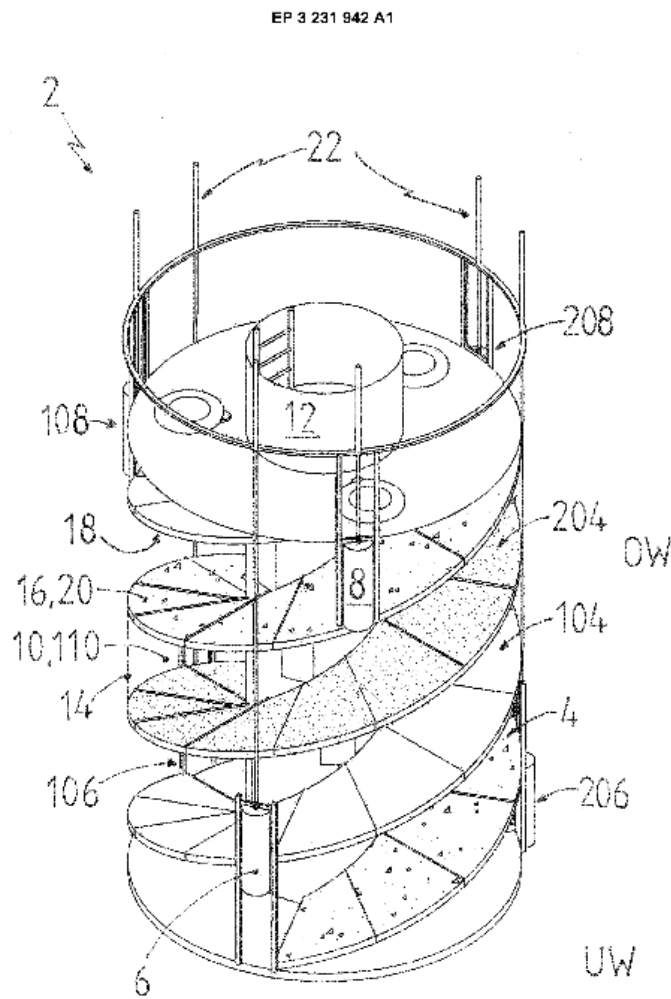


Fig.1

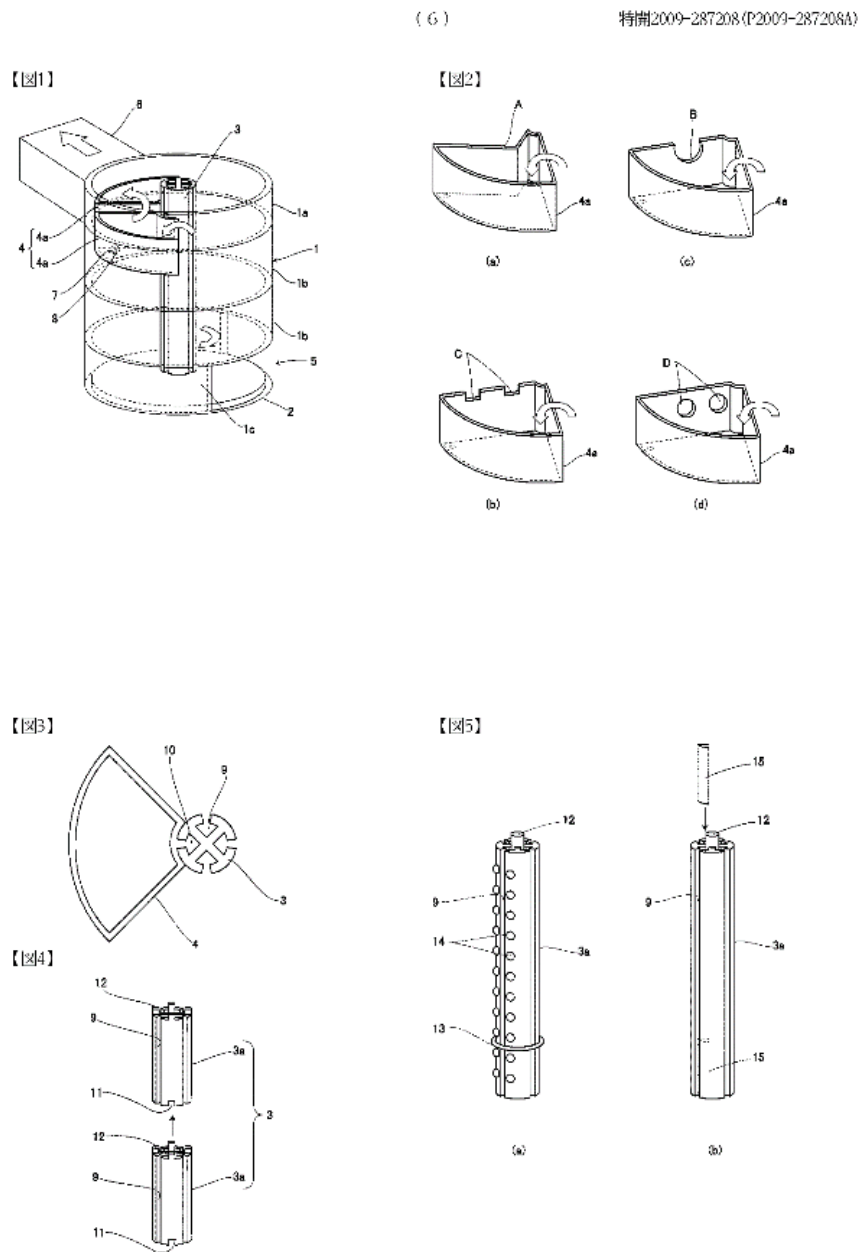
**Figure B2.** Fish ladder (Zeiler & Flach B, 2017)

**JP 2009287208A Spiral Fish ladder**

**Applicants:** Univ Niigata

**Inventors:** Arita Hiroyuki

A fish pass that is easy to install and does not require much space. Units are assembled in a central column. (Niigata, 2009)



**Figure B3.** Spiral Fish ladder (Niigata, 2009)

**JP2000352040A SPIRAL FISH WAY STRUCTURE**

**Applicants:** Ohbayashi Corp

**Inventors:** Hosono Seiichi; Okamoto Hideyasu

Spiral formed fishway created by fan-shaped fishway blocks. Design that, according to descriptions, provide a quick and easy assembly. (Ohbayashi C., 2000)

!(4) 000-352040 (P2000-352040A)

- 【図4】(a), (b)は本発明による魚道ブロックの平面分解図及び組立て平面図である。
- 【図5】(a), (b)は同分解斜視図及び組立て視図である。
- 【図6】図5(b)のA部を拡大して示す説明図である。
- 【図7】同魚道ブロックを1螺旋ピッチ分積層して組立てた状態を示す平面図である。
- 【符号の説明】
- 20 魚道ブロック
- 20a 中心穴
- 22, 24 分割ブロック
- 23 接合面
- 26, 32 底板
- 28 内壁部
- 30 外壁部
- 36 設置部
- 38 位置決め孔
- 40 位置決めピン
- 44 コッター用溝穴
- 46 コッター
- 48 目地

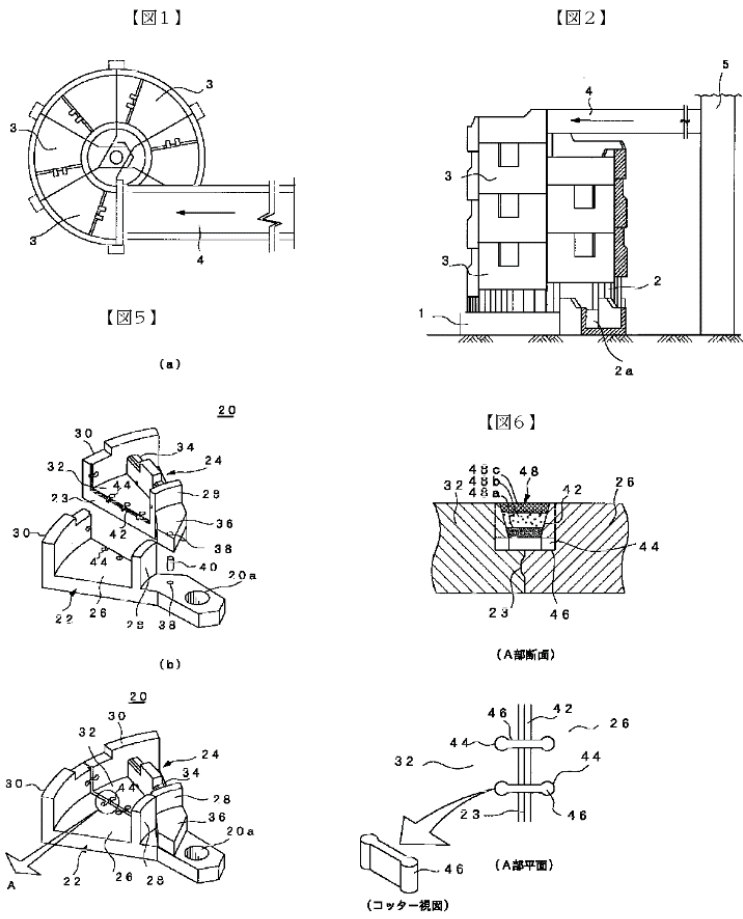


Figure B4. Spiral fishway structure (Ohbayashi C., 2000)

# Appendix C – Pairwise Comparison Matrix

Different expectations are compared, and, in this comparison, they are given values of 0 or 1. 0, if not prioritised over the other expectations, or 1, if prioritised over the other expectation.

*Table C1. Ranking of expectations through a one-to-one comparison.*

	Optimal connectivity is enabled for fish	Same design can be sold to many customers	Design is easy to produce	Design is easy to install	The investment is affordable	Design is reliable	Design is easy to maintain	Design respect local values	Design respect regional values
Optimal connectivity is enabled for fish		0	0	0	1	0	0	0	1
Same design can be sold to many customers	1		0	0	1	0	0	0	1
Design is easy to produce	1	1		0	1	1	0	1	1
Design is easy to install	1	1	1		1	1	1	1	1
The investment is affordable	0	0	0	0		0	0	0	1
Design is reliable	1	1	0	0	1		0	1	1
Design is easy to maintain	1	1	1	0	1	1		1	0
Design respect local values	1	1	0	0	1	0	0		1
Design respect regional values	0	0	0	0	0	0	1	1	
<b>SUM</b>	<b>6</b>	<b>5</b>	<b>2</b>	<b>0</b>	<b>7</b>	<b>3</b>		<b>5</b>	<b>7</b>

# Appendix D – List of Requirements

Table D1. Final list of requirements and Requests.

Stakeholder Needs	Criteria	Requirement / Request
<b>Enable targeted species to pass</b>	Sufficient dimensions to manoeuvre	Requirement
	Sufficient attraction water to find fishway	Requirement
	Sufficient water flow to fulfil passage of fishway	Requirement
	Design can easy be connected to the inlet and outlet	Requirement
	Placement of inlet is easy for fish to find	Requirement
	Step height meets requirements of targeted species	Requirement
<b>Avoid harm to fish</b>	Lightness/darkness in fishway is comfortable for fish	Request
	Noice in fishway is comfortable for fish	Request
	Turbulence in fish passage is not causing stress to fish	Request
	Fish does not risk being injured in fishway	Requirement
	Fishway does not increase the risk for fish to be attacked (by for example birds)	Request
	Fish does not risk falling out of fishway	Requirement
<b>Possible to count fish</b>	Fish camera/measurement equipment is possible to install	Request
	Data from camera is possible to access	Request
	Accessed data is possible to analyse	Request
<b>Adaptable to different hinder heights</b>	The design is modular	Requirement
	Different number of modules result in different heights	Requirement
<b>Possible to install in varying site conditions</b>	Limited groundwork is needed	Request
	Design is space efficient	Requirement
	Implementation process follows regulations and guidelines for dam safety	Requirement
	Design does not require heavy transport vehicles	Request

<b>Reliable resources for production</b>	The design can be customised for manufacture in several suitable materials	Request
	The availability of the material is guaranteed	Request
	Manufacturing technology is proven effective	Request
	Available manufacturers located in Sweden	Request
<b>Scalable production method</b>	Standardised sizing	Requirement
	Scalable packaging and logistics	Request
	Design has few components	Request
<b>Efficient installation process</b>	Groundwork can be done efficiently	Request
	No heavy and large transport vehicles are required for installation	Request
	Installation time is short	Requirement
	Design has error-proofing features	Request
	The design is developed for intuitive installation process	Request
	Clear feedback of success or failure during installation	Request
	Design has few components	Request
	All installation points can be reached with ease during installation and dismantling	Request
	Assembly consists of few steps	Request
	Modules can be packed efficiently during transport	Request
	Shape of design does not require sealants	Request
	Design can be lifted and handled by a smaller loader	Request
	Design has low weight-strength ratio	Request
<b>Ergonomic assembly and installation</b>	No critical positions during maintenance	Request
	Minimise assembly directions	Requirement
	The modules can be handled without heavy manual lifting	Request
	No need of big and/or heavy assisting tools/machines	Request

	Modular components can easily be assembled and disassembled	Request
<b>Low long-term costs</b>	Materials with properties that prevent leakage (production loss)	Request
	Design minimises the accumulation of debris	Request
	Design consists of low-maintenance materials	Request
	Design consists of detachable modules	Request
	Repair only requires standardised tools	Request
	Design can be accessed for repairs and maintenance	Request
	Materials in design have long lifespan	Request
	The materials are resistant to UV radiation	Request
	Assembly and maintenance require standardised tools.	Request
	Maintenance only requires one person	Requirement
<b>Low short-term costs</b>	Design can be packed and transported efficiently	Requirement
	Design has low manufacturing costs	Request
	Design has low material costs	Request
	Design is standardised	Requirement
	Design is tested and validated	Requirement
	Installation requires minimal groundwork	Requirement
	Installation requires no expensive tools	Request
	Installation requires a maximum of 2-3 people	Request
<b>Predictable final costs</b>	Modular design	Requirement
	Tried and tested materials	Requirement
	Standardised production process	Requirement
	Standardised installation process	Requirement
	Predictable maintenance need	Requirement

<b>Well dimensioned design</b>	Strength calculations have been carried out to ensure resistance to wind loads	Requirement
	Modules are self-supporting	Requirement
	Construction can handle bigger floating objects, such as fallen trees	Request
	Design has a shape that minimises stress concentrations	Request
	Construction can handle different frequencies from water and wind without creating self-resonance	Requirement
	Design can withstand loads from ice formation	Requirement
	Materials in contact with water has high water resistance	Requirement
	Construction can handle varying water flow	Requirement
	Modules are well connected	Requirement
	Design withstands varying temperatures	Requirement
<b>Easy and efficient maintenance</b>	Maintenance does not require the assistance of advanced tools	Requirement
	Design is made of materials that do not collect dirt	Request
	Shape of design prevents branches and debris from clogging the modules	Request
	Modules are easy to access	Request
<b>Ergonomic accessibility during maintenance</b>	Maintenance does not require work above shoulder height or other unergonomic positions	Request
	Handling should not require manual lifting over 25kg	Requirement
	Maximum height when working from a ladder for more than 15 minutes is 5 metres	Requirement
	Design has handrails where there is a risk of falling	Requirement
	Possible to maintain according to safety regulations	Requirement
<b>Provide status and feedback of maintenance</b>	Clear feedback of success or failure during maintenance	Request
	Possible to see where maintenance is needed	Requirement
	Possible to monitor maintenance status remotely	Request

<b>Not destroying historical sites and important infrastructure</b>	The entire construction takes up less space than existing fish passage solutions	Requirement
	The entire construction takes up < 12 m2	Request
	Design requires no changes to neighbouring buildings or infrastructures	Requirement
<b>Low emissions and environmental impact</b>	No toxic substances in material are emitted	Requirement
	Design has low emissions in relation to lifetime	Requirement
	Design can be transported efficiently (local production)	Request
	Design can be transported efficiently (efficient packaging)	Request
	Maintenance requires no cleaning agents with harmful substances	Requirement
	Modules can be repaired	Request
	Modules can be recycled	Request
	Modules can become part of a circular system	Request
<b>Avoid production-loss</b>	Design uses no more water than needed to allow targeted fish species to pass	Requirement
	Design avoid leakage	Requirement

# Appendix E – Compilation of SPD Workshop-method

Results from Sustainable Product Development Workshop-method

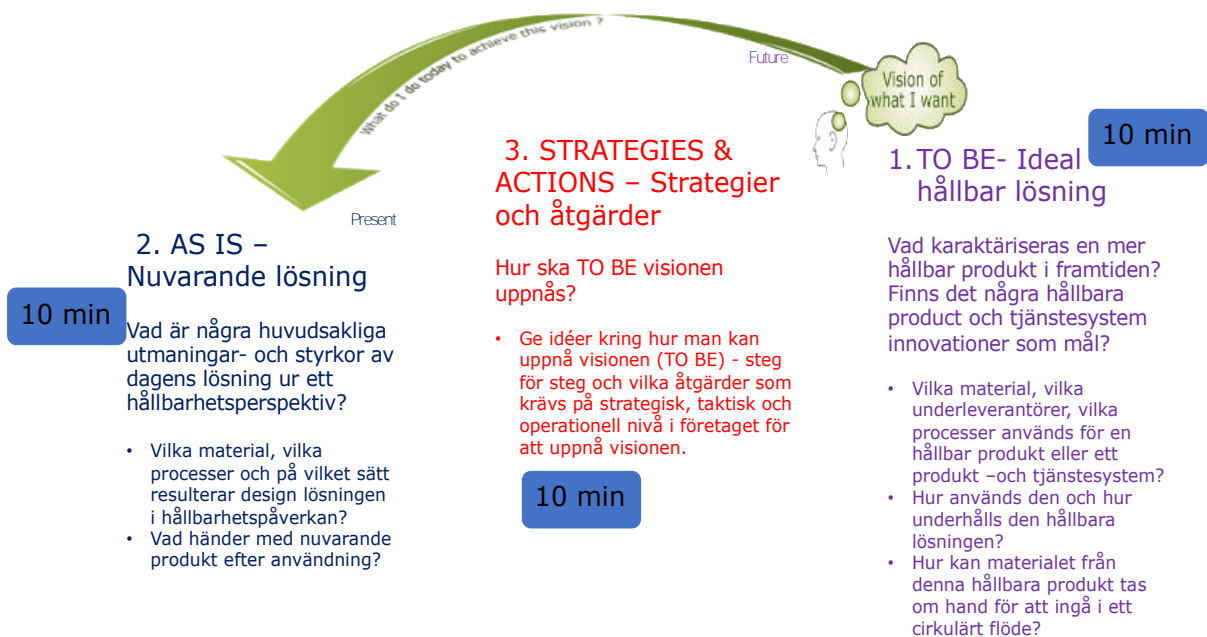


Figure E1. Structure of the SPD workshop methodology.

Part 1 – To be

Table E1. Part one, Filled in workshop sheet.

**Sustainable Product Development  
Workshop-method**

**1. 'To be'**      **What characteristics does your solution need to have to fit into a sustainable society?**

Use the guiding questions to identify characteristics

<i>Guiding questions</i>	<b>Answers</b>
<i>What materials are needed for a sustainable Solution?</i>	Glass - Recycled plastic - Recyclable Glass-fibre composite - Green concrete - Wood (larch, pressure impregnated), Aluminum
<i>What are sustainable suppliers?</i>	Swedish glassblowing company - recycled plastic from former fish ladders - local supplier, wood-based with sustainable additives - one of Sweden's concrete suppliers - Locally grown wood.
<i>How is the sustainable Solution produced and manufactured?</i>	Regardless of the material, it is manufactured in Sweden or neighbouring countries for short transports and with transparency in the process. Recycled materials are used in a circular system. The energy for manufacturing comes from renewable energy with maximum utilisation of resources.
<i>How is the sustainable Solution used and maintained?</i>	The solution has a long lifespan and requires little maintenance as the material is durable and easy to clean. If components break, they can be easily replaced
<i>How can the sustainable Solution be taken care of in a circular manner?</i>	By being built from a single material, or through the future's improved ability to separate different material fibres, the whole solution can be recycled and become either a new fish ladder or something else.
<i>What happens with the sustainable Solution at end of life?</i>	The solution is dismantled, the materials are recycled and become new fish ladders or something else creating a circular system. Alternatively, the material breaks down by itself after the desired lifespan.
<i>How is maximum social, ecological and economic value provided by the Solution?</i>	The solution enables fish migration, more fish in Swedish waters, the fishing industry is promoted, interest in fish and animals increases, and jobs are created.

## Part 2 – As is

Table E2. Part two, Filled in workshop sheet.

Sustainable Product Development Workshop-method		2. 'As is' What are the current preconditions to designing and delivering these characteristics? Use the guiding questions to identify challenges and opportunities in all three sustainability dimensions, across all lifecycle phases.		
Lifecycle phase	Guiding questions	Ecological dimension	Social dimension	Economic dimension
Raw material acquisition and production (sourcing)	What are current strengths and weaknesses with current materials?	e.g. metal alloys, chemical processing, land use Concrete is long-lasting and easy to maintain but has high emissions in production, is difficult to change, degrades and harms fish. There is little supply and material available today for this purpose.	e.g. conflict material, hazardous substances, pollution, corruption Concrete production is a major source of carbon dioxide emissions.	e.g. resilience of supplier network Hard to predict costs,
	What are current strengths and weaknesses with intended manufacturing processes?	material efficiency, chemical processing, water consumption, energy source Concrete requires large amounts of water but also energy for its production.	influence, competence development, str Conflict between local and state authorities over limestone mining.	e.g., human capital, knowledge sharing Knowledge of old methods and processes that could be valuable is lost as generations pass away.
Packaging and distribution	What are current strengths and weaknesses with the intended means of distribution?	e.g. waste, energy source Today's solutions are site-specific and must be built on site. They become completely solid and are difficult to change or move. Heavy materials and large dimensions require heavy transport.	e.g., injuries, stress, accidents The site can be dangerous with all the rushing water which can lead to accidents. Difficult environment to work in.	e.g., human capital, knowledge sharing
	What challenges or opportunities may occur related to the intended use?	remanufacturability, user behaviour, energy and water Today's concrete fish ladders require little maintenance, but the disadvantage is that when the surface breaks down, fish can be injured by the rough surfaces. It is difficult to access for maintenance. Trees, spruces, and leaves get stuck in the fish ladder.	e.g. safety, integrity, accidents Difficult to access and risky to maintain fish ladders due to slippery conditions and rushing water. Many people live far from the site and do not see the need for maintenance.	e.g. legal compliance of partner companies Unclear who is responsible for maintenance. No one wants to spend money on maintenance.
Use and maintenance (includes re-use)	What are strengths and weaknesses related to waste minimization and material upgradeability?	e.g. ease of disassembly, number of materials, toxic substances Many materials degrade and risk releasing microparticles into the water. Concrete fish ladders cannot be dismantled and recycled. Wooden fish ladders have a short lifespan and degrade and lose	e.g. hazardous chemicals, working conditions There are pressures, legislation that will lead to action being taken.	e.g., costs or benefits of waste management solutions or partnerships Difficult to predict costs. Especially expensive for small-scale hydropower owners. There is little money in recycling today and it is difficult to implement.

## Part 3 - Strategy & actions

Table E3. Part two, Filled in workshop sheet.

Sustainable Product Development Workshop-method	
Lifecycle phase	Strategi och åtgärder
i Raw material acquisition and production (sourcing)	Use recycled materials, look at recycling possibilities, what is done in other countries?
ii Manufacturing (including re-manufacturing)	Local options, energy consumption, repairability, dismantlable modules.
iii Packaging and distribution	Space efficient design and packaging, reusable packaging, light weight
iv Use and maintenance (includes re-use)	Easy disassembly, Design requiring minimal maintenance, standard tools, modular construction for site-independent design.
v Upgrading and end-of-life	Measuring instruments for assessment of status and maintenance needs, Strategy for recycling systems

# Appendix F – Morphological Matrix

*Table F1. Morphological matrix where combinations of sub-solutions result in three conceptual ideas. Pool, Boards and Skeleton.*

CONCEPT POOL							
CONCEPT BOARDS							
CONCEPT SKELETON							
Main Function	Sub-Function	Ideated Solutions					
<b>Fish ladder is transported</b>	Modules are placed on transportation vehicle	Roll on wheels	Lift with handles	Lift with crane	Drag on ground	Lift without handles	Roll on lorry
	Modules are packed efficiently	Cone formed modules are stapled in each other	Placed in different directions on each other	Toblerone -packaging in truck	Triangular puzzle	Modules are flat (board material that are assembled on site)	Smaller and smaller modules are stapled in each other
	Modules are transported	Truck	Car	Helicopter	Tractor	Crane lorry	
	Modules are lifted off transport vehicles	Manually	Lifting crane	Tractor	Drone		
<b>Fish ladder is assembled</b>	User understands assembly process	Manual with description	Symbols on modules	Shape signalling correct pairing	App with "how-to-videos"		
	User assemble modules with each other	Plugging	Joining with sealant	Screwing	Welding	Click joint	Sealing strip

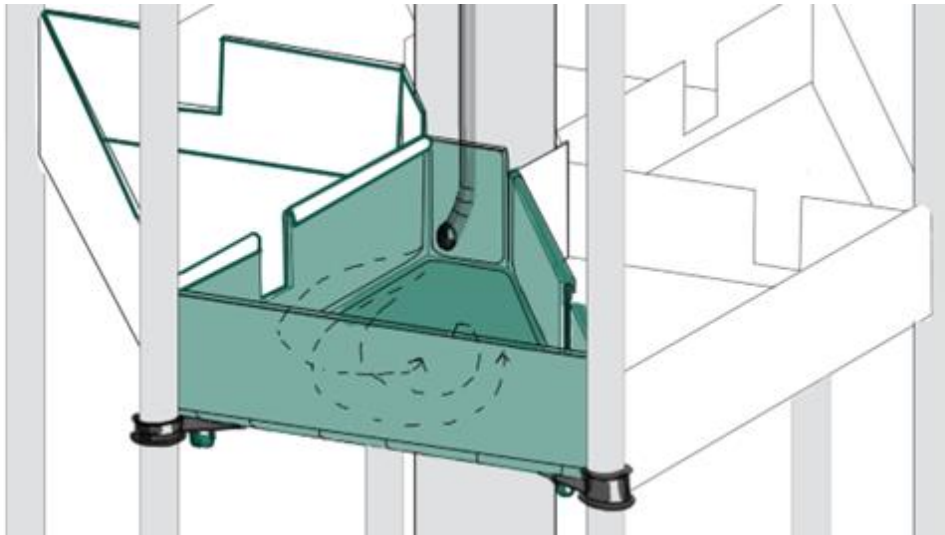
	--II--	Gluing	Utilise existing forces	Wedge together	Riveted together	Pressed together with existing forces (for example load of water/self-weight)	Modules are only locked to bearing structure (not assembled in each other)
	User assemble modules with bearing columns	Plugging	Screwing	Welding	Click joint	Gluing	Wedging
<b>Fish ladder is maintained</b>	User gets feedback about maintenance status	Floating solution in each module	Sensor in each module	Transparent material	Blocked module overflows	Camera in each module	Assistive systems (app)
	--II--	Mirrors to investigate modules	Light colour makes it easy to see stacked organic waste	User can investigate modules			
	User understand maintenance procedure	Manual	Signs	Voice	Lights	App	Intuitive design
	User clean modules	Openable hatches, and flush out	Remove manually with hands	Create turbulence in water so that stacked waste can be flushed away	Scrubbing with a brush and soap	Use of a rake	High pressure washing
	--II--	Wash with ultraclean water	Sludge vacuum cleaner	Shuttling blocks in passage that removes stuck waste	Sprinkler system in each module that uses high water pressure to wash away organic waste.	Flush away with high pressure from inner pole	Only cleaning upper level of modules from "grid roof"

	Design avoids accumulation of organic waste	Low-friction material in modules avoids accumulation	Modules have no confined spaces	Materials that are resistant to algae growth and fouling	Surface water grid hinder organic waste from entering	"Seaweed-grid" hinder organic waste from entering	Protecting roof on construction
	--II--	Huge volumes of modules with big passages and flow	Floating barriers hinder waste from entering, and lead it sideways				
	User handle organic waste	Organic waste is spread out in nature around fishway	Organic waste is put at specific place manually	Organic waste is put at specific place via a gutter	Organic waste is put at specific place via a conveyor belt	Organic waste is automatically continuing to downstream canal	
	User accesses modules	Ladders surrounding construction	Standardised ladder can be moved and used from each direction	Modules can be accessed by lifting crane	Surrounding building with staircase inside	No need to access individual modules	
	User repair modules	Modules can be slide out on rails	Dismantle modules from top to bottom and when rebuild with replaced parts	Modules are unbreakable for 40 years due to shape and material	Damaged module individually unscrewed and replaced		
<b>Fish ladder handle loads</b>	Modules handle external forces and stresses	Thick material in module	Shape that carries stress concentrations efficiently	Bearing structure protect modules	Roof protects modules	Material with high strength in modules	Railings and "grid roof" protect modules
	Modules handle self-weight	Thick material in module	Shape that carries load efficiently	Bearing structure carry modules	Material with high strength in modules		

	Modules avoids water damage	Whole module consists of material with high water resilience	Areas in contact with water consists of material with high water resilience	Easy to replace parts before complete damage	Modules are in constant contact with water and is therefore not affected of drying/getting wet		
	Modules handle varying temperatures	Fish ladder built in a protective building	The material can withstand variations in temperature	Design is made to compensate to differences in shape due to temperature variations	Built-in heating system to maintain an even temperature	(Constant and even waterflow avoids icing)	
	Modules handle sunlight	Modules in UV-Resilient material	Roof protects modules	Shape creates shadow	Fish ladder built in a protective building		
<b>Fish ladder is dismantled</b>	User understands dismantling process	Manual with description	Symbols on modules	Shape signalling correct dismantling	App with "how-to-videos"		
	User dismantle modules with each other	Picking off from the top down	Modules can be slide out	Modules are demolished			
	User dismantle modules with bearing columns	Unscrew	Break	Saw	Click out		
	Modules are taken care of	Modules are repaired and reused	Modules are recycled	Modules are discarded	Old modules can be used for other application/purpose		

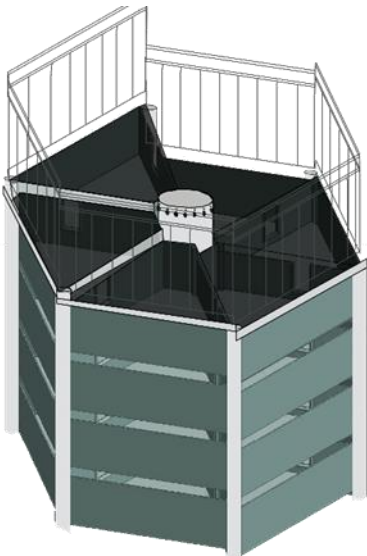
# Appendix G – Conceptual ideas

## Pool-concepts



*Figure G1. Illustration of concept Pool with high pressure flushing as maintenance system.*

**Description:** The first conceptual design suggestion is based on a seamless shape that is casted or form pressed in one piece. This design approach not only provides flexibility in shape but also reduces the necessity for joints, as the shape can allow built-in assembly-system. Therethrough, the design's shape aims to provide simple and fast interlocking of modules, as well as simple attachment to the supporting structure.



*Figure G2. Illustration of concept Pool maintenance platform.*

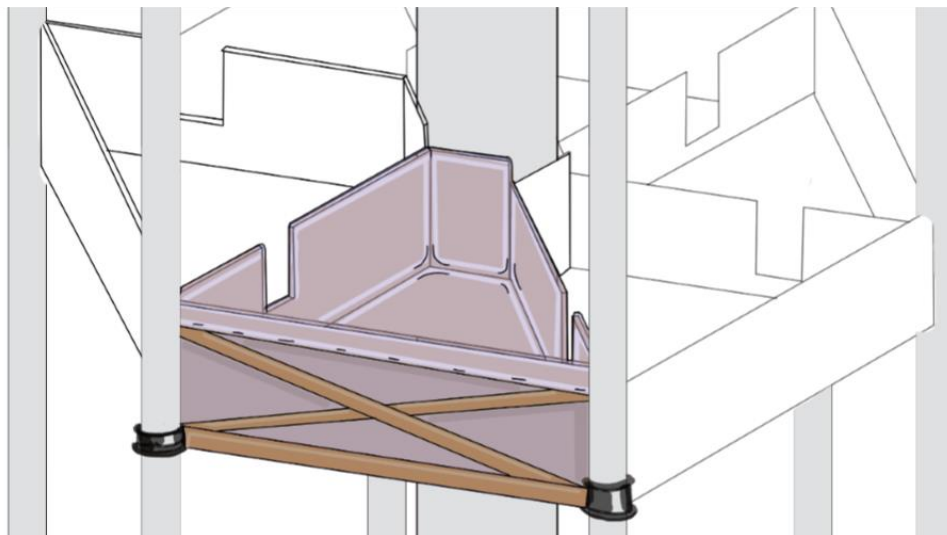
**Maintenance:** The pool-formed concepts clean their modules by generating turbulence within each module using a high-pressure waterjet. The maintenance personnel stand at the top of the ladder, where they can connect the pressure washer to each module. To clean all modules in the fish ladder, the maintenance personnel start from the top module and work their way downwards. When the

pressure washer is connected to a module, the waterjet creates a circulating movement in the pool, dislodging any debris that may be stuck. The maintenance personnel have the option to either allow the module to flood or stop the jet, allowing the dislodged debris to flow to the next module. This process is then repeated.

Feedback of maintenance need can either be done with sensors, and alert maintainer through an app or webpage, or with just the natural visual feedback as a module flood.

**Repairs:** This concept prioritizes longevity, long-term cost effectiveness and leakage prevention over reparability. The shape can be crafted using topology design to optimize strength relative to material usage. Unusual repairs of the fish ladder are made through unclicking each module from the top and rebuild the fishway from the replaced module. This repairing method is motivated by the fact that it simplifies the placement of the surrounding bearing pillars, and therethrough the design of each module. It enables a bearing system where the modules are supporting/bearing each other.

### 5.2.2 Skeleton-concepts



*Figure G3. Illustration of concept Skeleton, one module.*

**Description:** This conceptual design comprises two distinct components: the skeleton and the tub. The skeleton bears the inner tub and transfers loads to the supporting structure, while the tub contains water and shields the skeleton from water damage.

This design affords the fish ladder owner flexibility in style and expression, as external panelling can be added to the wooden skeleton. This customization option grants the owner greater influence over the final visual outcome.

**Assembly:** The framework of each module is preferably prefabricated but could also be assembled on site. The skeleton is thereafter assembled with the bearing structure with screws. The tubs are prefabricated and assembled with the skeleton. To avoid water leakage a sealant strip/list will seal the gap between the modules. As it is not crucial that the whole module is in one piece as it is mounted, there are more alternatives for transportation, and need of recourses during installation. If needed it could be installed by one or two construction workers, with a screwdriver and car trailer.

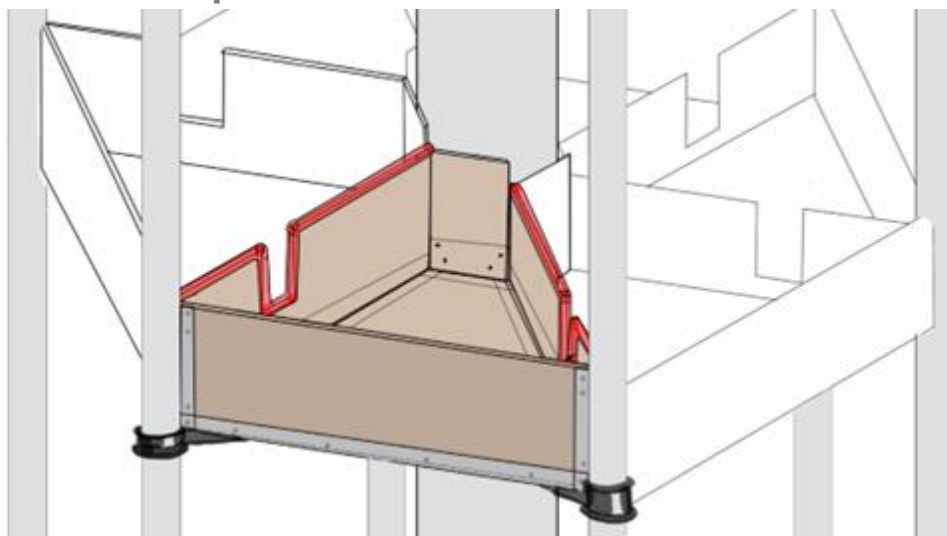


**Figure G4.** Illustration of concept Skeleton, maintenance platform.

**Maintenance:** In the Skeleton concept, cleaning is performed from the upper level of the fish ladder. Maintenance personnel can stand on the grid-roof and easily assess whether any of the six upper modules require cleaning. The light colour of the plastic enhances visibility, aiding in the detection of dirt and determining the cleaning status. In case of cleaning needs, the maintainer can lift the grid for each module and manually remove dirt or waste by hand or with a rake. The underlying principle of the concept is that if dirt passes through all six upper modules, it is likely to traverse the entire fish ladder. Therefore, only cleaning of the first lap is considered in this concept.

**Repairs:** Each module is designed to allow dismantling of individual modules, and each module can therefore be unscrewed and replaced with a new or repaired one. If only the tub is damaged, it is feasible to replace this one separately. A broken module can be recycled, as the design ensures that the two materials (skeleton and tub) can be separated easily for recycling purposes.

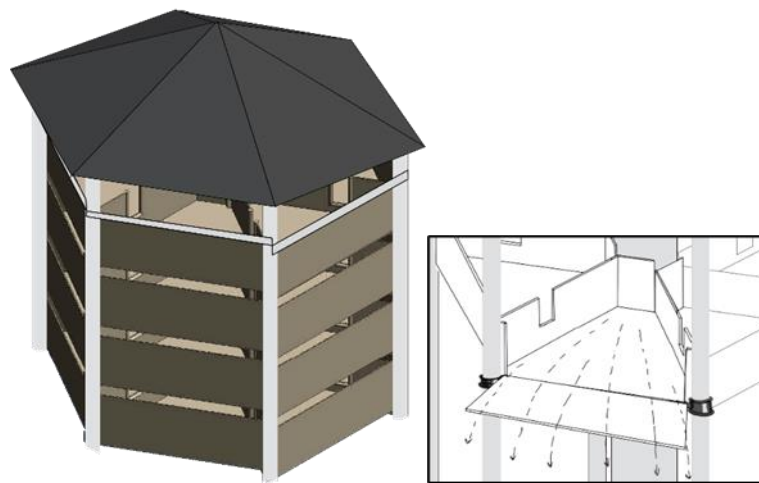
### 5.2.3 Board-concepts



**Figure G5.** Illustration of concept Board, one module.

**Description:** The board concept is designed for easy and cheap transportation and assembly, drawing inspiration from IKEA's packaging approach. Each module is constructed from sheets and delivered in flat packages, facilitating installation onto the supporting structure with an easy-to-follow manual. All components are designed to be easily lifted, handled, and assembled by one or two individuals. Consequently, professional assistance is only necessary for installing the supporting structure, which comprises columns with supports allowing each wooden board to be attached with screws.

**Assembly:** Boards are separately assembled with screws in the bearing structure. In this way, this concept differs from the others, as the modules are not assembled as they are delivered but are created on site as the boards are assembled with the bearing structure. In the end, sealants need to be added, to avoid leakage.



**Figure G6.** Left: Openable hatches in case of maintenance needs. Right: Overview of concept Board with protective roof.

**Maintenance:** In Board concepts, each module can be accessed from the outside for maintenance purposes. The maintainer reaches the modules using a ladder from the adjacent side. All sides can be accessed by moving the ladder accordingly. There are either hatches that can be opened, or the entire outer wall can be dismantled with a screwdriver to access the inner part of each module. Once accessed, the module can be cleaned by hand or by using a rake.

**Repairs:** In this concept repairability is crucial. If a part is damaged, it can be ordered and delivered to the owner. The broken part can then be unscrewed and replaced with the new part, after which the user can apply sealant to ensure there is no leakage. Since the principle of the concept is to facilitate easy self-care of the construction, both maintenance and repair should be achievable with standard tools.

# Appendix H – Analysis of Applications of Relicensing

Analysis of Applications of Relicensing of Modern Environmental Legal Conditions

*Table H1. Summary of the analysis from 10 applications of relicensing of modern environmental law conditions.*

Type of fishway	Limited construction area	Water flow/ Target species	Vehicle accessibility	Soil type
Vertical slot fishway	No, but only a few months per year when soil is ice or frost free	1m <sup>3</sup> /s, but during winter season 0.5m <sup>3</sup> /s Mainly sea trout	Relatively good accessibility	Morain
Vertical slot fishway	No	0.6 m <sup>3</sup> /s Larger salmon, eel, sea lamprey and river lamprey	Good accessibility	Rock
Pool and Wire fishway	Yes	0.1 m <sup>3</sup> /s Trout and eel. Runs during winter	Limited accessibility for larger machines (steep terrain)	Rock
Larinier super-active baffle fishway	No	0.12 m <sup>3</sup> /s	Limited accessibility	Rock
Vertical slot fishway	No	0.4 - 1 m <sup>3</sup> /s	Relatively good accessibility	Rock
Vertical slot fishway	Yes	0.4 - 1 m <sup>3</sup> /s	Relatively good accessibility	Morain and rock
Vertical slot fishway	No	1 m <sup>3</sup> /s	Good accessibility	Morain
Vertical slot fishway	No	0.7-0.85 m <sup>3</sup> /s	Good accessibility	Ice river sediments and possibly landslide-prone soil
Vertical slot fishway	Yes	0.2 m <sup>3</sup> /s Mainly trout. No weak-swimming species	Limited accessibility	Bedrock and sandy moraine
Vertical slot fishway	No	0.2 m <sup>3</sup> /s	Limited accessibility	Ice river sediments and sandy moraine

# Appendix I – Kesselring Matrix

The ranking 1-5 in the Kesselring matrix is an estimation how well the concept meets the need. 1 is the lowest value, and 5 is the highest value.

**Table II.** Completed Kesselring matrix for scenario 1, 2 and 3 with ranking of concepts.

Years of validity: 2024 - 2064

			Rank weight:								
			Scenario						POOL SKELETON BOARD		
Stakeholder	Stakeholder Expectations	Stakeholder Needs	1	2	3	C1	C2	C3	C4	C5	C6
Biologist	Optimal connectivity is enabled for fish	Enable targeted species to pass	Req.	Req.	Req.						
		Avoid harm to fish	Req.	Req.	Req.						
		Possible to count fish	4%	5%	5%	3	3	3	2	2	3
Design Firm	Same design can be sold to many customers	Adaptable to different hinder hights	Req.	Req.	Req.						
		Possible to install in varying site conditions	15%	5%	16%	2	2	4	4	5	4
Manufacturing Firm	Design is easy to produce	Reliable resources for production	Req.	Req.	Req.						
		Scalable production method	5%	15%	13%	5	4	3	2	3	3
Constructing Firm	Design is easy to install	Efficient installation process	8%	1%	3%	5	5	3	3	4	4
		Ergonomic assembly and installation	0%	0%	0%	4	2	3	3	3	2
Financial provider*	The investment is affordable	Low long-term costs	10%	12%	15%	3	3	3	3	2	3
		Low short-term costs	20%	17%	10%	2	3	4	2	5	4

		Predictable final costs	5%	5%	5%	4	4	3	3	3	3
Powerplant Owner	Design is reliable	Well dimensioned design	Req.	Req.	Req.						
		Design's functional status is communicated	10%	10%	8%	3	2	3	3	3	5
Maintainer	Design is easy to maintain	Easy and efficient maintenance	7%	13%	10%	5	5	5	5	1	1
		Ergonomic accessibility during maintenance	2%	3%	3%	4	4	4	4	1	1
		Provide status and feedback of maintenance	5%	7%	5%	2	2	4	4	2	2
Local society	Design respect local values	Not destroying historical sites and important infrastructure	Req.	Req.	Req.						
Government	Design respect regional values	Low emissions and environmental impact	9%	7%	7%	2	3	5	1	4	2
		Avoid production loss	Req.	Req.	Req.						
			100%	100%	100%						

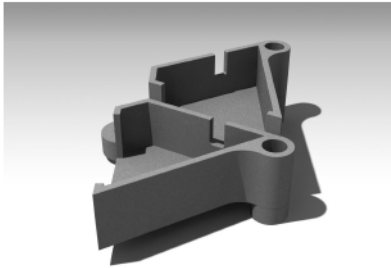
\* In this case: Hydropowerplant owner (15%) and the Hydroelectric Environmental Fund (85%)

# Appendix J – Evaluation form

Evaluation with members of SVAF

## Utvärdering av modulär fisktrappa i spiralform

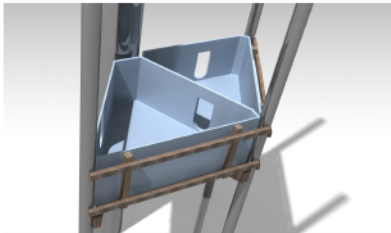
### VALKYRIA



1	Material	10
1	Funktion	10
1	Pris	10

Kommentar: .....

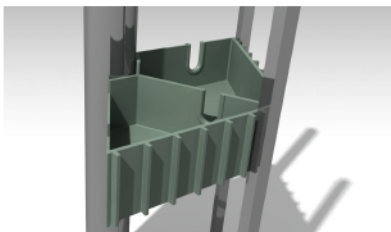
### BALDER



1	Material	10
1	Funktion	10
1	Pris	10

Kommentar: .....

### COLORADO



1	Material	10
1	Funktion	10
1	Pris	10

Kommentar: .....

*Figure J1. Layout of the concept evaluation form with the members of SVAF.*

# Appendix K – Summary of evaluation form

Summary of answers– Evaluation of Balder, Valkyria and Kållerado with members of SVAF

*Table K1. Evaluation of Balder*

Respondant	BALDER			
1	Material	Funktion	Pris	Kommentar:
2	7	10	10	Underhåll? Tveksam till plastens hållbarhet
3	5	5	7	
4	10	10	10	Trä är trevligt material
5	6.5	7	8	
6	4	5	6	
7	6	7	8	
8	1	1	1	Ful! Passar inte i kulturmiljö
9	10	5	1	
10	1	7	5	
11	5	7	10	
12	5	7	6	
13	10	10	9	
14	6	8	5	
15	8	4	7	
16	10	7	10	
17	7	5	6	
18	8	8	2	
19	9	9	6	
20	7	8	10	Billigare, men kräver mer underhåll så kanske dyrare i längden initialt?
	4	5	5	Lämplig i sep byggelement, golv väggar. Enkel att packa och frakta. Kräver ingen form.

Total Score      129.5      135    132

**Table K2. Evaluation of Valkyria**

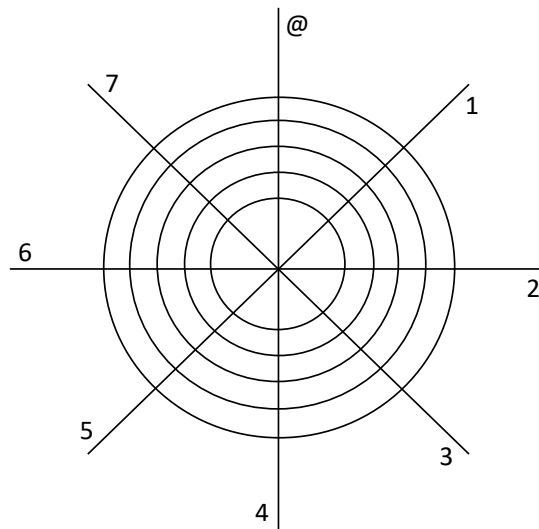
<b>Respondant</b>	<b>VALKYRIA</b>			
<b>1</b>	<b>Material</b>	<b>Funktion</b>	<b>Pris</b>	<b>Kommentar:</b>
<b>2</b>	10	10	10	Långsiktig investering!
<b>3</b>	8	2	7	
<b>4</b>	5	10	5	Känns positiv, Robust!
<b>5</b>	5	6	8	
<b>6</b>	6	7	8	
<b>7</b>	5	6	7	
<b>8</b>	1	1	1	Betong miljömässigt dåligt och fult! Passar inte i en kulturmiljö. Varför inte i trä?
<b>9</b>	2	3	5	
<b>10</b>	2	7	3	
<b>11</b>	6	8	7	
<b>12</b>	7	7	8	
<b>13</b>	4	3	5	
<b>14</b>	8	8	8	
<b>15</b>	8	8	3	
<b>16</b>	2	10	6	
<b>17</b>	6	4	5	
<b>18</b>	1	8	3	
<b>19</b>	10	8	4	
<b>20</b>	9	9	7	Bra för miljö om grön cement och hållbar
	8	5	3	Enkelt att forma i gjutform. Antal formar för ökad bygghastighet. Lite dyr metod
<b>Total Score</b>	<b>113</b>	<b>130</b>	<b>113</b>	

*Table K3. Evaluation of Kållerado*

KÅLLERADO				
Respondant	Material	Funktion	Pris	Kommentar:
1	3	10	10	Hållbarhet? Återvinning?
2	2	7	3	Jag tror varje modul måste gå att rensa separat.
3	10	10	1	Troligen smidigast att hantera
4	8	7.5	9	
5	8	8	9	
6	9	7	6	
7	1	1	1	Ful! Passar inte i kulturmiljö
8	8	5	8	
9	1	6	2	
10	10	10	7	
11	6	7	5	
12	10	8	6	
13	2	8	8	
14	8	8	5	
15	10	6	10	
16	4	5	6	
17	5	7	1	
18	4	5	4	
19	5	8	6	Saknar återvinningslösning --> Ej bra
20	3	5	2	Mindre återvinningsbar, kräver form. Kräver skydd vid tillverkning. Kemikalier!

Total Score            117        138.5    109

# Appendix L – Template of LiDS Wheel tool



Evaluate the ecoperformance in each ecodesign level:

*Product component level*  
1: Selection of low-impact materials  
2: Reduction of materials usage

*Product structure level*  
3: Optimization of production techniques  
4: Optimization of distribution system  
5: Reduction of impact during use

*Product system level*  
6: Optimisation of initial lifetime  
7: Optimization of end-of-life system

*New concept development*  
- dematerialization  
- shared use of the product  
- integration of functions  
- functional optimisation of product (components)

The circles can be used as a qualitative scale from 'worst case' to 'best' scenario. You can use it to map out the current performance of an existing concept, with input from e.g. a MET or MECO matrix. You can then map out the desired performance of a new concept, using input from e.g. 10 Golden Rules of Ecodesign.

In this way you can compare different concepts and visualize the differences.

Adapted from H. Brezet and C. van Hemel (1997) *EcoDesign: A promising approach to*

Figure L1. Eco Design Strategy Wheel worksheet (Wever & Vogtlander, 2014).

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