Title	Life Cycle Assessment of the water pipe replacement process
Description	The report consists of an LCA study of the water pipe replacement process, with the focus on the installation of the water valve system and the preparation and restoration of the excavated work site. The study is assessing the possible effects of a reduction of the trench size, due to RobSub's involvement by enabling a robot solution to assist in the valve system installation.
Time frame	September 2023 – February 2024
Company	RobSub Aps
Practitioner	Alexander Staben
Contributing Partners	Aarhus Vand, HOFOR, VandCenter Syd
Critical review company	Bureau Veritas HSE Denmark A/S
Reviewers	Julie Marie Vejsgaard Larsen, LCA & EPD Consultant, Waldemar Corydon Hemdrup, LCA & EPD Consultant, and Odyssefs Papagiannidis, LCA & EPD Consultant from Bureau Veritas HSE A/S Denmark

Terminology and abbreviations

1,4 – DCB	1,4 - Dichlorobenzene
AV	Aarhus Vand
CO2 -eq.	Carbon dioxide equivalents
HOFOR	Hovedstadsområdets Forsyningsselskab
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NRW	Non-Revenue Water
PE	Polyethylene
PFD	Process Flow Diagram
Trench/Hole	The excavated area in which the work is being done.
VCS	VandCenter Syd

Water Line System

1	Electrofusion coupler (PE/PE); Brass repair coupling (PE/other material)
2	Electrofusion coupler
3	Stop valve / Service connection valve.
4	Consist of: • Electrofusion saddle (VCS) • Electrofusion tapping saddle (HOFOR/AV) • Reducer (VCS) • Angle electrofusion coupler (VCS) • Electrofusion coupler (HOFOR/AV)

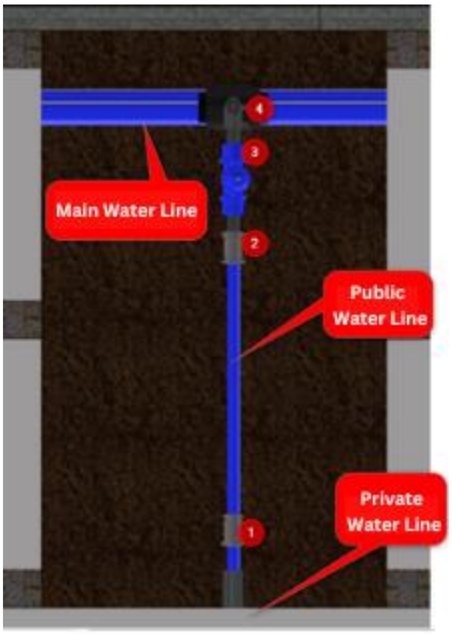

Figure 1 - Water Line System

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Executive Summary

The purpose of the study is to assess the process of planned water pipe replacement and the effect of reduction of the trench size, according to the environmental impact categories on a midpoint level. The LCA methodology according to ISO 14040 and ISO 14044 are being used to structure the study with the consequential approach. The analyzed system is being modelled according to the life cycle stages: Product stage, construction stage, and end of life stage. This model is to be seen as an average of the three partner utility companies Aarhus Vand, HOFOR, and VandCenter Syd. It is assumed that by implementing a robot solution to perform the installation of the valve system, the size of the trench can be reduced by 50% (new process).

The intial impact assessment has been set up on three scenarios to be analyzed: **(1)** a single trench, **(2)** daily, and **(3)** yearly. The daily scenario is an average of 35 trenches, which is based on the yearly estimation of 9010 trenches divided by the annual average of 260 working days. The yearly estimations is based on HOFOR's estimation of around 6000 trenches being excavated in connection with the planned valve replacement. This is being extrapolated by referencing the number of the companies's number of customers in their drinking water distribution system. But during the analysis of the scenarios, it shows that the results are of these scenaraios are being multiples related to the number of trenches. Which shows the same relativness between the impact categories. Therefore, the main focus is on a single trench, while the daily and yearly scenario are being used show reduction in the four chosen impact categories. which can be extrapolated according to the desired number of trenches. As a part of interpretating the results, a contribution analysis has been conducted to investigate which process is contributing the most to the impact categories. The chosen impact categories to focus on are freshwater ecotoxicity, global warming, land use, and water consumption. The reason for choosing freshwater ecotoxicity and water consumption, is that stakeholders have a high interest in water safety and water consumption. As soil has a large potential influence on the process, the land use impact category is chosen to highlight how the reduction of the trench size is affecting this impact category. When communicating the results of the study, the global warming impact category is a useful indicator of the process environmental contribution. The calculations involved in the impact assessment revealed that during a single installation the process with the reduced trench size decreases the impact categories by 25% on average, with a size reduction of 50% of the trench. In the impact category global warming, the current process has a value of 251,6 kg CO2 eq, whilet the reduced trench size has value of 167,3 kg CO2 eq., which is 33% lower and accounts for 84,34 kg CO2 eq. On a yearly basis there could potentially be saved 759.876 kg CO2 eq. and 29.566 m3 water.

The reduction of the trench size has an important impact on the overall environmental performance of the process, but the results of the study are merely an approximation and to be viewed with caution. To achieve these results, RobSub's robot solution needs to be developed to reduce the size of the trench. The results are useable for creating awareness of the possible advantages of reducing certain resources in the process of replacing water valve systems.

Introduction

RobSub

RobSub ApS was established in April 2022 with an initiative to introduce robot technology in the utility sector. RobSub's main objective is to utilize robot technology to automize maintenance and replacements of water pipe systems. RobSub's current mission is the development of a robot solution, that can install a valve system which connects the consumer with the main water line (Figure 2), and by doing so will contribute to improvements in working conditions, resource use, time efficiency and costs. By using the robotic solution for valve replacements, the welders will no longer have to work in trenches, thereby reducing the size of the trench and need for excavation of soil. This could eventually lead to reducing resources in both new material and discarded material, such as contaminated soil, while minimizing the harsh working environment for the workers. Beside the reduction of resource use and the improving of the work environment, the innovation could help with decreasing bottlenecks in projects: The partner companies, Aarhus Vand, Hofor, and VandCenter Syd are experiencing a decrease in skilled welders, who can perform this installation which leads to projects taking up more time than anticipated and budgeted for.

Figure 2 - Trench with new valve system

Along with these direct industry pains, RobSub suggests their solution can contribute to solving, the maintenance of the water pipe network plays a role in a bigger picture. Meeting the UN's targets for drinking water by 2030 will require a four time increase in the pace of progress. According to the UN, at current rates 1.6 billion people will lack safely managed drinking water by 2030. Currently more than 733 million people live in countries with critical levels of water stress (United Nations, 2023). One of the main threats to the target is the concept of Non-Revenue-Water (NRW), which is the difference between the water that is pumped out and the water that is invoiced – it is the water that is lost somewhere in the pipe network. For some countries, up to 50% of clean drinking water is lost before it reaches the consumer (DANVA, 2022).

In Denmark, there is a loss of only 7.55%, throughout the country's 45.000 kilometers drinking water pipes – Danish utility companies are fined with a penalty tax if more than 10% is lost in their network. Keeping the NRW level low is thus motivated by both economic, social, and environmental factors. High quality maintenance of the pipe networks is one of the main pillars in keeping a low NRW level (LEAKMAN, 2022).

VUDP collaboration

This LCA project is carried out by RobSub in collaboration with some of Denmark's largest water Utility Companies, HOFOR, Aarhus Vand, and VandCenter Syd. The objective of the collaboration is first and foremost to develop innovative technology that can improve the water utility instalments and secondly to map and analyze the Utility Companies' processes, resource use and emissions using LCA as tool. This project is partially funded by VUDP and carried out through a valuable collaboration with RobSub's industry partners.

The Process

The process this LCA study is focusing on, is the planned replacement work of water pipe valve systems. The full and descriptive version of the process flow diagram can be seen in Appendix A.1. The overall process of replacing the water pipe system consist of five main processes: **(1)** Surface removal, which has three sub-categories: Tiles, asphalt, and grass, as each surface category is being handled differently in terms of tools being used, disposal and/or reuse of the removed material. **(2)** Trench preparation consists of excavating the area around the valve system to create space to execute the work and securing the trench with plywood to support the walls and decrease the risk of soil sliding into the trench. This work is being done by using both machinery and labor work, as in some cases, other utility lines can be above the water line and to not damage those, the workers dig parts of the trench manually with a shovel. **(3)** The pipe work, in which a welder connects the new valve system both to the new main water line and via the public water line with the private water line. This work can vairy between different utility companies and different installations as some steps might involve a different type of electrofusion saddle, and some might need more parts to connect the service connection valve with the private water line. In this study, the most common scenario is being used to simplify the process for the analysis. This scenario involves the use of one electrofusion saddle, one reducer, one angle electrofusion coupler, one stop valve, one electrofusion coupler, one extension spindle, one brass repair coupling, and one stop valve cover. It is assumed that all installations are being installed on existing private water lines, for which the brass repair coupling is used for connecting the public water line with the private water line. **(4)** Trench restoration, by filling new sand around the pipe and compressing it each layer. If the excavated soil is reusable, it can be used as a refill in the layers which do not need a specific type of soil/sand. **(5)** Surface restoration is categorized into tile, asphalt, and grass. Both Tile and asphalt need a base ground protection and stable ground bearing layer, to support the asphalt and tiles of bearing load. Depending on the location of these planned replacement projects, waste materials can be stored at the site before being disposed or if it's not possible they are being disposed as soon as possible. In this case, it is assumed that three containers are being used in total to transport waste: Two for sand, soil, and grass (gardening), and one container for asphalt, tiles, and other waste which can be separated at the landfill.

In this study the processes of pipebursting and moling are being excluded from the system. Pipebursting is the process of pulling an expansion head through the old pipe, which leads to the pipe being forced outward and breaking it. The new pipe is attached to the pipebursting tool, which allows for the pipe to be placed at the same time. The moling process is similarly, except for it to be shot through the ground instead of being pulled through an existing pipe.

Life Cycle Assessment

Life Cycle Assessment is a method, which is being defined by the ISO 14044 and ISO 14040 standards as a method to "address the environmental aspects and potential environmental impacts throughout a product´s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO, 2008).

There are four phases included in the LCA method (Figure 3):

1. The goal and scope definition phase,
2. The inventory analysis phase
3. The impact assessment phase
4. The interpretation phase

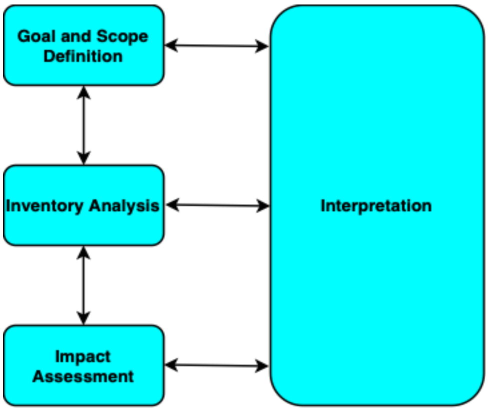

Figure 3 - LCA phases according to ISO 14040 and ISO 14044

The modelling choice for the LCA is the consequential approach, which is being defined as a "System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit" in the UNEP/SETAC Shonan guidance on LCA. Thus, RobSub is trying to understand how the environmental impact categories are influenced by introducing the a reduction of the trench size.

Methodology

Goal Definition

Intended Application

The intended application of the LCA study is to analyze the environmental impact of the current process of replacing the valve system, which connects the consumer to the main water line, with the focus on the pre and post operation of creating the trench where the installation work is being executed. Furthermore, the goal is to compare the process with the reduction of resources by minimizing the trench size, as a result of utilizing a robot solution. The results should be used as a communication tool with current, as well as future partners and investors, and possible customers. As the product, which shall allow for a reduction of the trench size and assisting the worker in the installation of the valve system, is not yet a finished concept, this study will focus on the difference between the current process and the reduction of the trench size. The results can be used as a guide to choose and improve concepts, ideas, and products according to environmental impact categories.

Limitations of the Study

The study is being carried out from September 2023 to January 2024. The data used for the inventory analysis is based on data gathered from RobSub's partners Aarhus Vand, HOFOR, and VandCenter Syd. The database, that is being used is continuously being updated and might not have the exact processes and flows needed for the study, in this case estimations and substitution are being made to be as close as possible to the primary data. As RobSub is currently still developing the product, it has been decided to exclude the entirety of robotic solution of the analysis due to its early-stage development from this study and focusing on the current process and the effect of reducing the size of the trench. The excluded parts are as following: the UR16e robot, which will perform the installation work. The frame rack on which the robot is being mounted on and used to position it over the trench. Lifting column from Linak, which are being used to lower the robot into the trench. The end of arm tools, which are being developed by RobSub to perform the different tasks during the installation work of the valve system.

Reason for study

As one of the reason for innovating the process is to help reducing the NRW, another reason for a robot solution for the water utility sector is to reduce the use of resources, which might come with environmental benefits. Therefore, an LCA study is a suitable addition to generate a more in depth understanding of the project and account for the environmental aspects of the project. In addition, this creates transparency for RobSub and their partners and can be used to assess and pinpoint other areas to be improved in terms of environmental impact.

Target Audience of Study

The results of the study are being communicated both internal and external. For the external communication the audience are the business partners and potential partners, investors, and customers. The external use of the LCA study require a critical review of the study for it to be used in this matter and to assure credibility of the results for the recipient. The reviewer for this study are Julie Marie Vejsgaard Larsen and Waldemar Corydon Hemdrup, both of them are LCA & EPD Consultant from Bureau Veritas HSE A/S Denmark. The internal use of the study is to gain a better understanding of the process and the contribution of the different parts to the environment.

Commissioner

The commissioner of the LCA study is RobSub ApS, with the practitioner being Alexander Staben, Sustainability Manager at RobSub ApS. The study is being created in collaboration with HOFOR, VandCenter Syd, and Aarhus Vand, as they are the main sources for gathering data and they have an interest for the results of the LCA study.

Scope Definition

Deliverables

The Deliverables of this study consist of the LCI results, which are the compilation of elementary flows over all the processes that are part of the LCI model (Hauschild, Rosenbaum, & Olsen, 2018), and the LCIA results, which consists of the midpoint H impact categories. This is according to the ISO standard 14044 "Environmental Management – Life Cycle Assessment – Requirements and Guidelines".

Object of the Assessment

Functional Unit

The functional unit is being defined as:

> The replacement of one valve system and public water service line, including the preparation and restoration work of the work area, with a service lifetime of 50 years.

During data gathering, the focus shall be to gain data as precisely as possible for a single trench to account for differences in terms of the surface characteristics. Where data cannot be traced to a singular trench, the responding overhead shall be documented accordingly to the number of trenches and an average shall be calculated. The lifetime might be shortened due to leakages, which result in unplanned maintenance and replacement work.

Reference Flow

Current process

The preparation and restoration process of the trench for the pipe replacement with a trench size of 1,5m*2m*1,7m.

Reduction

The preparation and restoration process of the trench for the pipe replacement with a trench size of 0,75m*2m*1,7m.

The reference flow in this instance involves the preparations and restoration of a trench with a width of 1,5m, a length of 2m, and a depth of 1,7m (VandCenter Syd A/S, 2021). The measurements are taken from the requirement specification by VandCenter Syd as the standard, even though observation in the field showed that those trenches are been excavated bigger, as the simple rectangle shape can't suit the working area. The reference flow covers the three different types of surface characteristic: Tiles, Asphalt, and Gras. A general average from these types is being simulated in the LCA software. Furthermore, the compared reference flow is the ideal situation where the hole width can be reduced by 50% to allow for enough space for the electrofusion saddle to be mounted onto the main water line, and for the robot to execute the work task.

System Boundaries

The analyzed system is being modelled according to the construction life cycle stages: Product Stage, Construction Stage, and End of Life Stage. The use phase of the system would have been the general usage of the valve and pipe system, which is not part of the scope.En This study is not including RobSub's product as it is still under development. The parts used in the product like the robot from universal robot and actuators from Linak, are being excluded due to non-available information about their life cycle. This also includes the fact that RobSub has no control of the production of these parts. Therefore,the focus will be on reporting the current process and to assess the environmental impacts. The reduction of the trench size will be assessed, and the output shall be used as an indicator threshold for possible concepts. The simplified Process Flow Diagram (PFD) can be seen in Figure 4.

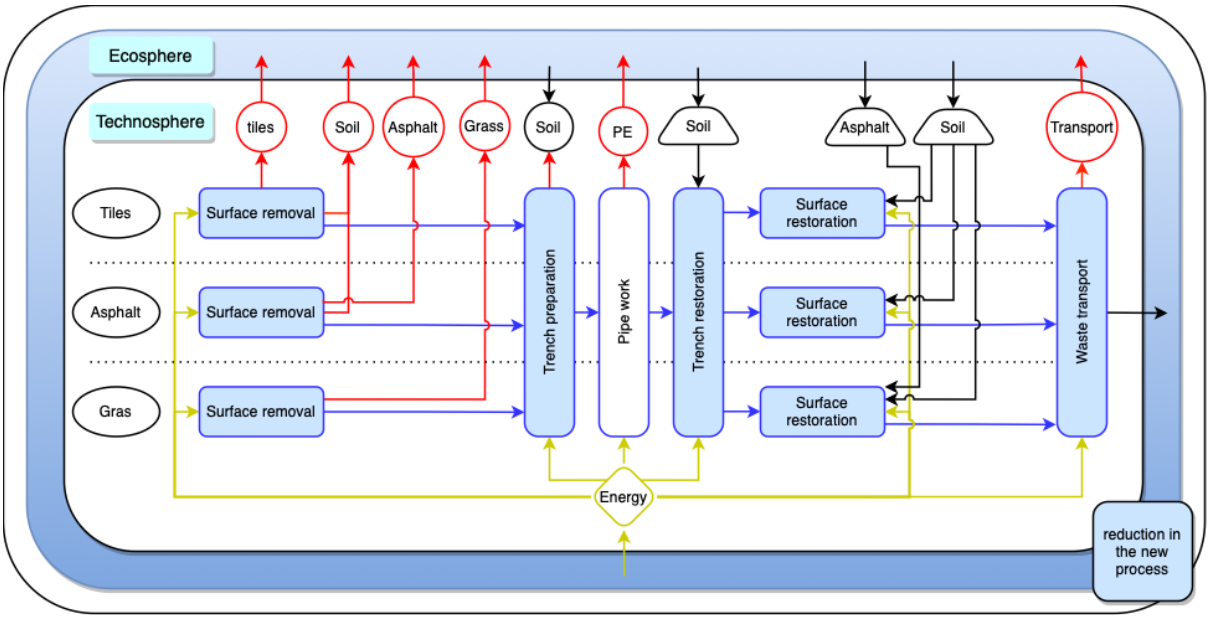

Figure 4 - simplified PFD

The process of the replacement of water pipe valve system is for this study located in Denmark, due to the RobSub's location and the geographical location of the companies where the data is gathered from. The time horizon consists of the duration of the pipe replacement project, from the start of gathering materials and excavating the trenches to the restoration of the ground and the waste transport, and the service lifetime of 50 years with possible leakage repairments, which are being closer analyzed in the sensitivity analysis. At the current stage, the product is being excluded from the study as it is still under ongoing physical and conceptual development. This includes also bigger parts such as the UR16e robot from Universal Robot, lifting column and actuators from Linak, as information regarding the LCA and the life cycle of these products are not available yet.

Cut-off

The model covers the valve installation work and the process that is being directly connected to this work and to the reduction of the trench size. This does not include the process of pipebursting or relining for establishing the new main water line and the use of a mole to establish a new private and/or public water line. The reason for excluding these processes is the inconsistency in them, as it can vairy which method is being used for the main water line and whether the moiling process is being executed or not. Furthermore, the process would be the same when reducing the size of the trench. The use phase of the system is being excluded, as it is outside of the scope for this study. The cut-off percentage in the the creation of the product systems in OpenLCA is being set to <1%.

Allocation

The allocation procedure will follow the three steps in chapter 4.3.4.2 of the ISO 14044 standard:

Step 1: Where possible, allocation should be avoided by expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or function in a way that reflects the underlying physical relationship between them; i.e., they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

Data Quality

Technological

The representativeness of the technological part of the LCI data is being achieved by gathering data from the utility companies on their projects, through experts (Peter Sletskov, Anders Kryger Bender, and Carsten Hammer) and the requirement specifications of Aarhus Vand, VandCenter Syd, and HOFOR. The primary data gathered from the companies is based on the functional unit and focuses on the work that is connected replacement of the water valve system. Furthermore, the data received from the utility companies is based on their measurements and estimates made by experts in the field. This includes the amount of material being used and discarded, the machinery usage in time, and the amount being transported, and the distance related to it. The secondary data used for the study is supporting the primary data in the OpenLCA software with the database ecoinvent_391_consequential_upr. This includes the different material types, as they are either not able to state the precise type of material or/and the material is not available in the database and an alternative need to be used instead. Especially when it comes to the different types of sand being used for the restoration of the trench and the surface, which are not available in the database. This also includes the use of machinery and tools, as it being assumed that every utility company are using the same tools and machinery, to be able to create a study which can represent the three partner companies.

Spatial

The geographical location for the study is being set to Denmark, as this is the main region in which these water pipe replacement projects are being executed by the named utility companies. For the parts in the valve system, which are being produced by GF Piping System, the location of the production in Europe is being set to Switzerland as stated on their website (GF Piping Systems, 2023).

Temporal

The study is being carried out in the period of September 2023 to January 2024, which is also the time frame in which data is being gathered. The data is an average estimation provided by the companies, which does not include differentiation according to time or weather. Furthermore, the data collection is based on the Utility Companie's requirement specifications, published in 2021 (Aarhus Vand), 2019 (HOFOR) and not dated (VandCenter Syd), which are the currently applied requirements for valve installations.

The assessment of the data quality is being done by using data quality requirements which range from "1" = Very good, to "5" = Very Poor, which are displayed in Table 1 - DQR Description. The data set used is the Ecoinvent 3.9.1 consequential upr.

Table 1 - DQR Description

Quality level	Geographical representativeness	Technical representativeness	Time representativeness
Very Good = 1	Data from study location	Data from processes and products under study. The same state of technology applied as defined in the goal and scope.	Less than 2 years difference between the reference year of the study and the time period of the data.
Good = 2	Average data from the nearby country (within europe)	Data from processes and products under study under study (with similar technology)	Less than 5 years of difference between the reference year of the study and the time period of the data.
Fair = 3	Data from an area with similar construction site condition. (europe)	Data from processes and products under study but from different technology.	Less than 10 years of difference between the reference year of the study and the time period of the data.
Poor = 4	Data from area with slightly similar construction site condition. (europe)	Data on related processes or products (similar utility projects)	Less than 15 years of difference between the reference year of the study and the time period of the data.
Very Poor = 5	Data from unknown or distinctly different area (outside of europe)	Data on related processes on but with a different scale or from different technology.	Age of data unknown or more than 15 years of difference between the reference year of the study and the time period of the data.

Table 2 - DQR Product Stage

Data	Country of production	OpenLCA 1.11.0/ Ecoinvent 3.9.1 consequential upr	Age of Ecoinvent data	Geographical	Technical	Time
Product stage						
Tiles	Denmark	concrete block production | concrete block | Consequential, U - DE	1.1.1997 - 8.12.2022	2	2	1
Asphalt	Denmark	mastic asphalt production | mastic asphalt | Consequential, U - CH	1.1.2000 - 8.12.2022	2	1	1
New soil	Denmark	gravel and sand quarry operation | sand | Consequential, U - RoW	1.1.1997 - 8.12.2022	2	2	1
Sand	Denmark	gravel and sand quarry operation | sand | Consequential, U - RoW	1.1.1997 - 8.12.2022	2	2	1
Topsoil	Denmark	gravel and sand quarry operation | sand | Consequential, U - RoW	1.1.1997 - 8.12.2022	2	2	1
Plywood	Denmark	plywood production | plywood | Consequential, U - RER	1.1.2012 - 8.12.2022	3	1	1
Shingle stone	Denmark	gravel and sand quarry operation | gravel, round | Consequential, U - RoW	1.1.1997 - 8.12.2022	2	2	1

Table 3 - DQR Construction Stage

Data	Country of production	OpenLCA 1.11.0/ Ecoinvent 3.9.1 consequential upr	Age of Ecoinvent data	Geographical	Technical	Time
Construction stage						
Grass seeds	Denmark	grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	1.1.1995 - 8.12.2022	2	1	1
Drill	Denmark	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	1.1.2014 - 8.12.2022	1	2	1
Welding machine	Denmark	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	1.1.2014 - 8.12.2022	1	2	1
Excavatior	Denmark	excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	1.1.1996 - 8.12.2022	3	1	1
Mini dumber	Denmark	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	1.1.2014 - 8.12.2022	5	2	1
Asphalt Saw	Denmark	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	1.1.2014 - 8.12.2022	5	2	1
Soil Compactor	Denmark	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	1.1.2014 - 8.12.2022	5	2	1
Transport	Denmark	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	1.1.2009 - 8.12.2022	3	2	1

Table 4 - DQR End of Life Stage

Data	Country of production	OpenLCA 1.11.0/ Ecoinvent 3.9.1 consequential upr	Age of Ecoinvent data	Geographical	Technical	Time
End of Life stage						
Transport	Denmark	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	1.1.2009 - 8.12.2022	3	2	1
Grass waste	Denmark	treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	1.3.2014 - 28.2.2022	3	3	1
Brass coupling	Denmark	(Flow: Metal waste)				
Valve System: copper	Denmark	treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	1.1.1994 - 8.12.2022	2	3	1
Valve System: steel	Denmark	treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	1.1.1994 - 8.12.2022	2	3	1
Soil	Denmark	market for soil, contaminated | soil, contaminated | Consequential, U - GLO	1.1.1998 - 8.12.2022	5	3	1
Asphalt	Denmark	treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	1.1.1994 - 8.12.2022	2	3	1
Tiles	Denmark	treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	1.1.1995 - 8.12.2022	3	3	1
Valve system: plastic	Denmark	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	1.1.1994 - 8.12.2022	2	3	1
PE pipe	Denmark	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	1.1.1994 - 8.12.2022	2	3	1
Plywood	Denmark	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	1.1.1994 - 8.12.2022	2	3	1

In some of the processes, the time representativeness of the data is described as the start date of the source, which are highlighted in the tables with bold font. The scoring of the time representativeness for these processes is being accounted for with two scoring values, as the first one is representing the time frame of the data, and the second one in the paranthese is representing the description in the process. There is a possibility that more processes could be based on data from earlier on but are not being specified in the description.

List of Assumptions

The assumptions made for the system, are being made due to available information and/or to simplify the the model of the system for the study. The Table 5 is a description of the assumptions being made.

Table 5 - List of Assumptions

Assumption	Description
Number of trenches	The total of trenches per year and per day is being estimated through extrapolating HOFOR numbers. The number of trenches of the daily and yearly calculations is calculated by using the number of trench operation provided by HOFOR and extrapolating it across the other two companies. The extrapolating is done by reviewing the number of customers of each company and calculating the yearly trenches according to it.
Valve System Parts	The weight of the materials within the parts are being assumed based on the respective datasheets, which can be accessed online by simply searching for the parts ID, which can be found in Table 37 - Valve System Parts, online.
Overall data	The overall data gathered is an average from the three utility companies. It referes to Appendix B.1.4 – Total Consumption, which gives an overview of the all the data gathered from the three utility companies and the calculated average.
Trench size reduction	We are assuming that with RobSub's solution the size of the trench can be reduced by 50%. This is being analysed in the sensitivity analysis.
Tools and machines	it is being assumed that across the three companies machines and tools are the sam
Soil	The different layers of soil, are being modeled as "sand" within the OpenLCA software. These include: Topsoil, levelling sand, gravel, base ground protection, stable ground bearing layer.
Transportation	In the results the average of 18,33 km is being used for the calculation of the impact categories. During the sensitivity analys the minimum of 10 km and the maximum of 30 km is being used.

Inventory Analysis

The consequential modelling method has been chosen as the principle for the inventory analysis, which involves the prediction of possible influence of a decision or an action on the environment, economy, and society. This includes the consideration of the direct and indirect effects of the decision. The software used to utilize the consequential modelling approach is the OpenLCA with the database "ecoinvent_391_consequential_upr".

Life Cycle Inventory

Figure 5 illustrates the life cycle stages. The product stage contains the different materials that are being used during the construction stage. This also includes the production of the valve system, which is currently based on assumptions as only a few information about their material content is known. The construction stage is the focus area in this system. The excavating of the trench and restoration work connected with it is being executed. Between the excavation and restoration work, the installation of the valve system is being completed. As mentioned before, the use phase is not applicable in this study, as the for the valve system the use phase would be operating the system and some hypothetical maintenance. The disposal of the materials is being managed under the end-of-life stage, while the recycling and reusing of materials is under other supplementary information.

The data used for the assessment and the calculation in OpenLCA, is derived from the data gathered through HOFOR, VandCenter Syd, and Aarhus Vand. The average of the data is being cumulated, to create an industry average for these three utility companies. As not all information about materials and tools can be found in the Ecoinvent 3.9.1 database, assumptions and substitutions are being made. Appendix B.2 contains a table of the data inputs used in OpenLCA, with the corresponding data points.

This study is not based on a multifunctional process, which eliminates the need for subdivision, system expansion, or allocation method. Though there might be some multifunctional processes out of the system boundaries, like the production of the valve system, this is out of the scope for this study, which is being represented by the grey box in Figure 5. The materials used in the valve system are being accounted for, as they are also being disposed of at the end of the lifecycle.

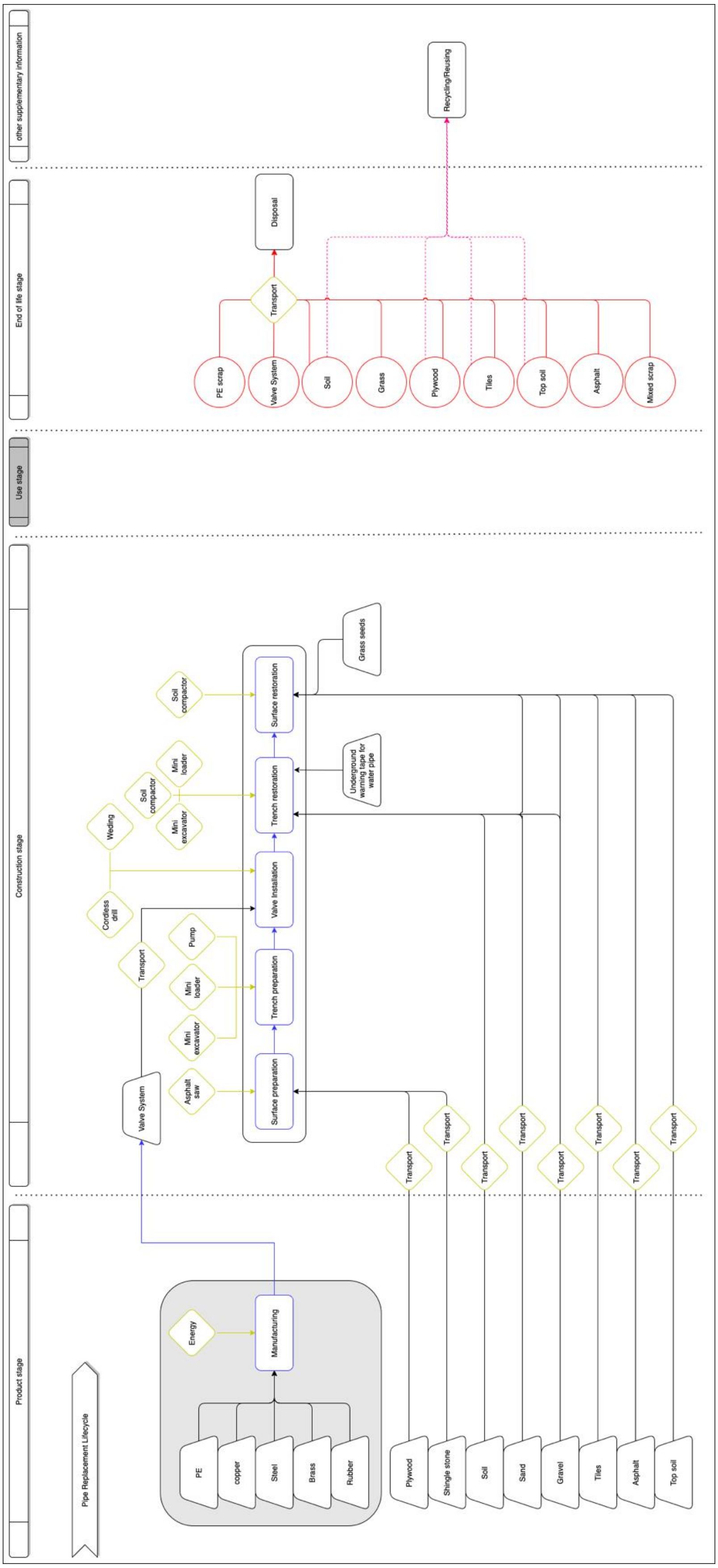

Figure 5 - Life Cycle Stages

Data collection

The collection of data is comprised of ethnography research, in form of visiting construction sites at the partner utility companies and observing the process of the installation work, studying the requirement specifications, communication with experts, and additional research to improve understanding of the process. The requirement specification has been used to create the basic understanding of the process and documenting the process flow diagram, which is being supplemented with the visitation of construction sites. Through meetings and conversation, the PFD is being reviewed and approved. A data sheet is being created and shared with the companies to be filled out with their data. An overview of the data set can be viewed in Appendix B – Data, this data sheet is available in Appendix B.1.

System Modelling per Life Cycle Stage

This section covers the Data that is included in each of these life cycle stages with the respective assumptions evaluation of their reliability and uncertainty. In Appendix B.2 – OpenLCA Ecoinvent Data a list of the processes and flows that are being used in the software to model the system. The life cycle stages are modelled as in Figure 5, which is based on the life cycle stages of buildings/constructions. The data that has been collected is being summarized and the average value is being used for the study.

Product Stage

The product stage comprises of the manufacturing of the parts included in the water pipe valve system, which consist of the electrofusion saddle, electrofusion coupler, electrofusion angle coupler, reducer, stop valve, extension spindle, brass repair coupling, and the stop valve cover. A more detailed list of the estimated numbers for the parts weight distribution across materials can be found in Appendix B.3. By studying the parts, the processes for manufacturing are being assumed, as for the plastic components intrusion marks have been found, which indicates a type of injection moulding. Furthermore, the materials used to restore the trench and the surface after finishing the installation are not fully accurate for the different types that is being used. Therefore, the different types of sand and soil have been generalized under the flow of “sand”. Some of the received data need to be converted to different unit, to be useable for the LCA software. In the Appendix B.1 notes on each data point can be found including links to the source of reference.

Construction Stage

The construction stage is covering the preparation and restoration of the work site, the transportation of materials, and the installation of work of the valve system. The total list of materials, tool and vehicle consumption, and transport can be seen in Appendix B.1.4 – Total Consumption.

The transport of the materials, and of the waste, is a rough estimate based on the hypothesis that all material is being transport by a truck which is carrying a container with the capacity of $8m^3$ (Marius Pedersen, n.d.). Furthermore, it is being estimated that soil, sand, shingle stone, and plywood is being transported together to the site, while asphalt and tiles are being transported together later in the process, due to the fact that these materials are being used in the surface restoration.

For the tools and machines, it is being assumed that across the three utility companies, the same machines and tools are being used, which simplifies the creation of the model and analysis in OpenLCA.

End of Life Stage

Due to the limited information on the end-of-life stage of the materials and products, that are being discarded, this stage is using general flows which represent the different materials as accurate as possible. Within OpenLCA the provider for each flow is the market mix for either Denmark, Europe, or Global, with the intention to be as close as possible to the spatial requirement.

Impact Assessment

To transform the life cycle inventory results into indicator scores, an impact assessment method is applied. The chosen impact assessment method is the ReCiPe 2016 midpoint with the cultural perspective "Hierarchist" (H). The hierarchist approach is often encountered in scientific models and is seen as the default consensus model (PRé, 2016). The midpoint impact assessment contains 18 categories, which can each be more focused on, depending on the relevance. The 18 impact categories and their units are listed in table 6.

Table 6 - ReCiPe 2016, 18 Midpoint Impact Categories

Impact Category	Unit of the Results
Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Freshwater ecotoxicity	kg 1,4-DCB
Freshwater eutrophication	kg P eq
Global warming	kg CO2 eq
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Ionizing radiation	kBq Co-60 eq
Land use	m2a crop eq
Marine ecotoxicity	kg 1,4-DCB
Marine eutrophication	kg N eq
Mineral resource scarcity	kg Cu eq
Ozone formation, Human health	kg NOx eq

Ozone formation, Terrestrial ecosystems	kg NOx eq
Stratospheric ozone depletion	kg CFC11 eq
Terrestrial acidification	kg SO2 eq
Terrestrial ecotoxicity	kg 1,4-DCB
Water consumption	m3

The four impact categories that have been chosen are: **(1)** Global warming, which is being chosen as a main component when communicating results of the study to stakeholders, as it is being associated the most when discussing environmental impacts. **(2)** The second impact category is Land use, as it is closely connected to the resources being used in this system. Land use measures the changes of soil quality, which are caused by agriculture, forestry production, urban settlement, and the extraction of minerals (Hauschild, Rosenbaum, & Olsen, 2018). The third and fourth impact categories have been chosen, because this study is within the water utility sector, where water safety and water consumption is important. **(3)** Freshwater ecotoxicity summarizes the impact on freshwater organisms of toxic substances, which are being emitted to the environment. With **(4)** water consumption, the consumption of water is being accounted for regarding water scarcity

Results

Life Cycle Impact Assessment Results

In this section a single trench is being analyzed and how the reduction of the trench size will affect the impact categories. The section consists of the LCIA results table and the relative LCIA results bar chart, which visualize how the two analyzed process compare to each other. In addition, the contribution tree for each of the four chosen impact categories is being presented to show which process is contributing to which impact category.

The results from the single trench operation can be extrapolated according to either the yearly estimate of operations or other number of trenches, as long as the base parameters are staying the same.

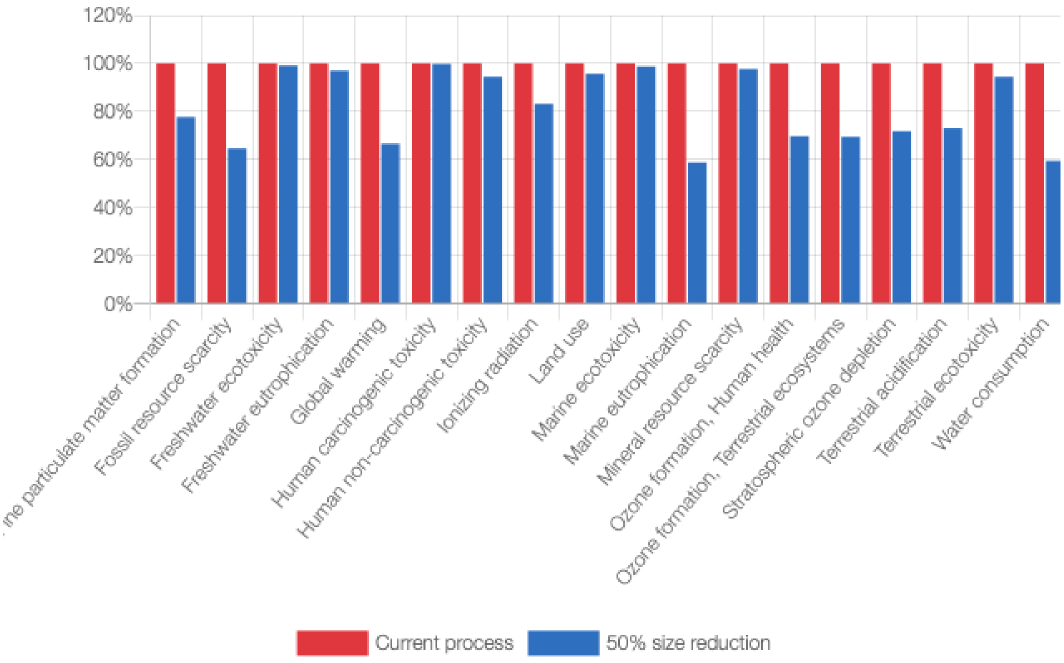

Figure 6 - single trench relative LCIA results

Table 7 - single trench LCIA results

Indicator	Current process	50% size reduction	Unit
Fine particulate matter formation	3,77E-01	2,93E-01	kg PM2.5 eq
Fossil resource scarcity	9,04E+01	5,83E+01	kg oil eq
Freshwater ecotoxicity	3,21E+01	3,18E+01	kg 1,4-DCB
Freshwater eutrophication	3,79E-02	3,67E-02	kg P eq
Global warming	2,52E+02	1,67E+02	kg CO2 eq
Human carcinogenic toxicity	1,68E+01	1,68E+01	kg 1,4-DCB
Human non-carcinogenic toxicity	2,18E+02	2,05E+02	kg 1,4-DCB
Ionizing radiation	9,92E-02	8,25E-02	kBq Co-60 eq
Land use	1,34E+02	1,28E+02	m2a crop eq
Marine ecotoxicity	3,99E+01	3,94E+01	kg 1,4-DCB
Marine eutrophication	2,34E-02	1,37E-02	kg N eq
Mineral resource scarcity	1,74E+00	1,70E+00	kg Cu eq
Ozone formation, Human health	1,31E+00	9,13E-01	kg NOx eq
Ozone formation, Terrestrial ecosystems	1,36E+00	9,43E-01	kg NOx eq
Stratospheric ozone depletion	1,28E-04	9,19E-05	kg CFC11 eq
Terrestrial acidification	7,37E-01	5,37E-01	kg SO2 eq
Terrestrial ecotoxicity	1,14E+03	1,07E+03	kg 1,4-DCB
Water consumption	8,07E+00	4,79E+00	m3

Global warming

The contribution tree for the global warming impact category shows that the contaminated soil, that is discarded, is the highest contributing process in the system with 48% for the current process (Figure 8) and 36% for the reduced process (Figure 9). The results in the reduced process for global warming is being decreased by 33%, wich is 84,34 kg CO_2 eq.

Table 8 – Global warming contribution tree: current process (single trench)

Contribution	Process	Amount	Unit
100.00%	Full Life Cycle : process	251.62595	kg CO2 eq
52.70%	End of Life: process - DK	132.61217	kg CO2 eq
47.97%	market for soil, contaminated | soil, contaminated | Consequential, U - GLO	120.69758	kg CO2 eq
02.23%	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	5.60038	kg CO2 eq
01.07%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	2.69701	kg CO2 eq
00.79%	treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	1.98101	kg CO2 eq
00.23%	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	0.57531	kg CO2 eq
00.22%	treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	0.55386	kg CO2 eq
00.12%	treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	0.29476	kg CO2 eq
00.08%	treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	0.20931	kg CO2 eq
00.00%	treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	0.00295	kg CO2 eq
40.62%	Product: process	102.20027	kg CO2 eq
12.23%	Extension_spindle - DK	30.78048	kg CO2 eq
09.07%	plywood production | plywood | Consequential, U - RER	22.83498	kg CO2 eq
07.08%	mastic asphalt production | mastic asphalt | Consequential, U - CH	17.81315	kg CO2 eq
04.07%	cast iron production | cast iron | Consequential, U - RER	10.24054	kg CO2 eq
03.74%	gravel and sand quarry operation | sand | Consequential, U - RoW	9.42128	kg CO2 eq
01.83%	concrete block production | concrete block | Consequential, U - DE	4.59637	kg CO2 eq
01.42%	Stop_valve - DK	3.56856	kg CO2 eq
00.70%	gravel and sand quarry operation | gravel, round | Consequential, U - RoW	1.74956	kg CO2 eq
00.23%	Electrofusion_saddle - CH	0.57757	kg CO2 eq
00.10%	Electrofusion_angle_coupler - CH	0.24204	kg CO2 eq
00.08%	Electrofusion_coupler - CH	0.20237	kg CO2 eq
00.05%	Reducer - CH	0.11632	kg CO2 eq
00.02%	Brass_repair_coupling	0.05704	kg CO2 eq
06.68%	Construction: Process - DK	16.81351	kg CO2 eq
04.82%	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	12.13864	kg CO2 eq
00.93%	excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	2.34397	kg CO2 eq
00.91%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	2.27932	kg CO2 eq
00.02%	grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	0.04895	kg CO2 eq
00.00%	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	0.00264	kg CO2 eq

Table 9 – Global warming contribution tree: size reduction 50% (single trench)

Contribution	Process	Amount	Unit
100.00%	Full Life Cycle : process	167.28857	kg CO2 eq
50.53%	Product: process	84.53504	kg CO2 eq
18.40%	Extension_spindle - DK	30.78048	kg CO2 eq
13.65%	plywood production | plywood | Consequential, U - RER	22.83498	kg CO2 eq
06.12%	cast iron production | cast iron | Consequential, U - RER	10.24054	kg CO2 eq
05.32%	mastic asphalt production | mastic asphalt | Consequential, U - CH	8.90658	kg CO2 eq
02.82%	gravel and sand quarry operation | sand | Consequential, U - RoW	4.71062	kg CO2 eq
02.13%	Stop_valve - DK	3.56856	kg CO2 eq
01.37%	concrete block production | concrete block | Consequential, U - DE	2.29793	kg CO2 eq
00.35%	Electrofusion_saddle - CH	0.57757	kg CO2 eq
00.14%	Electrofusion_angle_coupler - CH	0.24204	kg CO2 eq
00.12%	Electrofusion_coupler - CH	0.20237	kg CO2 eq
00.07%	Reducer - CH	0.11632	kg CO2 eq
00.03%	Brass_repair_coupling	0.05704	kg CO2 eq
41.27%	End of Life: process - DK	69.04060	kg CO2 eq
36.07%	market for soil, contaminated | soil, contaminated | Consequential, U - GLO	60.34879	kg CO2 eq
03.35%	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	5.60038	kg CO2 eq
00.59%	treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	0.99051	kg CO2 eq
00.43%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.71671	kg CO2 eq
00.34%	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	0.57531	kg CO2 eq
00.33%	treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	0.55386	kg CO2 eq
00.09%	treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	0.14745	kg CO2 eq
00.06%	treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	0.10464	kg CO2 eq
00.00%	treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	0.00295	kg CO2 eq
08.20%	Construction: Process - DK	13.71293	kg CO2 eq
07.26%	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	12.13864	kg CO2 eq
00.70%	excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	1.17446	kg CO2 eq
00.23%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.37761	kg CO2 eq
00.01%	grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	0.01958	kg CO2 eq
00.00%	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	0.00264	kg CO2 eq

Land use

The process which is contributing the most to land use, is the production of plywood, which is used for supporting the walls of the trench, with 91% for the current process (Table 10) and 95% for the reduced process (Table 11). In total 5,8 m2a crop eq. can be saved, which is 4% of the current process.

Table 10 - Land use contribution tree: current process (single trench)

Contribution	Process	Amount	Unit
100.00%	Full Life Cycle : process	133.63938	m2a crop eq
94.21%	Product: process	125.90382	m2a crop eq
90.70%	plywood production | plywood | Consequential, U - RER	121.20724	m2a crop eq
02.05%	mastic asphalt production | mastic asphalt | Consequential, U - CH	2.73854	m2a crop eq
00.67%	gravel and sand quarry operation | sand | Consequential, U - RoW	0.89064	m2a crop eq
00.35%	Extension_spindle - DK	0.46954	m2a crop eq
00.15%	Stop_valve - DK	0.20423	m2a crop eq
00.13%	gravel and sand quarry operation | gravel, round | Consequential, U - RoW	0.16885	m2a crop eq
00.09%	cast iron production | cast iron | Consequential, U - RER	0.12385	m2a crop eq
00.09%	concrete block production | concrete block | Consequential, U - DE	0.11913	m2a crop eq
00.01%	Brass_repair_coupling	0.01288	m2a crop eq
-00.00%	Electrofusion_coupler - CH	-0.00049	m2a crop eq
-00.00%	Electrofusion_angle_coupler - CH	-0.00280	m2a crop eq
-00.01%	Reducer - CH	-0.00679	m2a crop eq
-00.02%	Electrofusion_saddle - CH	-0.02099	m2a crop eq
05.59%	End of Life: process - DK	7.46939	m2a crop eq
04.99%	market for soil, contaminated | soil, contaminated | Consequential, U - GLO	6.66872	m2a crop eq
00.25%	treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	0.33921	m2a crop eq
00.19%	treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	0.24799	m2a crop eq
00.07%	treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	0.08935	m2a crop eq
00.07%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.08880	m2a crop eq
00.03%	treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	0.03854	m2a crop eq
00.00%	treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	0.00186	m2a crop eq
-00.00%	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	-0.00039	m2a crop eq
-00.00%	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	-0.00469	m2a crop eq
00.20%	Construction: Process - DK	0.26617	m2a crop eq
00.13%	grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	0.17539	m2a crop eq
00.06%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.07505	m2a crop eq
00.03%	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	0.04324	m2a crop eq
-00.00%	excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	-0.00336	m2a crop eq
-00.02%	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	-0.02415	m2a crop eq

Table 11 - Land use contribution tree: size reduction 50% (single trench)

Contribution	Process	Amount	Unit
100.00%	Full Life Cycle : process	127.84271	m2a crop eq
96.89%	Product: process	123.86081	m2a crop eq
94.81%	plywood production | plywood | Consequential, U - RER	121.20724	m2a crop eq
01.07%	mastic asphalt production | mastic asphalt | Consequential, U - CH	1.36927	m2a crop eq
00.37%	Extension_spindle - DK	0.46954	m2a crop eq
00.35%	gravel and sand quarry operation | sand | Consequential, U - RoW	0.44532	m2a crop eq
00.16%	Stop_valve - DK	0.20423	m2a crop eq
00.10%	cast iron production | cast iron | Consequential, U - RER	0.12385	m2a crop eq
00.05%	concrete block production | concrete block | Consequential, U - DE	0.05956	m2a crop eq
00.01%	Brass_repair_coupling	0.01288	m2a crop eq
-00.00%	Electrofusion_coupler - CH	-0.00049	m2a crop eq
-00.00%	Electrofusion_angle_coupler - CH	-0.00280	m2a crop eq
-00.01%	Reducer - CH	-0.00679	m2a crop eq
-00.02%	Electrofusion_saddle - CH	-0.02099	m2a crop eq
03.04%	End of Life: process - DK	3.88190	m2a crop eq
02.61%	market for soil, contaminated | soil, contaminated | Consequential, U - GLO	3.33436	m2a crop eq
00.27%	treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	0.33921	m2a crop eq
00.10%	treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	0.12400	m2a crop eq
00.03%	treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	0.04469	m2a crop eq
00.02%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.02360	m2a crop eq
00.02%	treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	0.01927	m2a crop eq
00.00%	treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	0.00186	m2a crop eq
-00.00%	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	-0.00039	m2a crop eq
-00.00%	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	-0.00469	m2a crop eq
00.08%	Construction: Process - DK	0.10000	m2a crop eq
00.05%	grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	0.07016	m2a crop eq
00.03%	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	0.04324	m2a crop eq
00.01%	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.01243	m2a crop eq
-00.00%	excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	-0.00169	m2a crop eq
-00.02%	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	-0.02415	m2a crop eq

Freshwater ecotoxicity

In the impact category Freshwater ecotoxicity, the main contributors is connected to the valve system parts, which involve the disposal of the steel and copper parts in them and the production of the stop valve, see Table 12 and Table 13. The impact category can be reduced by 1% by reducing the trench size, which accounts for 0,3 kg 1,4-DCB.

Table 12 - Freshwater ecotoxicity contribution tree: current process (single trench)

Contribution	Process	Amount	Unit
100.00%	P Full Life Cycle : process	32.11546	kg 1,4-DCB
73.07%	P End of Life: process - DK	23.46734	kg 1,4-DCB
51.38%	P treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	16.50223	kg 1,4-DCB
19.58%	P treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	6.28905	kg 1,4-DCB
00.97%	P market for soil, contaminated | soil, contaminated | Consequential, U - GLO	0.31270	kg 1,4-DCB
00.53%	P treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	0.17168	kg 1,4-DCB
00.45%	P treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	0.14395	kg 1,4-DCB
00.14%	P treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	0.04467	kg 1,4-DCB
00.01%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00272	kg 1,4-DCB
00.00%	P treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	0.00024	kg 1,4-DCB
00.00%	P treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	0.00011	kg 1,4-DCB
26.90%	P Product: process	8.64037	kg 1,4-DCB
20.10%	P Stop_valve - DK	6.45511	kg 1,4-DCB
03.84%	P Extension_spindle - DK	1.23356	kg 1,4-DCB
01.31%	P plywood production | plywood | Consequential, U - RER	0.41954	kg 1,4-DCB
01.27%	P cast iron production | cast iron | Consequential, U - RER	0.40673	kg 1,4-DCB
00.27%	P gravel and sand quarry operation | sand | Consequential, U - RoW	0.08627	kg 1,4-DCB
00.10%	P concrete block production | concrete block | Consequential, U - DE	0.03144	kg 1,4-DCB
00.05%	P gravel and sand quarry operation | gravel, round | Consequential, U - RoW	0.01448	kg 1,4-DCB
00.03%	P Electrofusion_saddle - CH	0.01097	kg 1,4-DCB
00.03%	P Electrofusion_angle_coupler - CH	0.00860	kg 1,4-DCB
00.03%	P Electrofusion_coupler - CH	0.00834	kg 1,4-DCB
00.01%	P Brass_repair_coupling	0.00175	kg 1,4-DCB
00.00%	P Reducer - CH	0.00078	kg 1,4-DCB
-00.12%	P mastic asphalt production | mastic asphalt | Consequential, U - CH	-0.03720	kg 1,4-DCB
00.02%	P Construction: Process - DK	0.00775	kg 1,4-DCB
00.01%	P machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	0.00464	kg 1,4-DCB
00.01%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00230	kg 1,4-DCB
00.00%	P excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	0.00075	kg 1,4-DCB
00.00%	P grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	5.33512E-5	kg 1,4-DCB
00.00%	P market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	3.95155E-6	kg 1,4-DCB

Table 13 - Freshwater ecotoxicity contribution tree: size reduction 50% (single trench)

Contribution	Process	Amount	Unit
100.00%	P Full Life Cycle : process	31.81404	kg 1,4-DCB
73.00%	P End of Life: process - DK	23.22298	kg 1,4-DCB
51.87%	P treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	16.50223	kg 1,4-DCB
19.77%	P treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	6.28905	kg 1,4-DCB
00.49%	P market for soil, contaminated | soil, contaminated | Consequential, U - GLO	0.15635	kg 1,4-DCB
00.45%	P treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	0.14395	kg 1,4-DCB
00.27%	P treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	0.08584	kg 1,4-DCB
00.14%	P treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	0.04467	kg 1,4-DCB
00.00%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00072	kg 1,4-DCB
00.00%	P treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	0.00012	kg 1,4-DCB
00.00%	P treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	5.26722...	kg 1,4-DCB
26.99%	P Product: process	8.58564	kg 1,4-DCB
20.29%	P Stop_valve - DK	6.45511	kg 1,4-DCB
03.88%	P Extension_spindle - DK	1.23356	kg 1,4-DCB
01.32%	P plywood production | plywood | Consequential, U - RER	0.41954	kg 1,4-DCB
01.28%	P cast iron production | cast iron | Consequential, U - RER	0.40673	kg 1,4-DCB
00.14%	P gravel and sand quarry operation | sand | Consequential, U - RoW	0.04313	kg 1,4-DCB
00.05%	P concrete block production | concrete block | Consequential, U - DE	0.01572	kg 1,4-DCB
00.03%	P Electrofusion_saddle - CH	0.01097	kg 1,4-DCB
00.03%	P Electrofusion_angle_coupler - CH	0.00860	kg 1,4-DCB
00.03%	P Electrofusion_coupler - CH	0.00834	kg 1,4-DCB
00.01%	P Brass_repair_coupling	0.00175	kg 1,4-DCB
00.00%	P Reducer - CH	0.00078	kg 1,4-DCB
-00.06%	P mastic asphalt production | mastic asphalt | Consequential, U - CH	-0.01860	kg 1,4-DCB
00.02%	P Construction: Process - DK	0.00542	kg 1,4-DCB
00.01%	P machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	0.00464	kg 1,4-DCB
00.00%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00038	kg 1,4-DCB
00.00%	P excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	0.00038	kg 1,4-DCB
00.00%	P grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	2.13405...	kg 1,4-DCB
00.00%	P market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	3.95155...	kg 1,4-DCB

Water consumption

The main contributors for the impact category water consumption is the gravel and sand quarry operation with 56% (current process) and 47% (reduced process). In both processes, the plywood production is the water consumption at 1,97174 m3. While it is contributing 24% at the current process (Table 14), it contributes 41% in the reduced process (Table 15), due to the reduction of other materials, which leads to the increase contribution percentage of the plywood production. In total can the reduction of the trench size save 3,28 m3 of water, for each trench operation, which is 41% of the current process.

Table 14 - Water consumption contribution tree: current process (single trench)

Contribution	Process	Amount	Unit
100.00%	P Full Life Cycle : process	8.07332	m3
98.20%	P Product: process	7.92789	m3
56.04%	P gravel and sand quarry operation | sand | Consequential, U - RoW	4.52443	m3
24.42%	P plywood production | plywood | Consequential, U - RER	1.97174	m3
10.67%	P gravel and sand quarry operation | gravel, round | Consequential, U - RoW	0.86146	m3
03.10%	P Extension_spindle - DK	0.25019	m3
01.94%	P mastic asphalt production | mastic asphalt | Consequential, U - CH	0.15627	m3
00.80%	P cast iron production | cast iron | Consequential, U - RER	0.06470	m3
00.55%	P concrete block production | concrete block | Consequential, U - DE	0.04464	m3
00.55%	P Stop_valve - DK	0.04428	m3
00.06%	P Electrofusion_saddle - CH	0.00521	m3
00.03%	P Electrofusion_angle_coupler - CH	0.00251	m3
00.03%	P Electrofusion_coupler - CH	0.00222	m3
00.01%	P Reducer - CH	0.00086	m3
-00.01%	P Brass_repair_coupling	-0.00062	m3
01.79%	P End of Life: process - DK	0.14418	m3
01.41%	P market for soil, contaminated | soil, contaminated | Consequential, U - GLO	0.11409	m3
00.34%	P treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	0.02775	m3
00.03%	P treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	0.00262	m3
00.02%	P treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	0.00170	m3
00.01%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00115	m3
00.01%	P treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	0.00074	m3
00.00%	P treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	3.57645E-5	m3
00.00%	P treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	1.00461E-5	m3
-00.05%	P treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	-0.00393	m3
00.02%	P Construction: Process - DK	0.00125	m3
00.01%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00097	m3
00.01%	P machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	0.00073	m3
00.00%	P market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	7.18668E-7	m3
00.00%	P grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	0.00000	m3
-00.01%	P excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	-0.00045	m3

Table 15 - Water consumption contribution tree: size reduction 50% (single trench)

Contribution	Process	Amount	Unit
100.00%	P Full Life Cycle : process	4.79181	m3
98.16%	P Product: process	4.70376	m3
47.21%	P gravel and sand quarry operation | sand | Consequential, U - RoW	2.26221	m3
41.15%	P plywood production | plywood | Consequential, U - RER	1.97174	m3
05.22%	P Extension_spindle - DK	0.25019	m3
01.63%	P mastic asphalt production | mastic asphalt | Consequential, U - CH	0.07813	m3
01.35%	P cast iron production | cast iron | Consequential, U - RER	0.06470	m3
00.92%	P Stop_valve - DK	0.04428	m3
00.47%	P concrete block production | concrete block | Consequential, U - DE	0.02232	m3
00.11%	P Electrofusion_saddle - CH	0.00521	m3
00.05%	P Electrofusion_angle_coupler - CH	0.00251	m3
00.05%	P Electrofusion_coupler - CH	0.00222	m3
00.02%	P Reducer - CH	0.00086	m3
-00.01%	P Brass_repair_coupling	-0.00062	m3
01.82%	P End of Life: process - DK	0.08738	m3
01.19%	P market for soil, contaminated | soil, contaminated | Consequential, U - GLO	0.05704	m3
00.58%	P treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH	0.02775	m3
00.05%	P treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH	0.00262	m3
00.02%	P treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH	0.00085	m3
00.02%	P treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH	0.00074	m3
00.01%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00030	m3
00.00%	P treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland	1.78802...	m3
00.00%	P treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH	1.00461...	m3
-00.04%	P treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW	-0.00196	m3
00.01%	P Construction: Process - DK	0.00066	m3
00.02%	P machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO	0.00073	m3
00.00%	P transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER	0.00016	m3
00.00%	P market for electricity, low voltage | electricity, low voltage | Consequential, U - DK	7.18668...	m3
00.00%	P grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW	0.00000	m3
-00.00%	P excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER	-0.00023	m3

When looking into the scenarios of the daily and yearly operations, we see that the relative results are staying unchangeable, while the LCIA results are being increased by the multiply factor in response to the number of trenches. In the Table 16 - Absolute reduction of the two scenariosthe difference between the current and new process can be viewed. The full list of the LCIA results can be seen in Table 17 -

LCIA results Dail scenario and Table 18 – LCIA results Yearly scenario. Through the size reduction could there be saved 759.876,37 kg CO2 eq. and 29.566,41 m3 of water in the estimated yearly trench operation, to point out two of the 18 impact categories.

Table 16 - Absolute reduction of the two scenarios

	Absolute reduction of the two scenarios				
Impact Category	**Single trench**	**Daily** (35 trenche	**Yearly** (9010 trenches)	**Difference in %**	Unit
Global Warming	84,34	2951,80	759876,37	34%	kg CO2 eq
Land Use	5,80	202,86	52221,96	4%	m2a crop eq
Freshwater Ecotoxicity	0,30	10,55	2716,51	1%	kg 1,4-DCB
Water Consumption	3,28	114,85	29566,41	41%	m3

The percentage of the calculated difference for the three scenarios are the same.

Table 17 - LCIA results Dail scenario

Indicator	Current process	50% size reduction	Unit
Fine particulate matter formation	1,32E+01	1,02E+01	kg PM2.5 eq
Fossil resource scarcity	3,16E+03	2,04E+03	kg oil eq
Freshwater ecotoxicity	1,12E+03	1,11E+03	kg 1,4-DCB
Freshwater eutrophication	1,33E+00	1,28E+00	kg P eq
Global warming	8,81E+03	5,86E+03	kg CO2 eq
Human carcinogenic toxicity	5,89E+02	5,88E+02	kg 1,4-DCB
Human non-carcinogenic toxicity	7,61E+03	7,18E+03	kg 1,4-DCB
Ionizing radiation	3,47E+00	2,89E+00	kBq Co-60 eq
Land use	4,68E+03	4,47E+03	m2a crop eq
Marine ecotoxicity	1,39E+03	1,38E+03	kg 1,4-DCB
Marine eutrophication	8,20E-01	4,81E-01	kg N eq
Mineral resource scarcity	6,09E+01	5,95E+01	kg Cu eq
Ozone formation, Human health	4,59E+01	3,19E+01	kg NOx eq
Ozone formation, Terrestrial ecosystems	4,76E+01	3,30E+01	kg NOx eq
Stratospheric ozone depletion	4,48E-03	3,22E-03	kg CFC11 eq
Terrestrial acidification	2,58E+01	1,88E+01	kg SO2 eq
Terrestrial ecotoxicity	3,99E+04	3,76E+04	kg 1,4-DCB
Water consumption	2,83E+02	1,68E+02	m3

Table 18 – LCIA results Yearly scenario

Indicator	Current process	50% size reduction	Unit
Fine particulate matter formation	3,40E+03	2,64E+03	kg PM2.5 eq
Fossil resource scarcity	8,15E+05	5,26E+05	kg oil eq
Freshwater ecotoxicity	2,89E+05	2,87E+05	kg 1,4-DCB
Freshwater eutrophication	3,41E+02	3,31E+02	kg P eq
Global warming	2,27E+06	1,51E+06	kg CO2 eq
Human carcinogenic toxicity	1,52E+05	1,51E+05	kg 1,4-DCB
Human non-carcinogenic toxicity	1,96E+06	1,85E+06	kg 1,4-DCB
Ionizing radiation	8,94E+02	7,43E+02	kBq Co-60 eq
Land use	1,20E+06	1,15E+06	m2a crop eq
Marine ecotoxicity	3,59E+05	3,55E+05	kg 1,4-DCB
Marine eutrophication	2,11E+02	1,24E+02	kg N eq
Mineral resource scarcity	1,57E+04	1,53E+04	kg Cu eq
Ozone formation, Human health	1,18E+04	8,22E+03	kg NOx eq
Ozone formation, Terrestrial ecosystems	1,23E+04	8,50E+03	kg NOx eq
Stratospheric ozone depletion	1,15E+00	8,28E-01	kg CFC11 eq
Terrestrial acidification	6,64E+03	4,84E+03	kg SO2 eq
Terrestrial ecotoxicity	1,03E+07	9,68E+06	kg 1,4-DCB
Water consumption	7,27E+04	4,32E+04	m3

Interpretation

Sensitivity Analysis

The sensitivity analysis is focusing on the transportation and the size reduction of the trench, as the results of the contribution analysis in the previous section revealed the significance of these parameters. A sensitivity of larger than 10% is being deemed as significant in this study.

Transport

During the data collection the distance of transportation varies between the three utility companies varies between 10 – 30 km, therefore its sensitivity is being analysed. The base case is for the distance value of 18,33km, which is the average distance of the data that has been collected.

Table 19 - Transportation sensitivity on global warming

Transportation distance	10km	30km
Base case, kg CO2 eq	251,626	251,626
Altered size, kg CO2 eq	250,399	257,899
Deviation, kg CO2 eq	-1,227	6,273
Deviation %	-0,49%	2,49%
Sensitivity %	0,49%	2,49%

The calculation shows that the distance has a low significant influence to the global warming impact category. This means that in the future when we are assessing the environmental impact, assumptions on transportation are acceptable.

Trench size

At the current state, the exact operation and the space needed to operate in the trench for the robot is not known, and therefore the possible size reduction of the trench can only be assumed. Table 20 shows the sensitivity of a trench size reduction of 33% in relation to the RobSubs alternative of 50%. The calculations shows that there is a significant sensitiy of 16%, which means that in the future the data quality in terms of the potential size reduction should be as precise as possible to create accurate calculations.

Table 20 – Trench size sensitivity global warming

Trench size	33%
Base case, kg CO2 eq	167,289
Altered size, kg CO2 eq	193,445
Deviation, kg CO2 eq	26,156
Deviation %	16%
Sensitivity %	16%

Conclusion

The study has been conducted by RobSub with support of the partner companies Aarhus Vand, HOFOR, and VandCenter Syd, who helped with approving the documentation of the process and providing data to be used in the Life Cycle Inventory. The framework of the report is according to the Life Cycle Assessment methodology as described by the ISO 14040 Environmental management – Life cycle assessment – Principles and framework and the ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines standards. The data of the study consists of estimations, which are being based on average values received by the partner companies and assumptions made through field study and research. This is being used to model the system as close as possible, which reflects the real word, but cannot represent it completely.

The study shows that reducing the size of the trench is on the average reducing the environmental impact of the process by 25%. The analysis of the contribution tree shows that the main contribution is coming from the product and end-of-life stages. The main processes involved in the contribution consists of the processes involving the gathering of new soil and the disposal of the old soil, the production and disposal of the steel components in the valve system parts, and the production of the plywood. The sensitivity analysis shows that global warming is not sensitive to the transportation, but it should not be neglected in the future, as in this case only the currently available shortest and longest distance are being investigated.

For further improvement of the study the quality of the data needs to be refined to decrease the degree of uncertainty, which can be achieved by the utility companies through implementing more thorough documentation during the replacement process for the next projects. In terms of data quality of parts produced by third parties, there is a possibility that in the future more reliable data will be available, as the need and demand for LCA on products is increasing. The size of the trench is an influential part in the assessment and is at the current stage only an estimation and need more investigation on the robot operation and the process of supporting and securing the walls of the trench.

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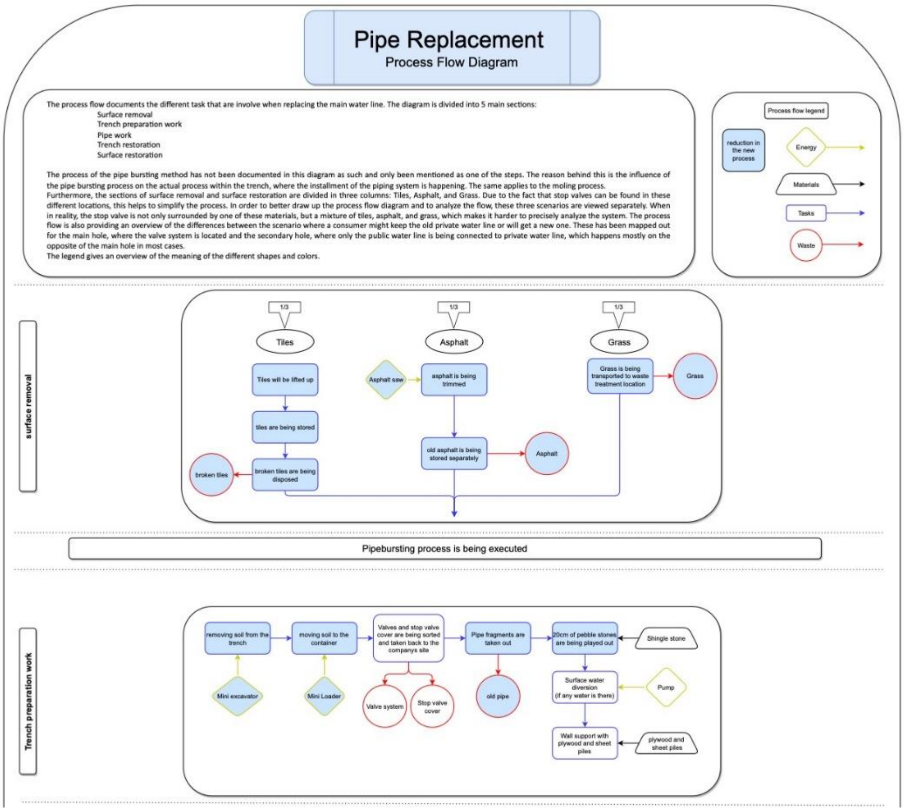
Appendix

Appendix A.1 – Pipe Replacement Process Flow Diagram



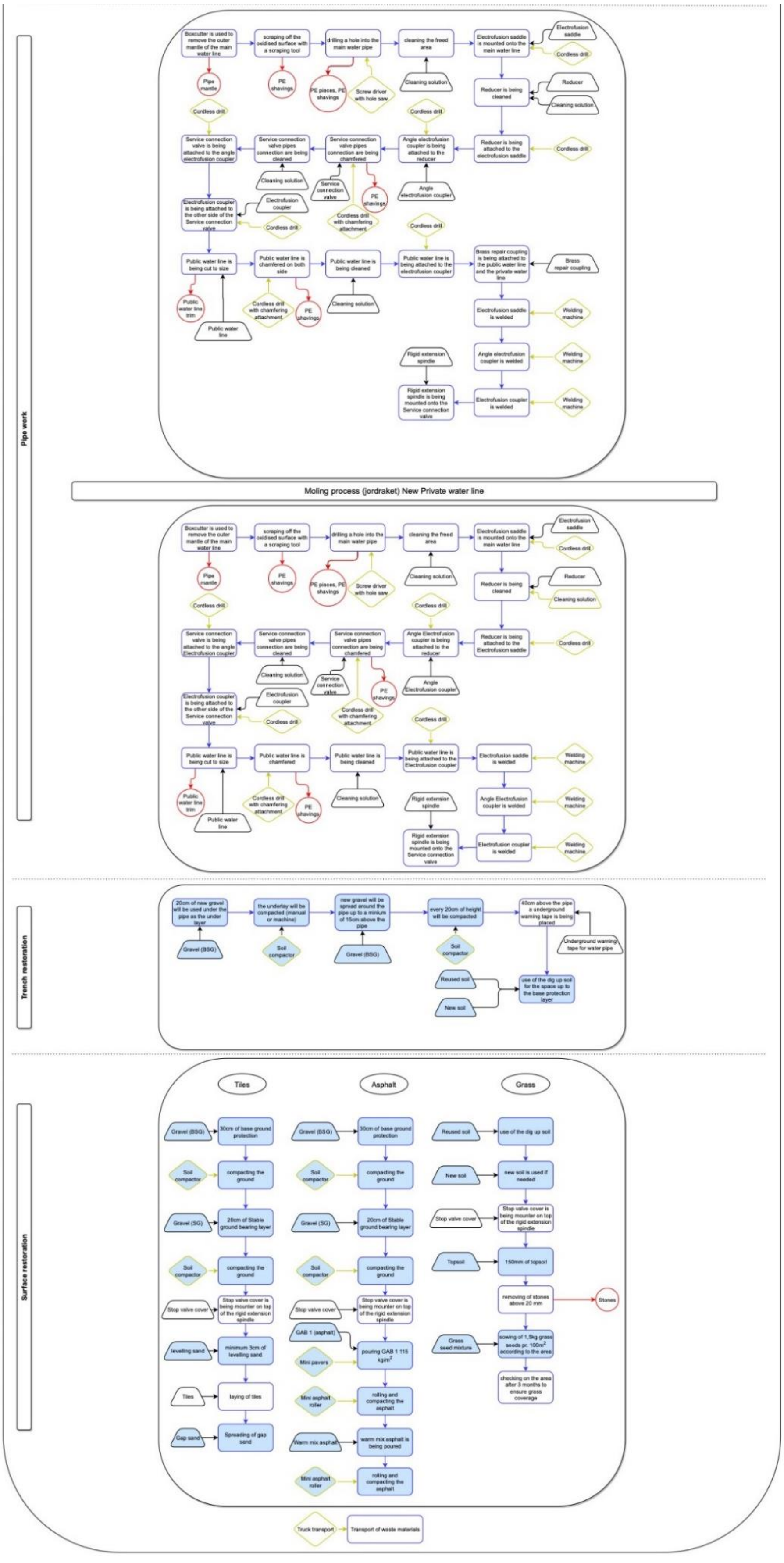


Figure 7 - Full Process Flow Diagram

Appendix B – Data

Appendix B.1 – Data Utility Companies

Appendix B.1.1 – Aarhus Vand

Table 21 – Aarhus Vand

			LCA								
Material	Amount	Unit	Amount2	Unit2	Stage	Process	Tool or form of manual labour	Amount3	Unit3	Notes	Additional links
Tiles	0,83	m2	0,08	m3	Construction	Surface preparation	shovel	N/A	N/A	use of shovels and iron poles to lift the tiles. Standard tiles: 10 cm thickness	
Broken Tiles	0,13	m2	28,75	kg	Construction, End of Life	Surface preparation, End of Life	Excavator	0,01	m3	use of excavator to scrap off broken tiles to a mini dumper. // 230kg/m2	*LINK*
Broken Tiles							Mini Dumper	0,50	hrs	transporting broken tiles to a container.	
New Tiles	0,13	m2	0,01	m3	Product	Surface restoration	Manual labour	N/A	N/A	Laying tiles.	
Asphalt	0,83	m2	135,33	kg	Construction/End of Life	Surface preparation, End of Life	Asphalt saw	5,00	min	cutting of asphalt. // thickness of 7cm // 2,32 t/m3	*LINK*
Asphalt							Mini Dumper	0,50	hrs	Transport of asphalt to a container.	
New Asphalt	0,83	m2	135,33	kg	Construction/End of Life	Surface restoration	Shovel	N/A	N/A	Laying of asphalt material // 2,32 t/m3	*LINK*
New Asphalt							Asphalt roller (manual)	N/A	N/A	Rolling of asphalt.	
Grass	0,83	m2	16,67	kg	Construction/End of Life	Surface preparation, End of Life	Excavator	0,13	m3	Removing of Grass. // 1m2= 16-20kg // estimate of 15 cm thickness, based on fieldwork	*LINK*
Grass							Mini Dumper	0,50	hrs	Transport of grass to a container.	
Topsoil Reuse	0,13	m3	200,00	kg	Product/Construction	Surface restoration	Shovel	N/A	N/A	Prepping the toplayer to be sown.	*LINK*
New Topsoil	0,38	m3	600,00	kg	Product/Construction	Surface restoration	Shovel	N/A	hrs	Prepping the toplayer to be sown.	*LINK*
Grass seeds	33,33	gram	0,10	kg	Construction	Surface restoration	Manual labour	N/A	N/A	Sowing of a grass seed mixture.	
Digged up Soil	2,50	m3	4000,00	kg	Construction	Trench preperation	Excavator	2,50	m3	Digging out the trench. The average of 1600kg per cubic meter of soil is taken for calculation in all type of sand and soil	*LINK*
Digged up Soil							Shovel	N/A	N/A	when reached the Underground warning tape, the area will be digged out carefully with a shovel.	
Digged up Soil							Mini Dumper	0,50	hrs	Transporting the soil to a container	*LINK*
New soil	1,25	m3	2000,00	kg	Product/Construction	Trench restoration	Shovel	N/A	N/A	filling the trench.	
New soil							Soil compactor	5,00	min	Compacting the soil. For each 40cm layer.	
Discarded soil	1,25	m3	2000,00	kg	End of Life	End of Life				Soil disposal.	*LINK*
Reused soil	1,25	m3	2000,00	kg	Product/Construction/ End of Life	Trench restoration	Shovel	N/A	N/A	filling the trench.	*LINK*
Reused soil							Soil compactor	5,00	min	Compacting the soil. For each 40cm layer.	
Sand	0,03	m3	48,00	kg	Product/Construction	Surface restoration	Manual labour	N/A	N/A	Levelling sand for tiles.	*LINK*
PE (water pipe)	0,40	m	0,12	kg	Construction/End of Life	Pipe work	Pipe scissor	N/A	N/A	Pipe is being cutted to size // 0,29 kg/m	*LINK*
Electrofusion Saddle	1,00	unit	0,44	kg	Product/Construction/ End of Life	Pipe work	Dismantling tool	N/A	N/A	removing the outer mantle of the main water line.	
Electrofusion Saddle							Surface scraper	N/A	N/A	prepping the exposed layer of the main water line for welding	
Electrofusion Saddle						(only VCS)	Cordless drill 650W	0,50	min	Drilling a hole in to main water line	
Electrofusion Saddle							Cordless drill 650W	1,00	min	fastening the screws	
Electrofusion Saddle							Welding machine	5,00	min	welding	*LINK*
Electrofusion coupler	1,00	unit	0,05	kg	Product/Construction/ End of Life	Pipe work	Cordless drill 650W	0,50	min	Chamfering	
Electrofusion coupler							Cordless drill 650W	1,00	min	fastening the screws	
Electrofusion coupler							Welding machine	3,00	min	welding	*LINK*
Electrofusion angle coupler	1,00	unit	0,09	kg	Product/Construction/ End of Life	Pipe work	Cordless drill 650W	0,50	min	Chamfering	
Electrofusion angle coupler							Cordless drill 650W	1,00	min	fastening the screws	
Electrofusion angle coupler							Welding machine	3,00	min	welding	*LINK*
Reducer	1,00	unit	0,11	kg	Product/Construction/ End of Life	Pipe work	Cordless drill 650W	0,50	min	Chamfering	
Stop valve	1,00	unit	1,40	kg	Product/Construction/ End of Life	Pipe work	Cordless drill 650W	0,50	min	Chamfering	
Extension spindle	1,00	unit	2,50	kg	Product/Construction/ End of Life	Pipe work	Manual labour	N/A	N/A	mounting spindle onto the stop valve	
Stop valve cover	1,00	unit	4,30	kg	Product/Construction/ End of Life	Surface restoration	Manual labour	N/A	N/A	mounting cover onto the spindle	
Brass repair coupling	2,00	unit	1,01	kg	Product/Construction/ End of Life	Pipe work	Manual labour	N/A	hrs	connecting the public water pipe with the private water line	*LINK*
Waste transport	2,22	ton	30,00	km	Construction	Transport	Truck/container			transport of material to disposal location.	
Waste transport	1,51	m3	30,00	km	Construction	Transport	Truck/container			the same waste only described in cubic metres.	
Plywood	3,00	m2	0,06	m3	Construction/End of Life	Trench preperation	Manual labour	N/A	N/A	wall support of the trench. Average weight of 575kg/m3	*LINK*
Shingle stone	750,00	kg	750,00	kg	Construction	Trench preperation	Manual labour	N/A	N/A	Trench floor is being layed out with 20 cm of shingle stones.	*LINK*
Material transport	3,60	ton	10,00	km	Construction	Transport	Truck/container			transport of material to construction site.	
Material transport	2,59	m3	10,00	km	Construction	Transport	Truck/container			transport of material to construction site.	

Total Tools/Machines			
Cordless drill 54W	0,09	hrs	
Asphalt saw	0,08	hrs	
Soil compactor	0,33	hrs	5 min for each 40 cm layer, roughly 4 layers in 1,4m deep
Welding machine	0,18	hrs	1300 W
Mini Dumper	2,00	hrs	
Excavator	2,64	m3	

Appendix B.1.2 – HOFOR

Table 22 - HOFOR

Material	Amount	Unit	LCA Amount2	Unit2	Stage	Process	Tool or form of manual labour	Amount3	Unit3	Notes	Additional links
Tiles	1,33	m2	0,13	m3	Construction	Surface preperation	shovel	0,50	hrs	use of shovels and iron poles to lift the tiles. Standard tiles: 10 cm thickness	
Broken Tiles	0,53	m2	122,67	kg	Construction	Surface preparation, End of Life	Excavator	0,05	m3	use of excavator to scrap off broken tiles to a mini dumper. // 230kg/m2	*LINK*
					End of Life		Mini Dumper	0,50	hrs	transporting broken tiles to a container.	
New Tiles	0,53	m2	0,05	m3	Product	Surface restoration	Manual labour	4,00	hrs	Laying tiles.	
Asphalt	1,33	m2	216,53	kg	Construction/End of Life	Surface preparation, End of Life	Asphalt saw	1,00	hrs	cutting of asphalt. // thickness of 7cm // 2,32 t/m3	*LINK*
							Mini Dumper	0,50	hrs	Transport of asphalt to a container.	
New Asphalt	1,33	m2	216,53	kg	Construction/End of Life	Surface restoration	Shovel	2,00	hrs	Laying of asphalt material // 2,32 t/m3	*LINK*
							Asphalt roller (manual)/ pladevibrator	0,50	hrs	Rolling of asphalt.	
Grass	1,33	m2	26,67	kg	Construction/End of Life	Surface preparation, End of Life	Excavator	0,20	m3	Removing of Grass. // 1m2= 16-20kg // estimate of 15 cm thickness, based on fieldwork	*LINK*
							Mini Dumper	0,50	hrs	Transport of grass to a container.	
Topsoil Reuse	0,07	m3	106,67	kg	Product/Construction	Surface restoration	Shovel	2,00	hrs	Prepping the toplayer to be sown.	*LINK*
New Topsoil	0,20	m3	320,00	kg	Product/Construction	Surface restoration	Shovel	included in the overall 4 hours per hole	hrs	Prepping the toplayer to be sown.	*LINK*
Grass seeds	20,00	gramm	0,02	kg	Construction	Surface restoration	Manual labour	0,25	hrs	Sowing of a grass seed mixture. // 1,5 kg per 100m^2	
Digged up Soil	6,00	m3	9600,00	kg	Construction	Trench preperation	Excavator	6,00	m3	Digging out the trench. The average of 1600kg per cubic meter of soil is taken for calculation in all type of sand and	*LINK*
							Shovel	4,00	hrs	when reached the Underground warning tape, the area will be digged out carefully with a shovel.	
							Mini Dumper	4,00	hrs	Transporting the soil to a container	*LINK*
New soil	2,00	m3	3200,00	kg	Product/Construction	Trench restoration	Shovel	4,00	hrs	filling the trench.	
							Soil compactor	0,50	hrs	Compacting the soil. For each 40cm layer.	
Discarded soil	2,00	m3	3200,00	kg	End of Life	End of Life				Soil disposal.	*LINK*
Reused soil	1,00	m3	1600,00	kg	Product/Construction/ End of Life	Trench restoration	Shovel	included in the overall 4 hours per hole		filling the trench. (	*LINK*
							Soil compactor	included in the overall 4 hours per hole		Compacting the soil. For each 40cm layer.	
Sand	0,33	m3	533,33	kg	Product/Construction	Surface restoration	Manual labour	included in the overall 4 hours per hole		Levelling sand for tiles.	*LINK*
PE (water pipe)	2,00	m	0,58	kg	Construction/End of Life	Pipe work	Pipe scissor	included in the overall 4 hours per hole		Pipe is being cutted to size // 0,29 kg/m	*LINK*
Electrofusion Saddle	1,00	unit	0,44	kg	Product/Construction/ End of Life	Pipe work	Dismantling tool	1,00	min	removing the outer mantle of the main water line.	
Electrofusion Saddle							Surface scraper	3,00	min	prepping the exposed layer of the main water line for welding	
Electrofusion Saddle						(only VCS)	Cordless drill	N/A	N/A	Drilling a hole in to main water line	
Electrofusion Saddle							Cordless drill	1,00	min	fastening the screws	
Electrofusion Saddle							Welding machine	5,00	hrs	welding	*LINK*
Electrofusion coupler	1,00	unit	0,05	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	1,00	min	Chamfering	
Electrofusion coupler							Cordless drill	1,00	min	fastening the screws	
Electrofusion coupler							Welding machine	3,00	hrs	welding	*LINK*
Electrofusion angle coupler	1,00	unit	0,09	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	1,00	min	Chamfering	
Electrofusion angle coupler							Cordless drill	1,00	min	fastening the screws	
Electrofusion angle coupler							Welding machine	3,00	hrs	welding	*LINK*
Reducer	1,00	unit	0,11	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	1,00	min	Chamfering	
Stop valve	1,00	unit	1,40	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	1,00	min	Chamfering	
Extension spindle	1,00	unit	2,50	kg	Product/Construction/ End of Life	Pipe work	Manual labour	3,00	min	mounting spindle onto the stop valve	
Stop valve cover	1,00	unit	4,30	kg	Product/Construction/ End of Life	Surface restoration	Manual labour	included in the overall 4 hours per hole	hrs	mounting cover onto the spindle	
Brass repair coupling	2,00	unit	1,01	kg	Product/Construction/ End of Life	Pipe work	Manual labour	N/A	hrs	connecting the public water pipe with the private water line	*LINK*
Waste transport	3,66	ton	10,00	km	Construction	Transport	Truck/container	2,00	hrs	transport of waste to disposal location	
Waste transport	2,51	m3	10,00	km	Construction	Transport	Truck/container	2,00	hrs	the same waste only described in cubic metres.	
Plywood	8,00	m2	0,16	m3	Construction/End of Life	Trench preperation	Manual labour	included in the overall 4 hours per hole	hrs	wall support of the trench.// Average weight of 575kg/m3	*LINK*
Shingle stone	200,00	kg	200,00	kg	Construction	Trench preperation	Manual labour	included in the overall 4 hours per hole	hrs	Trench floor is being layed out with 20 cm of shingle stones.	*LINK*
Material transport	4,68	ton	10,00	km	Construction	Transport	Truck/container			transport of material to construction site.	
Material transport	3,64	m3	10,00	km	Construction	Transport	Truck/container			transport of material to construction site.	

Total Tools/Machines			
Manual Labour	4	hrs	overvall manual labour around preperation and restoration work
Cordless drill 54W	0,12	min	
Asphalt saw	1	hrs	
Soil compactor	0,5	hrs	for a complete hole
Welding machine	0,18	hrs	1300 W
Mini Dumper	4	hrs	for preperation and restoration
Excavator	6,253333333	m3	

Appendix B.1.3 – VandCenter Syd

Table 23 - VandCenter Syd

			LCA								
Material	**Amount**	**Unit**	**Amount2**	**Unit2**	**Stage**	**Process**	**Tool or form of manual labour**	**Amount3**	**Unit3**	**Notes**	**Additional links**
Tiles	1	m2	0,1	m3	Construction	Surface preperation	shovel	N/A	hrs	use of shovels and iron poles to lift the tiles. Standard tiles: 10 cm thickness	
Broken Tiles	0,5	m2	115	kg	Construction	Surface preparation, End of Life	Excavator	0,05	m3	use of excavator to scrap off broken tiles to a mini dumper. // 230kg/m2	*LINK*
					End of Life		Mini Dumper	0,5	hrs	transporting broken tiles to a container.	
New Tiles	0,5	m2	0,05	m3	Product	Surface restoration	Manual labour	N/A	hrs	Laying tiles.	
Asphalt	1	m2	162,4	kg	Construction/End of Life	Surface preparation, End of Life	Asphalt saw	5	min	cutting of asphalt. // thickness of 7cm // 2,32 t/m3	*LINK*
							Mini Dumper	0,5	hrs	Transport of asphalt to a container.	
New Asphalt	1	m2	162,4	kg	Construction/End of Life	Surface restoration	Shovel	N/A	hrs	Laying of asphalt material // 2,32 t/m3	*LINK*
							Asphalt roller (manual)/ pladevibrator	N/A	hrs	Rolling of asphalt.	
Grass	1	m2	20	kg	Construction/End of Life	Surface preparation, End of Life	Excavator	0,15	m3	Removing of Grass. // 1m2= 16-20kg // estimate of 15 cm thickness, based on fieldwork	*LINK*
							Mini Dumper	0,5	hrs	Transport of grass to a container.	
Topsoil Reuse	0	m3	0	kg	Product/Construction	Surface restoration	Shovel	N/A	hrs	Prepping the toplayer to be sown.	*LINK*
New Topsoil	0,15	m3	240	kg	Product/Construction	Surface restoration	Shovel	N/A	hrs	Prepping the toplayer to be sown.	*LINK*
Grass seeds	15	gramm	0,015	kg	Construction	Surface restoration	Manual labour	N/A	hrs	Sowing of a grass seed mixture.	
Digged up Soil	5,1	m3	8160	kg	Construction	Trench preperation	Excavator	5,1	m3	Digging out the trench. The average of 1600kg per cubic meter of soil is taken for calculation in all type of sand and	*LINK*
							Shovel	N/A	hrs	when reached the Underground warning tape, the area will be digged out carefully with a shovel.	
							Mini Dumper	0,5	hrs	Transporting the soil to a container	*LINK*
New soil	1,7	m3	2720	kg	Product/Construction	Trench restoration	Shovel	N/A	hrs	filling the trench. // 70% new soil	
							Soil compactor	20	min	Compacting the soil. For each 40cm layer.	
Discarded soil	1,7	m3	2720	kg	End of Life	End of Life				Soil disposal. // assuming that 70% of soil being discarded	*LINK*
Reused soil	3,4	m3	5440	kg	Product/Construction/ End of Life	Trench restoration	Shovel	N/A	hrs	filling the trench. // assuming that 30% is being reused	*LINK*
							Soil compactor	10	min	Compacting the soil. For each 40cm layer.	
Sand	0,03	m3	48	kg	Product/Construction	Surface restoration	Manual labour	N/A	hrs	Levelling sand for tiles. // 3cm thickness	*LINK*
PE (water pipe)	1,5	m	0,435	kg	Construction/End of Life	Pipe work	Pipe scissor	N/A	hrs	Pipe is being cutted to size // 0,29 kg/m	*LINK*
Electrofusion Saddle	1	unit	0,435	kg	Product/Construction/ End of Life	Pipe work	Dismantling tool / manual	N/A	min	removing the outer mantle of the main water line.	
Electrofusion Saddle							Surface scraper	N/A	min	prepping the exposed layer of the main water line for welding	
Electrofusion Saddle						(only VCS)	Cordless drill	0,5	min	Drilling a hole in to main water line	
Electrofusion Saddle							Cordless drill	0,5	min	fastening the screws	
Electrofusion Saddle							Welding machine	5	min	welding	*LINK*
Electrofusion coupler	1	unit	0,053	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	0,5	min	Chamfering	
Electrofusion coupler							Cordless drill	0,5	min	fastening the screws	
Electrofusion coupler							Welding machine	3	min	welding	*LINK*
Electrofusion angle coupler	1	unit	0,094	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	0,5	min	Chamfering	
Electrofusion angle coupler							Cordless drill	0,5	min	fastening the screws	
Electrofusion angle coupler							Welding machine	3	min	welding	*LINK*
Reducer	1	unit	0,113	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	0,5	min	Chamfering	
Stop valve	1	unit	1,4	kg	Product/Construction/ End of Life	Pipe work	Cordless drill	0,5	min	Chamfering	
Extension spindle	1	unit	2,5	kg	Product/Construction/ End of Life	Pipe work	Manual labour	N/A	min	mounting spindle onto the stop valve	
Stop valve cover	1	unit	4,3	kg	Product/Construction/ End of Life	Surface restoration	Manual labour	N/A	hrs	mounting cover onto the spindle	
Brass repair coupling	2	unit	1,008	kg	Product/Construction/ End of Life	Pipe work	Manual labour	N/A	hrs	connecting the public water pipe with the private water line	*LINK*
Waste transport	3,085866	ton	15	km	Construction	Transport	Truck/container			transport of material to disposal location	
Waste transport	2,089072	m3	15	km	Construction	Transport	Truck/container			the same waste only described in cubic metres.	
Plywood	5,9536	m2	0,119072	m3	Construction/End of Life	Trench preperation	Manual labour	N/A	hrs	wall support of the trench. // 22x1220x2440mm plywood // Average weight of 575kg/m3	*LINK*
Shingle stone	900	kg	900	kg	Construction	Trench preperation	Manual labour	N/A	hrs	Trench floor is being layed out with 20 cm of shingle stones.	*LINK*
Material transport	4,253866	ton	10	km	Construction	Transport	Truck/container			transport of material to construction site.	
Material transport	2,919072	m3	10	km	Construction	Transport	Truck/container			transport of material to construction site.	

Total Tools/Machines			
Manual Labour	N/A	hrs	overvall manual labour around preperation and restoration work
Cordless drill 54W	0,06	hrs	
Asphalt saw	0,083	hrs	
Soil compactor	0,5	hrs	for a complete hole
Welding machine	0,18	hrs	1300 W
Mini Dumper	2	hrs	for preperation and restoration
Excavator	5,3	m3	for preperation and restoration

Appendix B.1.4 – Total Consumption

Table 24 - Total Material Consumption

Material	VCS	Aarhus Vand	HOFOR	Average	unit	VCS	Aarhus Vand	HOFOR	Average	unit
	amount	amount	amount	amount		amount	amount	amount	amount	
Tiles	0,10	0,08	0,13	**0,11**	m3	0,10	0,08	0,13	**0,11**	m3
Broken Tiles	115,00	28,75	122,67	**88,81**	kg	0,05	0,01	0,05	**0,04**	m3
New Tiles	0,05	0,01	0,05	**0,04**	m3	0,05	0,01	0,05	**0,04**	m3
Asphalt	162,40	135,33	216,53	**171,42**	kg	0,07	0,06	0,09	**0,07**	m3
New Asphalt	162,40	135,33	216,53	**171,42**	kg	0,07	0,06	0,09	**0,07**	m3
Grass	20,00	16,67	26,67	**21,11**	kg	0,15	0,13	0,20	**0,16**	m3
Topsoil Reuse	0,00	200,00	106,67	**102,22**	kg	0,00	0,13	0,07	**0,06**	m3
New Topsoil	240,00	600,00	320,00	**386,67**	kg	0,15	0,38	0,20	**0,24**	m3
Grass seeds	0,02	0,10	0,02	**0,05**	kg					
Digged up Soil	8160,00	4000,00	9600,00	**7253,33**	kg	5,10	2,50	6,00	**4,53**	m2
New soil	2720,00	2000,00	3200,00	**2640,00**	kg	1,70	1,25	2,00	**1,65**	m3
Discarded soil	2720,00	2000,00	3200,00	**2640,00**	kg	1,70	1,25	2,00	**1,65**	m3
Reused soil	5440,00	2000,00	1600,00	**3013,33**	kg	3,40	1,25	1,00	**1,88**	m3
Sand	48,00	48,00	533,33	**209,78**	kg	0,03	0,03	0,33	**0,13**	m3
PE water pipe scrap	0,44	0,12	0,58	**0,38**	kg					
Electrofusion Saddle	0,44	0,44	0,44	**0,44**	kg					
Electrofusion coupler	0,05	0,05	0,05	**0,05**	kg					
Electrofusion angle coupler	0,09	0,09	0,09	**0,09**	kg					
Reducer	0,11	0,11	0,11	**0,11**	kg					
Stop valve	1,40	1,40	1,40	**1,40**	kg					
Extension spindle	2,50	2,50	2,50	**2,50**	kg					
Stop valve cover	4,30	4,30	4,30	**4,30**	kg					
Brass repair coupling	1,01	1,01	1,01	**1,01**	kg					
Plywood	0,12	0,06	0,16	**0,11**	m3	0,12	0,06	0,16	**0,11**	m3
Plywood	68,47	34,50	92,00	**64,99**	kg					
Shingle stone	900,00	750,00	200,00	**616,67**	kg	0,20	0,17	0,27	**0,21**	m3
Waste transport	15,00	30,00	10,00	**18,33**	km					
Waste transport soil/grass	2,74	2,02	3,23	**2,66**	ton	1,85	1,38	2,20	**1,81**	m3
Waste transport asphalt/tiles/plywood	0,35	0,16	0,34	**0,28**	ton	0,24	0,13	0,31	**0,23**	m3
Total waste amount	3,09	2,18	3,57	**2,944**	ton	**2,09**	**1,51**	**2,51**	**2,03**	m3
Material transport	10,00	10,00	10,00	**10,000**	km					
Material transport Soil/sand/shingle stone/plywood	3,98	3,43	4,35	**3,9**	ton	2,05	1,79	2,47	**2,10**	m3
Material transport asphalt/tiles	0,28	0,16	0,34	**0,26**	ton	0,12	0,07	0,15	**0,11**	m3
Total Material amount	4,25	3,60	4,68	**4,18**	ton	**2,17**	**1,86**	**2,61**	**2,22**	m3

Table 25 - Total Tools and Machines Consumption

Tools/Machines	VCS	Aarhus Vand	HOFOR	Average	unit
	amount	amount	amount	amount	
Cordless drill	0,06	0,08	0,12	**0,09**	hrs
Asphalt saw	0,08	0,08	1,00	**0,39**	hrs
Soil compactor	0,50	0,33	0,50	**0,44**	hrs
Welding machine	0,18	0,18	0,18	**0,18**	hrs
Mini Dumper	2,00	2,00	4,00	**2,67**	hrs
Excavator	5,30	2,64	6,25	**4,73**	m3

Table 26 - Transport Calculation (waste)

Container/trips Waste	1 Trench	Daily	Yearly	
Soil/grass (m3)	1,81	63	16293	
Soil/grass (container)	0,23	8	2037	maxi container 8 m3 from marius pedersen
Asphalt/tiles/plywood (m3)	0,23	8	2032	
Asphalt/tiles/plywood (container)	0,03	1	254	maxi container 8 m3 from marius pedersen
Total containers/trips	**0,25**	**9**	**2291**	maxi container 8 m3 from marius pedersen
Total km	**4,66**	**163,13**	**41994,92**	
Total (ton)	**2,94**	**103,05**	**26526,89**	
t*km	**13,723**	**16810,072**	**1113994570,696**	

Table 27 - Transport Calculation (material)

Material Transport	1 Trench	Daily	Yearly	
Soil/sand/shingle stone/plywood (m3)	2,10	74	18946	maxi container 8 m3 from marius pedersen
Soil/sand/shingle stone/plywood (container)	0,26	9	2368	
Asphalt/tiles (m3)	0,11	4	1014	
Asphalt/tiles (container)	0,01	0	127	maxi container 8 m3 from marius pedersen
Total containers/trips	**0,28**	**9,69**	**2494,96**	maxi container 8 m3 from marius pedersen
Total km	**2,77**	**96,92**	**24949,57**	
Total (ton)	**4,18**	**146,24**	**37646,73**	
t*km	**11,570**	**14173,490**	**939269635,571**	

Appendix B.2 – OpenLCA Ecoinvent Data

Appendix B.2.1 – Process

Appendix B.2.1.1 – Product Stage

Table 28 -Product Stage OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
Brass_repair_coupling	_RobSub/Parts	1.0	Item(s)	Brass_repair_coupling
cast iron	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	Stop_valve_cover	kg	cast iron production | cast iron | Consequential, U - RER
concrete slab	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2395:Manufacture of articles of concrete, cement and plaster	Tiles	m3	concrete slab production | concrete slab | Consequential, U - RoW
Electrofusin_coupler	_RobSub/Parts	1.0	Item(s)	Electrofusion_coupler - CH
Electrofusion_angle_coupler	_RobSub/Parts	1.0	Item(s)	Electrofusion_angle_coupler - CH
Electrofusion_saddle	_RobSub/Parts	1.0	Item(s)	Electrofusion_saddle - CH
Extension_spindle	_RobSub/Parts	1.0	Item(s)	Extension_spindle - DK
gravel, round	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	Shingle_stone	kg	gravel and sand quarry operation | gravel, round | Consequential, U - RoW
mastic asphalt	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2399:Manufacture of other non-metallic mineral products n.e.c.	Asphalt	kg	mastic asphalt production | mastic asphalt | Consequential, U - CH
plywood	C:Manufacturing/16:Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials/162:Manufacture of products of wood, cork, straw and plaiting materials/1621:Manufacture of veneer sheets and wood-based panels	Plywood	m3	plywood production | plywood | Consequential, U - RER
Reducer	_RobSub/Parts	1.0	Item(s)	Reducer - CH
sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	Sand_tile	kg	gravel and sand quarry operation | sand | Consequential, U - RoW
sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	Topsoil	kg	gravel and sand quarry operation | sand | Consequential, U - RoW
sand	B:Mining and quarrying/08:Other mining and quarrying/081:Quarrying of stone, sand and clay/0810:Quarrying of stone, sand and clay	Refill	kg	gravel and sand quarry operation | sand | Consequential, U - RoW
Stop_valve	_RobSub/Parts	1.0	Item(s)	Stop_valve - DK

Output

Flow	Category	Amount	Unit	Provider
Product: process	_RobSub/Life Cycle Stages/Processes	1.0	Item(s)	

Appendix B.2.1.2 – Construction Stage

Table 29 - Construction Stage OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
electricity, low voltage	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/351:Electric power generation, transmission and distribution/3510:Electric power generation, transmission and distribution	Cordless_Drill*54	Wh	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK
electricity, low voltage	D:Electricity, gas, steam and air conditioning supply/35:Electricity, gas, steam and air conditioning supply/351:Electric power generation, transmission and distribution/3510:Electric power generation, transmission and distribution	Welding*1300	Wh	market for electricity, low voltage | electricity, low voltage | Consequential, U - DK
excavation, hydraulic digger	F:Construction/43:Specialized construction activities/431:Demolition and site preparation/4312:Site preparation	excavator	m3	excavation, hydraulic digger | excavation, hydraulic digger | Consequential, U - RER
grass seed, organic, for sowing	A:Agriculture, forestry and fishing/01:Crop and animal production, hunting and related service activities/016:Support activities to agriculture and post-harvest crop activities/0164:Seed processing for propagation	Grass_Seeds	kg	grass seed production, organic, for sowing | grass seed, organic, for sowing | Consequential, U - RoW
machine operation, diesel, < 18.64 kW, low load factor	F:Construction/43:Specialized construction activities/431:Demolition and site preparation/4312:Site preparation	mini_Dumper	h	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO
machine operation, diesel, < 18.64 kW, low load factor	F:Construction/43:Specialized construction activities/431:Demolition and site preparation/4312:Site preparation	Asphalt_Saw	h	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO
machine operation, diesel, < 18.64 kW, low load factor	F:Construction/43:Specialized construction activities/431:Demolition and site preparation/4312:Site preparation	Soil_Compactor	h	machine operation, diesel, < 18.64 kW, low load factor | machine operation, diesel, < 18.64 kW, low load factor | Consequential, U - GLO
transport, freight, lorry 7.5-16 metric ton, EURO5	H:Transportation and storage/49:Land transport and transport via pipelines/492:Other land transport/4923:Freight transport by road	trans_total_km * material_weight	t*km	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
Construction: Process	_RobSub/Life Cycle Stages/Processes	1.0	Item(s)	

Appendix B.2.1.3 – End of Life Stage

Table 30 - End of Life Stage OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
transport, freight, lorry 7.5-16 metric ton, EURO5	H:Transportation and storage/49:Land transport and transport via pipelines/492:Other land transport/4923:Freight transport by road	trans_singletrench_km * waste_weight	t*km	transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
biowaste, garden waste	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_Grass	kg	treatment of garden biowaste, home composting in heaps | biowaste, garden waste | Consequential, U - RoW
End of Life: process	_RobSub/Life Cycle Stages/Processes	1.0	Item(s)	
Metal waste	Elementary flows/Waste/ecopoints 97, CH	EOL_Brass	kg	
scrap copper	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_CopperValve System	kg	treatment of scrap copper, municipal incineration | scrap copper | Consequential, U - CH
scrap steel	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_SteelValveS ystem	kg	treatment of scrap steel, municipal incineration | scrap steel | Consequential, U - CH
soil, contaminated	C:Manufacturing/23:Manufacture of other non-metallic mineral products/239:Manufacture of non-metallic mineral products n.e.c./2394:Manufacture of cement, lime and plaster	EOL_Soil	kg	market for soil, contaminated | soil, contaminated | Consequential, U - GLO
waste asphalt	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_Asphalt	kg	treatment of waste asphalt, sanitary landfill | waste asphalt | Consequential, U - CH
waste concrete	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_Tiles	kg	treatment of waste concrete, inert material landfill | waste concrete | Consequential, U - Europe without Switzerland
waste polyethylene	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_PlasticValve System	kg	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH
waste polyethylene	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_PEpipe	kg	treatment of waste polyethylene, municipal incineration | waste polyethylene | Consequential, U - CH
waste wood, untreated	E:Water supply; sewerage, waste management and remediation activities/38:Waste collection, treatment and disposal activities; materials recovery/382:Waste treatment and disposal/3821:Treatment and disposal of non-hazardous waste	EOL_Plywood	kg	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Consequential, U - CH

Appendix B.2.1.4 – Full Life Cycle

Table 31 - Full Life Cycle OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
Construction: Process	_RobSub/Life Cycle Stages/Processes	1.0	Item(s)	Construction: Process - DK
End of Life: process	_RobSub/Life Cycle Stages/Processes	1.0	Item(s)	End of Life: process - DK
Product: process	_RobSub/Life Cycle Stages/Processes	1.0	Item(s)	Product: process

Output

Flow	Category	Amount	Unit	Provider
Full Life Cycle : process	_RobSub/Life Cycle Stages/Processes	1.0	Item(s)	

Appendix B.2.2 – Valve System Parts

Appendix B.2.2.1 – Brass Repair Coupling

Table 32 - Brass Repair Coupling OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
casting, brass	C:Manufacturing/24:Manufacture of basic metals/243:Casting of metals/2432:Casting of non-ferrous metals	Repair_coupler	kg	casting, brass | casting, brass | Consequential, U - CH
synthetic rubber	C:Manufacturing/20:Manufacture of chemicals and chemical products/201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2013:Manufacture of plastics and synthetic rubber in primary forms	O_ring	kg	synthetic rubber production | synthetic rubber | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
Brass_repair_coupling	_RobSub/Parts	1.0	Item(s)	

Appendix B.2.2.2 – Electrofusion Angle Coupler

Table 33 - Electrofsuion Angle Coupler OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
injection moulding	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	angle_PE	kg	injection moulding | injection moulding | Consequential, U - RER
steel, low-alloyed	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	bolt	kg	steel production, electric, low-alloyed | steel, low-alloyed | Consequential, U - CH
wire drawing, copper	C:Manufacturing/24:Manufacture of basic metals/242:Manufacture of basic precious and other non-ferrous metals/2420:Manufacture of basic precious and other non-ferrous metals	angle_copper	kg	wire drawing, copper | wire drawing, copper | Consequential, U - RER
zinc coat, pieces	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service activit/2592:Treatment and coating of metals; machining	zinc_coat	cm2	zinc coating, pieces | zinc coat, pieces | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
Electrofusion_angle_coupler	_RobSub/Parts	1.0	Item(s)	

Appendix B.2.2.3 – Electrofusion Coupler

Table 34 - Electrofusion Coupler OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
injection moulding	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	coupler_PE	kg	injection moulding | injection moulding | Consequential, U - RER
steel, low-alloyed	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	bolt	kg	steel production, electric, low-alloyed | steel, low-alloyed | Consequential, U - CH
wire drawing, copper	C:Manufacturing/24:Manufacture of basic metals/242:Manufacture of basic precious and other non-ferrous metals/2420:Manufacture of basic precious and other non-ferrous metals	coupler_copper	kg	wire drawing, copper | wire drawing, copper | Consequential, U - RER
zinc coat, pieces	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service activit/2592:Treatment and coating of metals; machining	zinc_coat	cm2	zinc coating, pieces | zinc coat, pieces | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
Electrofusin_coupler	_RobSub/Parts	1.0	Item(s)	

Appendix B.2.2.4 – Electrofusion Saddle

Table 35 - Electrofusion Saddle OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
injection moulding	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	saddle_PE	kg	injection moulding | injection moulding | Consequential, U - RER
steel, low-alloyed	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	bolt	kg	steel production, electric, low-alloyed | steel, low-alloyed | Consequential, U - CH
wire drawing, copper	C:Manufacturing/24:Manufacture of basic metals/242:Manufacture of basic precious and other non-ferrous metals/2420:Manufacture of basic precious and other non-ferrous metals	saddle_copper	kg	wire drawing, copper | wire drawing, copper | Consequential, U - RER
zinc coat, pieces	C:Manufacturing/25:Manufacture of fabricated metal products, except machinery and equipment/259:Manufacture of other fabricated metal products; metalworking service activit/2592:Treatment and coating of metals; machining	zinc_coat	cm2	zinc coating, pieces | zinc coat, pieces | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
Electrofusion_saddle	_RobSub/Parts	1.0	Item(s)	

Appendix B.2.2.5 – Extension Spindle

Table 36 - Extension Spindle OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
casting, steel, lost-wax	C:Manufacturing/24:Manufacture of basic metals/243:Casting of metals/2431:Casting of iron and steel	cast_steel	kg	market for casting, steel, lost-wax | casting, steel, lost-wax | Consequential, U - GLO
drawing of pipe, steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	lock_spring	kg	drawing of pipe, steel | drawing of pipe, steel | Consequential, U - RER
extrusion, plastic pipes	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	PE_parts	kg	extrusion, plastic pipes | extrusion, plastic pipes | Consequential, U - RER
injection moulding	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	centre_sleeve	kg	injection moulding | injection moulding | Consequential, U - RER
reinforcing steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	inner_tube	kg	reinforcing steel production | reinforcing steel | Consequential, U - Europe without Austria

Output

Flow	Category	Amount	Unit	Provider
Extension_spindle	_RobSub/Parts	1.0	Item(s)	

Appendix B.2.2.6 – Reducer

Table 37 - Reducer OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
injection moulding	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	reducer	kg	injection moulding | injection moulding | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
Reducer	_RobSub/Parts	1.0	Item(s)	

Appendix B.2.2.7 – Stop Valve

Table 38 - Stop Valve OpenLCA process

Input

Flow	Category	Amount	Unit	Provider
acrylonitrile-butadiene-styrene copolymer	C:Manufacturing/20:Manufacture of chemicals and chemical products/201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2013:Manufacture of plastics and synthetic rubber in primary forms	wiper_ring	kg	acrylonitrile-butadiene-styrene copolymer production | acrylonitrile-butadiene-styrene copolymer | Consequential, U - RER
brass	C:Manufacturing/24:Manufacture of basic metals/242:Manufacture of basic precious and other non-ferrous metals/2420:Manufacture of basic precious and other non-ferrous metals	brass	kg	brass production | brass | Consequential, U - CH
injection moulding	C:Manufacturing/22:Manufacture of rubber and plastics products/222:Manufacture of plastics products/2220:Manufacture of plastics products	body_pipe	kg	injection moulding | injection moulding | Consequential, U - RER
polyethylene terephthalate, granulate, amorphous	C:Manufacturing/20:Manufacture of chemicals and chemical products/201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2013:Manufacture of plastics and synthetic rubber in primary forms	insert	kg	polyethylene terephthalate production, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Consequential, U - RER
reinforcing steel	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	stem	kg	reinforcing steel production | reinforcing steel | Consequential, U - Europe without Austria
steel, low-alloyed	C:Manufacturing/24:Manufacture of basic metals/241:Manufacture of basic iron and steel/2410:Manufacture of basic iron and steel	friction_ring	kg	steel production, converter, low-alloyed | steel, low-alloyed | Consequential, U - RER
synthetic rubber	C:Manufacturing/20:Manufacture of chemicals and chemical products/201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, plastics/2013:Manufacture of plastics and synthetic rubber in primary forms	o_ring	kg	synthetic rubber production | synthetic rubber | Consequential, U - RER

Output

Flow	Category	Amount	Unit	Provider
Stop_valve	_RobSub/Parts	1.0	Item(s)	

Appendix B.2.3 – Parameters

Table 39 - OpenLCA Parameters

Context	Parameter	Value (current)	Value (50% size)	Value (66% size)	Unit
Brass_repair_coupling	O_ring	0,01	0,01	0,01	kg
Brass_repair_coupling	Repair_coupler	1,00	1,00	1,00	kg
Construction: Process - DK	Asphalt_Saw	0,39	0,39	0,39	hrs
Construction: Process - DK	Cordless_Drill	0,09	0,09	0,09	hrs
Construction: Process - DK	Excavator	4,37	**2,37**	**3,12**	m3
Construction: Process - DK	Grass_Seeds	0,05	**0,02**	**0,03**	kg
Construction: Process - DK	material_weight	4,18	**1,81**	**2,37**	kg
Construction: Process - DK	Mini_Dumper	2,67	2,67	2,67	hrs
Construction: Process - DK	Soil_Compactor	0,44	0,44	0,44	hrs
Construction: Process - DK	trans_total_km	2,77	**1,39**	**1,83**	km
Construction: Process - DK	Welding	0,18	0,18	0,18	hrs
Electrofusion_angle_coupler - CH	Angle_copper	0,01	0,01	0,01	kg
Electrofusion_angle_coupler - CH	Angle_PE	0,09	0,09	0,09	kg
Electrofusion_angle_coupler - CH	Bolt	0,06	0,06	0,06	kg
Electrofusion_angle_coupler - CH	Zinc_coat	20,00	20,00	20,00	cm2
Electrofusion_coupler - CH	Bolt	0,06	0,06	0,06	kg
Electrofusion_coupler - CH	Coupler_copper	0,00	0,00	0,00	kg
Electrofusion_coupler - CH	Coupler_PE	0,05	0,05	0,05	kg
Electrofusion_coupler - CH	Zinc_coat	20,00	20,00	20,00	cm2
Electrofusion_saddle - CH	Bolt	0,06	0,06	0,06	kg
Electrofusion_saddle - CH	Saddle_copper	0,03	0,03	0,03	kg
Electrofusion_saddle - CH	Saddle_PE	0,41	0,41	0,41	kg
Electrofusion_saddle - CH	Zinc_coat	20,00	20,00	20,00	cm2
End of Life: process - DK	EOL_Asphalt	171,42	**85,71**	**113,14**	kg
End of Life: process - DK	EOL_Brass	1,00	1,00	1,00	kg
End of Life: process - DK	EOL_CopperValveSystem	0,04	0,04	0,04	kg
End of Life: process - DK	EOL_Grass	21,11	**10,56**	**13,93**	kg
End of Life: process - DK	EOL_PEpipe	0,38	0,38	0,38	kg
End of Life: process - DK	EOL_PlasticValveSystem	1,49	1,49	1,49	kg
End of Life: process - DK	EOL_Plywood	64,99	64,99	64,99	kg
End of Life: process - DK	EOL_Soil	2.640,00	**1.320,00**	**1.742,40**	kg
End of Life: process - DK	EOL_SteelValveSystem	7,15	7,15	7,15	kg
End of Life: process - DK	EOL_Tiles	88,81	**44,40**	**58,61**	kg
End of Life: process - DK	trans_singletrench_km	4,66	**2,46**	**3,16**	km
End of Life: process - DK	waste_weight	2,94	**1,48**	**1,95**	ton
Extension_spindle - DK	Cast_steel	0,70	0,70	0,70	kg
Extension_spindle - DK	Centre_sleeve	0,05	0,05	0,05	kg
Extension_spindle - DK	Inner_tube	1,32	1,32	1,32	kg
Extension_spindle - DK	Lock_spring	0,03	0,03	0,03	kg
Extension_spindle - DK	PE_parts	0,40	0,40	0,40	kg
Product: process	Asphalt	171,42	**85,71**	**113,14**	kg
Product: process	Plywood	0,11	0,11	0,11	m3
Product: process	Refill	2.640,00	**1.320,00**	**1.742,40**	kg
Product: process	Sand_tile	209,78	**104,89**	**138,45**	kg
Product: process	Shingle_stone	616,67	**-**	**-**	kg
Product: process	Stop_valve_cover	4,30	4,30	4,30	kg
Product: process	Tiles	88,81	**44,40**	**58,61**	kg
Product: process	Topsoil	386,67	**193,33**	**255,20**	kg
Reducer - CH	Reducer	0,11	0,11	0,11	kg
Stop_valve - DK	Body_pipe	0,30	0,30	0,30	kg
Stop_valve - DK	Brass	0,22	0,22	0,22	kg
Stop_valve - DK	Friction_ring	0,10	0,10	0,10	kg
Stop_valve - DK	Insert	0,05	0,05	0,05	kg
Stop_valve - DK	O_ring	0,02	0,02	0,02	kg
Stop_valve - DK	Stem	0,70	0,70	0,70	kg
Stop_valve - DK	Wiper_ring	0,01	0,01	0,01	kg

Appendix B.3 – Valve System Parts

Table 40 - Valve System Parts

Parts	Material	weight kg	note
Electrofusion saddle	PE	0,405	GFPS 193137097
Electrofusion saddle	copper wire	0,03	GFPS 193137097
Electrofusion coupler	PE	0,04982	GFPS 753911608
Electrofusion coupler	copper wire	0,00318	GFPS 753911608
Electrofusion angle coupler	PE	0,08836	GFPS 753101608
Electrofusion angle coupler	copper wire	0,00564	GFPS 753101608
Reducer	PE	0,113	GFPS 753901060
Stop valve	reinforced steel	0,7	AVK 16-032-81-024
Stop valve	NBR rubber	0,01	AVK 16-032-81-024
Stop valve	EPDM rubber	0,02	AVK 16-032-81-024
Stop valve	stainless steel	0,1	AVK 16-032-81-024
Stop valve	Brass	0,22	AVK 16-032-81-024
Stop valve	PBT	0,05	AVK 16-032-81-024
Stop valve	POM	0,15	AVK 16-032-81-024
Stop valve	PE	0,15	AVK 16-032-81-024
Extension Spindle	Cast stainless steel	0,7	AVK 04-032-2-0501
Extension Spindle	PE	0,4	AVK 04-032-2-0501
Extension Spindle	Steel	1,32	AVK 04-032-2-0501
Extension Spindle	stainless steel	0,03	AVK 04-032-2-0501
Extension Spindle	Plastic	0,05	AVK 04-032-2-0501
Stop valve cover	Ductile iron	4,3	AVK 04-007-25-05900
Brass repair coupling	Brass	1	101-32X32 REPAIR COUPLING
Brass repair coupling	EPDM rubber	0,008	101-32X32 REPAIR COUPLING

Total	Plastic	1,49418
	Steel	7,15
	Copper	0,03882

Appendix B.4 – DQR Valve System Parts

Table 41 - DQR Valve System parts

Data	Country of production	OpenLCA 1.11.0/ Ecoinvent 3.9.1 consequential upr	Age of Ecoinvent data	Geographical	Technical	Time
Brass repair coupling						
Brass	Switzerland	casting, brass | casting, brass | Consequential, U - CH	1.1.2011 - 8.12.2022	1	3	1
Rubber	Switzerland	synthetic rubber production | synthetic rubber | Consequential, U - RER	1.1.1995 - 8.12.2022	3	3	1
Electrofusion angle coupler						
Injection moulding	Switzerland	injection moulding | injection moulding | Consequential, U - RER	1.1.1993 - 8.12.2022	3	3	1
Bolt	Switzerland	steel production, electric, low-alloyed | steel, low-alloyed | Consequential, U - CH	1.1.2012 - 8.12.2022	1	3	1
Copper	Switzerland	wire drawing, copper | wire drawing, copper | Consequential, U - RER	1.1.2000 - 8.12.2022	3	3	1
Zinc coating	Switzerland	zinc coating, pieces | zinc coat, pieces | Consequential, U - RER	1.1.1996 - 8.12.2022	3	3	1
Electrofusion coupler						
Injection moulding	Switzerland	injection moulding | injection moulding | Consequential, U - RER	1.1.1993 - 8.12.2022	3	3	1
Bolt	Switzerland	steel production, electric, low-alloyed | steel, low-alloyed | Consequential, U - CH	1.1.**2012** - 8.12.2022	1	3	1
Copper	Switzerland	wire drawing, copper | wire drawing, copper | Consequential, U - RER	1.1.**2000** - 8.12.2022	3	3	1
Zinc coating	Switzerland	zinc coating, pieces | zinc coat, pieces | Consequential, U - RER	1.1.1996 - 8.12.2022	3	3	1
Electrofsuion saddle						
Injection moulding	Switzerland	injection moulding | injection moulding | Consequential, U - RER	1.1.1993 - 8.12.2022	3	3	1
Bolt	Switzerland	steel production, electric, low-alloyed | steel, low-alloyed | Consequential, U - CH	1.1.2012 - 8.12.2022	1	3	1
Copper	Switzerland	wire drawing, copper | wire drawing, copper | Consequential, U - RER	1.1.2000 - 8.12.2022	3	3	1
Zinc coating	Switzerland	zinc coating, pieces | zinc coat, pieces | Consequential, U - RER	1.1.1996 - 8.12.2022	3	3	1
Extension spindle						
Steel	Switzerland	market for casting, steel, lost-wax | casting, steel, lost-wax | Consequential, U - GLO	1.1.2012 - 8.12.2022	5	3	1
Lock spring	Switzerland	drawing of pipe, steel | drawing of pipe, steel | Consequential, U - RER	1.1.1997 - 8.12.2022	3	3	1
PE	Switzerland	extrusion, plastic pipes | extrusion, plastic pipes | Consequential, U - RER	1.1.1993 - 8.12.2022	3	3	1
Centre sleeve	Switzerland	injection moulding | injection moulding | Consequential, U - RER	1.1.1993 - 8.12.2022	3	3	1
Inner tube	Switzerland	reinforcing steel production | reinforcing steel | Consequential, U - Europe without Austria	1.1.2000 - 8.12.2022	3	3	1
Reducer						
Injection moulding	Switzerland	injection moulding | injection moulding | Consequential, U - RER	1.1.1993 - 8.12.2022	3	3	1
Stop valve cover						
Steel	Switzerland	cast iron production | cast iron | Consequential, U - RER	1.1.2001 - 8.12.2022	3	3	1
Stop valve						
Wiper ring	Switzerland	acrylonitrile-butadiene-styrene copolymer production | acrylonitrile-butadiene-styrene copolymer | Consequential, U - RER	1.1.1996 - 8.12.2022	3	3	1
Brass	Switzerland	brass production | brass | Consequential, U - CH	1.1.2011 - 8.12.2022	1	3	1
Pipe	Switzerland	injection moulding | injection moulding | Consequential, U - RER	1.1.1993 - 8.12.2022	3	3	1
Insert	Switzerland	polyethylene terephthalate production, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Consequential, U - RER	1.1.1999 - 8.12.2022	3	3	1
Stem	Switzerland	reinforcing steel production | reinforcing steel | Consequential, U - Europe without Austria	1.1.2000 - 8.12.2022	3	3	1
Friction ring	Switzerland	steel production, converter, low-alloyed | steel, low-alloyed | Consequential, U - RER	1.1.2013 - 8.12.2023	3	3	1
O ring	Switzerland	synthetic rubber production | synthetic rubber | Consequential, U - RER	1.1.2000 - 8.12.2022	3	3	1

Appendix C – OpenLCA results

Appendix C.1 – Sensitivity Analysis

Table 42 - Transportation sensitivity

Indicator	10 km	18,33 km	30 km	Unit
Fine particulate matter formation	3,76E-01	3,77E-01	3,81E-01	kg PM2.5 eq
Fossil resource scarcity	9,00E+01	9,04E+01	9,24E+01	kg oil eq
Freshwater ecotoxicity	3,21E+01	3,21E+01	3,21E+01	kg 1,4-DCB
Freshwater eutrophication	3,78E-02	3,79E-02	3,79E-02	kg P eq
Global warming	2,50E+02	2,52E+02	2,58E+02	kg CO2 eq
Human carcinogenic toxicity	1,68E+01	1,68E+01	1,68E+01	kg 1,4-DCB
Human non-carcinogenic toxicity	2,17E+02	2,18E+02	2,18E+02	kg 1,4-DCB
Ionizing radiation	9,91E-01	9,92E-02	9,96E-02	kBq Co-60 eq
Land use	1,34E+02	1,34E+02	1,34E+02	m2a crop eq
Marine ecotoxicity	3,99E+01	3,99E+01	3,99E+01	kg 1,4-DCB
Marine eutrophication	2,34E-02	2,34E-02	2,36E-02	kg N eq
Mineral resource scarcity	1,74E+00	1,74E+00	1,74E+00	kg Cu eq
Ozone formation, Human health	1,31E+00	1,31E+00	1,33E+00	kg NOx eq
Ozone formation, Terrestrial ecosystems	1,36E+00	1,36E+00	1,38E+00	kg NOx eq
Stratospheric ozone depletion	1,27E-04	1,28E-04	1,32E-04	kg CFC11 eq
Terrestrial acidification	7,35E-01	7,37E-01	7,47E+01	kg SO2 eq
Terrestrial ecotoxicity	1,14E+03	1,14E+03	1,14E+03	kg 1,4-DCB
Water consumption	8,07E+00	8,07E+00	8,08E+00	m3

Table 43 - Trench size sensitivity

Indicator	100% trench size	66% trench size	50% trench size	Unit
Fine particulate matter formation	3,77E-01	3,18E-01	2,93E-01	kg PM2.5 eq
Fossil resource scarcity	9,04E+01	6,84E+01	5,83E+01	kg oil eq
Freshwater ecotoxicity	3,21E+01	3,19E+01	3,18E+01	kg 1,4-DCB
Freshwater eutrophication	3,79E-02	3,69E-02	3,67E-02	kg P eq
Global warming	2,52E+02	1,93E+02	1,67E+02	kg CO2 eq
Human carcinogenic toxicity	1,68E+01	1,68E+01	1,68E+01	kg 1,4-DCB
Human non-carcinogenic toxicity	2,18E+02	2,09E+02	2,05E+02	kg 1,4-DCB
Ionizing radiation	9,92E-02	8,71E-02	8,25E-02	kBq Co-60 eq
Land use	1,34E+02	1,30E+02	1,28E+02	m2a crop eq
Marine ecotoxicity	3,99E+01	3,95E+01	3,94E+01	kg 1,4-DCB
Marine eutrophication	2,34E-02	1,68E-02	1,37E-02	kg N eq
Mineral resource scarcity	1,74E+00	1,71E+00	1,70E+00	kg Cu eq
Ozone formation, Human health	1,31E+00	1,04E+00	9,13E-01	kg NOx eq
Ozone formation, Terrestrial ecosystems	1,36E+00	1,07E+00	9,43E-01	kg NOx eq
Stratospheric ozone depletion	1,28E-04	1,03E-04	9,19E-05	kg CFC11 eq
Terrestrial acidification	7,37E-01	5,98E-01	5,37E-01	kg SO2 eq
Terrestrial ecotoxicity	1,14E+03	1,09E+03	1,07E+03	kg 1,4-DCB
Water consumption	8,07E+00	5,57E+00	4,79E+00	m3

Appendix D – Issues Log

Table 44 - Issues Log

Comment #	Chapter/Paragraph	Type of Comment [Editorial (Ed), General (Ge) or Technical (Te)]	Comment and recommendation	LCA Owner answer	Final Verifier Statement	Date of Closure
1						
2	First page	Ed	**Version 1:** Please provide the full name and title of the two reviewers "Julie Marie Vejsgaard Larsen, LCA & EPD Consultant, and Waldemar Corydon Hemdrup, LCA & EPD Consultant from Bureau Veritas HSE A/S Denmark" **Version 2:** Please add "Odyssefs Papagiannidis, LCA & EPD consultant" aswell.	**Version 1:** added **Version 2:** Added	**27/2 2024** - OK approved	**27/2 2024**
3	Executive summary	Te	Please elaborate on why these are chosen? Due to their impact, their importance, or something third?	explained.	**13/2 2024** - OK approved	**13/2 2024**
5	Introduction	Ge	I find it difficult to understand the point made here - please elaborate on the meeting for better understanding	discussed in meeting	**13/2 2024** - OK approved	**13/2 2024**
7	Intended Application	Ed	This is a bit to loaded - Please delete the marked, and end the sentence.	deleted	**13/2 2024** - OK approved	**13/2 2024**

8	Reason for study	Ed	Please change to impact - ”Sustainability” is to loaded a word	changed	**13/2 2024** - OK approved	**13/2 2024**
9	Commissioner	Ge	Alexander Staben is the practitioner of the study, the commissioner the company or people deciding that this needs to be done	changed	**13/2 2024** - OK approved	**13/2 2024**
11	Scope definition	Ge	**Version 1:** This section is missing a description of the allocation procedures, list of assumptions, and Data Quality Requirements **Version 2:** See comment 58 + 59 - When these are corrected this is approved aswell	**Version 1:** Added. Not sure about the allocation procedure, due it’s being consequential and difficult to see the multifunctionality in this system. **Version 2:** added	**27/2 2024** - OK approved	**27/2 2024**
12	Representative of LCI Data	Te	Is the data also representing September 2023 - January 2024? If so, does this not introduce uncertainty regarding different operating procedures or time or the like, when the weather is different?	explained.	**14/2 2024** - OK approved	**14/2 2024**
13	Life Cycle Inventory	Ed	Please explain why this reference is used, or exclude it from the report	removed	**14/2 2024** - OK approved	**14/2 2024**
14	Introduction	Ge	Please add the ISO standards the report is following	added	**14/2 2024** - OK approved	**14/2 2024**
15	Appendix B.2	Ge	**Version 1:** Please provide the entire name of the data from EcoInvent **Version 2:** Not able to see the pictures, (is it possible to make it into tables?)	**Version 1:** provided **Version 2:** Sending A link instead of file, hoping it will solve the problem	**27/2 2024** - OK approved	**27/2 2024**

16	Life Cycle Inventory	Ge	From what i can see in Figure 4 the production of the valve system is a part of the life cycle and not outside the system boundaries?	edited	**14/2 2024** - OK approved	**14/2 2024**
17	Target audience of study	Ge	**Version 1:** According to the ISO 14044 chapter 4.2.3.8 the scope of the study shall define: Whether a critical review is necessary and if so how to conduct it (This has been done here), The type of critical review needed (Please add) Who would conduct the review and their level of expertise (Please add) **Version 2:** Delete this sentence ". For this an independent external review is being chosen with an expertise within LCA and critical review." then approved	**Version 1:** added further description of the critical review **Version 2:** deleted the sentence	**27/2 2024** - OK approved	**27/2 2024**
18	System modelling per life cycle stage	Ed	See comment 13	Edited.	**14/2 2024** - OK approved	**14/2 2024**
19	Impact assessment	Ge	Great with an explanation on which impact categories are chosen as focus and why - I would recommend to move it below the results, since some of them are relating to the results	I think it fits better here, as it parts of the section.	**14/2 2024** - OK approved, has also been added earlier in the report so no further comments!	**14/2 2024**
20	Results	Te	It is not clear to see what process is contributing what. Please show the calculations at the meeting	showed during meeting.	**14/2 2024** - OK approved	**14/2 2024**
21	First page	Ed	Please change to: Bureau Veritas HSE Denmark A/S	changed	**14/2 2024** - OK approved	**14/2 2024**

22	Whole report	Ed	Entire report - Please check references to tables and figures	checked	**14/2 2024** - OK approved	**14/2 2024**
23	Executive summary	Ge	Please explain in more detail what the daily and the yearly scenarios are.	explained.	**14/2 2024** - OK approved	**14/2 2024**
24	Executive summary	Ge	A ”mandeår” is 1924 hours, which i 260 workdays. What is 240 days based on?	changed to 260, and updated calculations	**14/2 2024** - OK approved	**14/2 2024**
25	Executive summary	Te	Please explain what the 99% means in this sentence.	changed	**14/2 2024** - OK approved	**14/2 2024**
26	Introduction	Ge	Please add a source for this claim.	changed	**14/2 2024** - OK approved	**14/2 2024**
27	Limitations of the study	Ge	This is not a limitation. LCA specialists are not certified. Please remove.	removed	**14/2 2024** - OK approved	**14/2 2024**
28	Limitations of the study	Te	Be specific what the ”product” is. It sound like you have excluded an essential thing, which is not the case. Explain what the robot is and what it does.	added further description on what the product that is being excluded is.	**14/2 2024** - OK approved	**14/2 2024**
29	Reason for study	Ed	What is the other reason?	added	**15/2 2024** - OK approved	**15/2 2024**
30	Commissioner	Ge	The commissioner is RobSub, not an employee of Robsub. Please change.	changed	**15/2 2024** - OK approved	**15/2 2024**
31	Decision Context	Ed	This is not necessary to add, but is not required to remove. We would recommend to remove this section.	removed	**15/2 2024** - OK approved	**15/2 2024**
32	System Boundaries	Ed	Please reword this sentence to make it better understood.	reworded	**15/2 2024** - OK approved	**15/2 2024**
33	System Boundaries	Te	Please provide a more detailed reason why this is excluded (we talked about it at our meeting, so please add that explanation to the report. You have no control	changed	**15/2 2024** - OK approved	**15/2 2024**

			over the production or the purchase of the robot).			
34	System Boundaries	Ge	This should be mentioned in the scope section of the report. Please also add it there.	It has been added in the limitation of the study (comment 28), it seems more fitting.	**15/2 2024** - OK approved	**15/2 2024**
35	Cut-off	Te	Please state if cut off is less than 1% or not.	stated.	**15/2 2024** - OK approved	**15/2 2024**
36	Representative of LCI Data	Te	**Version 1:** Please use the scoring system instead. List the DQR for each process used including the validity. DQR should only made for secondary data. **Version 2:** See comment 59	**Version 1:** added **Version 2**: edited	**27/2 2024** - OK approved	**27/2 2024**

37	Representative of LCI Data	Te	**Version 1:** You need to mention that this is a consequential LCA and not attributional at the very beginning of the report. This is important for the reader and reviewer to know. **Version 2:** It is mentioned explicately in the Executive summary and then implicit in the rest of the report. There should be a explicit mention of this in the report, outside of the Executive summary. I would suggest where Life Cycle Assessment is mentioned. Further, there should be more explanation for choosing consequential LCA over attributional (e.g. stakeholders view, more fitting with product or study etc.) See: https://consequential-lca.org/clca/why-and-when/	**Version 1:** done **Version 2:** added in the "Life Cycle Assesment" section, page 10	**6/3 2024** Ok approved	**6/3 2024**
38	Representative of LCI Data	Te	**Version 1:** Show directly which materials has been changed and what they have been changed to. **Version 2:** What specifically us this relating to? The explanation in the original section would be beneficial	**Version 1:** added in "list of assumptions" section **Version 2:** edited	**27/2 2024** - OK approved	**27/2 2024**
39	Representative of LCI Data	Te	**Version 1:** All assumptions should be listed in the scope of the report. Please add them there. **Version 2:** See comment 38	**Version 1:** added **Version 2:** edited	**27/2 2024** - OK approved	**27/2 2024**

40	Representative of LCI Data	Te	Why has a full year of data not been used?	explained.	**15/2 2024** - OK approved	**15/2 2024**
41	Life Cycle Inventory	Ed	You are not making an EPD, please remove this reference.	removed	**15/2 2024** - OK approved	**15/2 2024**
42	Figure 4	Ed	Can't read this figure. Please provide at the meeting.	provided in meeting	**15/2 2024** - OK approved	**15/2 2024**
43	System modelling per life cycle stage	Te	See comment 19. No references to EPD's should be present in this report.	Edited. Not sure how it relates to comment 19.	**15/2 2024** - OK approved **-** True this does not relate to comment 19, mistake from our site, but it has been corrected appropriately	**15/2 2024**
44	Use stage	Te	Remove this section or write that it has not been considered.	removed	**15/2 2024** - OK approved	**15/2 2024**
45	Impact assessment	Te	Since you are using a model with 18 impact categories and not 16, be very specific in your reference and list them here. With their full name, unit and indicator. Use table 1.4 from your source as inspiration.	added	**15/2 2024** - OK approved	**15/2 2024**
46	Impact assessment	Te	Normalization shold be avoided and falls outside the stanard. Please remove.	removed	**15/2 2024** - OK approved	**15/2 2024**
47	Impact assessment	Te	When using normalised data to see hotspot, you are no longer objective. Please remove. Normalisation is also only used together with weighting.	removed	**15/2 2024** - OK approved	**15/2 2024**
48	Scenario 1: Single Trench	Te	Please remove all normalised data.	removed	**15/2 2024** - OK approved	**15/2 2024**
49	Scenario 1: Single Trench	Ge	Show data for all impact categories	added	**15/2 2024** - OK approved	**15/2 2024**

50	Scenario 1: Single Trench	Ge	Please show contribution tree during meeting.	showed during meeting.	**27/2 2024** - OK approved	**27/2 2024**
51	Scenario 1: Single Trench	Te	**Version 1:** Has the 18000 excavations been weighted to be based on customers served? **Version 2:** Where did the results for daily and yearly go?	**Version 1:** Has been added in comment 23. **Version 2:** shorten the part of the daily and yearly to only showing the difference between the current and new process for the 4 chosen impact categories. (full tables with all impact categories are included)	**27/2 2024** - OK approved	**27/2 2024**
52	Scenario 1: Daily	Ed	See comment 48	removed	**15/2 2024** - OK approved	**15/2 2024**
53	Scenario 1: Daily	Ed	**Version 1:** See comment 49 **Version 2:** Where did the results for daily and yearly go?	**Version 1:** added **Version 2:** shorten the part of the daily and yearly to only showing the difference between the current and new process for the 4 chosen impact categories. (full tables with all impact categories are included	**27/2 2024** - OK approved	**27/2 2024**

54	Scenario 3: Yearly	Ed	**Version 1:** See above. **Version 2:** Where did the results for daily and yearly go?	**Version 1:** removed **Version 2:** shorten the part of the daily and yearly to only showing the difference between the current and new process for the 4 chosen impact categories. (full tables with all impact categories are included	**27/2 2024** - OK approved	**27/2 2024**
55	Sensitivity Analysis	Ge	**Version 1:** Sensitivity should be presented as shown in Annex B in ISO 14044. Please change. **Version 2:** For the transportation, we are missing an explanation of what this shows us (e.g. that the number is appropriate to use, that the worst case should be used or something third). For the trench sizes, the calculation is not correct. The sensitivity shall be calculated on the difference of the two possible reductions of trench sizes (50% compared to 66%) and not the current situation compared to the reduced trench size (NOT 100% compared to 50% and 66%). Further we are missing the procedure and the conclusions of this analysis.	**Verison 1:** changed **Version 2:** edited	**27/2 2024** - OK approved	**27/2 2024**

56	Table 12	Ge	Remove these values as they fall outside standard.	removed	**15/2 2024** - OK approved	**15/2 2024**
57	Appendix C.1	Ge	**Version 1:** These results should be in the report. Please update. **Version 2:** See comment 51+53+54	**Version 1:** added **Version 2:** Awaiting answer	**27/2 2024** - OK approved	**27/2 2024**

58	Scope definition	Ge	**Version 2:** Regarding the allocation procedure: Please add the allocation procedure seen in chapter 4.3.4.2 of the ISO 14044 standard **Version 3:** Please write the following: "The allocation procedure will follow the three steps in chapter 4.3.4.2 of the ISO 14044 standard: **Step 1:** Where possible, allocation should be avoided by expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3 **Step 2:** Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or function in a way that reflects the underlying physical relationship between them; i.e., they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. **Step 3:** Where physical relationship alone cannot be established or used as the basis for allocation the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example,	**Version 2:** Added **Version 3:** change the text to the suggested text.	**6/3 2024** Ok approved	**6/3 2024**

			input and output data might be allocated between co-products in proportion to the economic value of the products."			

59	Scope definition	Ge	**Version 2:** Regarding the Data Quality Requirements: Please correct table 1 so it fits with the DQR description, and the values DQR of the production, construction, and EoL stages in Tables 2-4. The country of production is the country where you get it produced, and not where the dataset is from. The validity of the data, temporal, is the last date, the first date is just an expression of when the data is made, and then it has since that date been updated to fit the current date. **Version 3:** "gravel and sand quarry operation l gravel, round l Consequential, U - RoW" is based on Switzerland and Europe, but is set as 5 geographical representation - would argue atleast a 2 or 3 and "treatment of garden biowaste, homecomposting in heaps l biowaste, garden waste l Consequential, U - RoW" is based on south west France, but rated 5 - i would argue a 3 - Please revist the DQR with focus on the Geographical representaiton of processes from regions	**Version 2:** changed **Version 3:** Revisit and changed accordingly	**6/3 2024** Ok approved	**6/3 2024**

60	Data quality - *Temporal - Page 16*	Ge	What sensitivity analysis is refered to here?	Has been deleted, as it was in a first draft and been overlooked during our review.	**27/2 2024** - OK approved	**27/2 2024**
61	Table 16	Ge	**Version 3:** Please add a column presenting the % difference, and make the numbers absolute reduction - e.g. change the name of the table to "Absolute reduction of the two scenarios"	**Version 3: added**	**6/3 2024** Ok approved	**6/3 2024**