Maintenance Emission Information Model

Developing an information model/tool to quantify CO_2 emissions from Maintenance activities of large number of assets in a Municipality

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by

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in partial fulfillment of the requirements for the degree of **Master of Science in Construction Management and Engineering** at **Delft University of Technology**

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This thesis is confidential and cannot be made public until January, 2023.

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface

This report is the final result of my thesis work that I conducted as per the requirement of the MSc program Construction Management and Engineering at TU Delft. Looking back at the past two-plus years reminds me of the countless experiences that I faced. I'm grateful for the past two years and would like to thank every person I have met throughout this journey from whom I've learned at least something. Over the past 6 plus months, I have delved into the actual research process and had several

learnings throughout the process. This research process would not have been possible without the committee members from the university and the company. I would like to express my sincere thanks to my Chairperson Prof. dr. H. M. (Henk) Jonkers for the guidance, support, and all the positiveness throughout the thesis. I would also like to thank my first supervisor Dr. ir. G. A. Van Nederveen for the valuable feedback throughout the graduation process and for providing direction on various matters from the beginning of my thesis. I want to convey my sincere thanks to Sweco NL and the Obsurv team for providing me with this opportunity to do my graduation with them. I enjoyed and learned a lot about the industrial aspects from both of my company supervisors Ir. Ben Visser and Ir. Shreenidhi Raghavendra Rao. They provided constant feedback and necessary input for the thesis work on a routine basis. I am grateful for all the support from my committee members.

On a personal note, my heartfelt gratitude towards my parents and siblings for their unconditional love and support for the past 2.5 years. Without them, it would have been still a dream to pursue this education. Starting a master's degree when COVID was still a thing and completing it will be cherished forever. Achieving this feat was not an easy task. My family and friends were the support system that helped me apart from the academic requirements. I would like to thank my friends Aditya, Adhil, Asit, Barshaleena, Mehna, Rahul, Vikas, and Zac for being there with me not only during the graduation process but throughout my master's. I am grateful for my close friends Ragav, Siddique, and Priya who were there for me whenever I needed them. Lastly, a sincere thanks to the CME Cohort of 2020 - 2022 for giving multiple opportunities, and learning experiences and providing ways to meet various personalities from all walks of life.

Uthirapathi Prabakaran
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Executive Summary

Introduction

The construction industry in the Netherlands are taking numerous measures throughout the industry to achieve the possible reduction of CO2 emission or GHG emission by 2050 to become carbon neutral. This goal is not only for the construction industry but for all the industries in the Netherlands. Though the term 'Sustainability' has been constantly in the spotlight of the world countries for the past three decades, the ability to achieve the goal has been achieved yet. To achieve the goal, every industry has to redefine the current measures taken in terms of reducing the GHG emissions. In the construction industry, the major focus is usually on the production and construction phase of a building or a civil infrastructure. To meet the requirements of the Paris Climate agreement and the Sustainable Development Goals (SDG), the municipalities and the stakeholders involved in the maintenance phase of civil structures has to improve the emission reduction process. This can be made possible if the quantification of the CO2 emission is improvised from the current status and focuses only on the maintenance activities alone.

Problem Statement

The lack of clarity in the LCA application like Dubocalc during the usage & maintenance phase of assets is the initial point of the research problem. The existing applications focus on the CO2 emissions from the major maintenance activities and the focus is less on the minor maintenance activities like the transportation caused by various inspections and other machinery usages etc. These minor activities are performed on a routine and emissions related to that have to be considered for the LCA applications or for the asset management process. For a single asset, the quantity might be minimal but every single municipality in the Netherlands posses hundreds or thousands of civil infrastructures under their territory. The quantity of emission for all these assets for lifetime is huge and it can become a major problem if not addressed. To address this issue and the research gap, the first step is to gather the required data and quantify the CO2 emission caused by all the maintenance measures of the asset them using practical methods. To achieve the desired outcome, the main research question was framed as following :

"How can the CO2 emission from maintenance activities of a large number of physical assets be quantified and used as an indicator by the municipality in decision making of an asset management plan?"

Research Approach

The research approach followed is practical and was based on a particular municipality in detail. To change the current scenario in estimating the CO2 emissions from the maintenance activities and to provide the outcome of this research, a four phase research methodology is used. The first phase involves the literature study and their findings, the second phase involves the development of the breakdown structures and the UML class diagram. The breakdown structures are to decompose the municipality into their assets and their respective components whereas the UML class diagrams are made to provide a schematic map to connect the assets with the maintenance activities and the maintenance activities with their respective CO2 emission data. This UML class diagrams also gives the user an understanding on the type of data required to achieve the CO2 emission. The third phase involves the development of the information model using the inputs obtained from the breakdown structures and the UML class diagrams. The last phase involves the verification & validation of the developed information tool followed by how the research outcome can be used by the stakeholders involved in the asset management industry.

Results

The results of the research are obtained from the developed information model. The MS-excel based information model allows the user to estimate the CO2 emissions of the assets located in the municipality of Schagen. The data obtained from the estimation of CO2 is used in the dashboard of the information model to visualise and compare the data in terms of different criteria like building materials, size of the assets, location of the assets, heavy machinery usage etc. This way, the decisions can be made by the involved stakeholders in the asset management in the strategies of maintenance planning of the assets or the overall municipality.

Verification & Validation

The verification process is done for the individual components of the research. The requirements for each of the components is verified in steps. The breakdown structure's requirement is verified as the requirement to obtain the decomposition of municipality's assets into their minor maintenance activities is achieved. The UML class diagram was verified as the requirement to connect the assets with their maintenance activities, maintenance activities with their CO2 emission and the to recognise what type of data are required to estimate the CO2 emission is achieved. The information model is verified as the requirement to obtain the CO2 emission data of all the assets of a single municipality was achieved. The validation of the information model is done by using the model for a different municipality (Zuidplas) to estimate the CO2 emission from the similar types of assets with the same maintenance measures. Hence the information model is both verified and validated for practical application.

Limitations

The research is focused on a particular municipality and the assets located in it. This makes the database restricted to assets located in that area. Assets apart from this municipality can be of different kinds and can have different minor maintenance activities. Hence this acts as a limitation. The information model is more based on a Dutch Municipality and the maintenance measures (maatregel) are specific to the count. There might be differences in the maintenance activities for other countries. The database of the assets and the minor maintenance activities are limited and due to this reason, the usability for other municipalities is limited. The data related to the minor maintenance activities like the distance travelled by the contractor to the construction site or the usage hours of the machinery are all assumed as the data might vary widely.

Recommendations

Practical Recommendations

1. For the Obsurv platform owners & users, the estimated CO2 emission data from the information model can be used as an input in the dashboard created for the various clients among the municipalities.
2. For the Municipalities, they can rely on the dashboard for the CO2 emission from the various assets and CO2 emissions based on the materials used for the construction of the civil infrastructures. Depending on such criteria and other important factors, these municipalities can take decisions based on the data.
3. For the municipalities, this information model can be more helpful in terms of civil infrastructures as it is solely focused on the maintenance activities of them. Hence this model can replace Dubocalc for the CO2 emission estimation particularly for the maintenance phase of the civil infrastructures.
4. For the maintenance contractors, the information model can provide useful data on the CO2 emissions for the materials used, machinery used for the maintenance activities of the assets. This can provide the contractors to decide on the type of materials and machinery used for the maintenance measures of the civil assets located in the municipality.

Future Recommendations

1. The data obtained can be refined by obtaining from the direct sources like the contractors involved in the minor maintenance activities. This can improve the quality of data and the output obtained from the information model.
2. The collected data, output can be used by the stakeholders to optimise the CO2 emission with regards to other criteria like cost and time.
3. The developed information model's output can be added to the LCA applications and refine the emission details of the civil structures in their usage and maintenance phase.
4. The MS-Excel based information model can be upgraded to Power Bi - to improvise the dashboards and create multiple criteria as per the user needs.

5. The information model can also be transformed into python model and make the model more automated compared to the current version.

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1 Introduction

This chapter gives a brief introduction to the research context of the thesis. From there, the research problem is identified and explained in the problem description. Further, the research objectives, the main research question, and the sub-research questions are explained. The final part focuses on the research outcomes.

The term sustainability has been in the spotlight for the past 30 years. Every nation, together and on its own, is striving hard for the ultimate goal of reduction of CO_2 emissions. (Ma et al., 2021) mentions that the reduction of CO_2 emissions is an intricate problem that engulfs multiple factors like technology, society, and the economy. Hence, it becomes a tougher challenge even for the developed Nations in the world. The Netherlands, one of the developed nations, has taken numerous measures to mitigate this problem. The measures are taken at the policy level, only which can have a true impact on reducing the emission process. To facilitate the SDG goals and the Paris Climate Agreement, the Netherlands pledged to cut down 49% of the CO_2 emissions by 2030 and achieve net-zero emissions by the year 2050(National Climate Report 2019). However, based on the Klimaat- en Energieverkenning 2021, the Netherlands will only be able to achieve emission levels of less than 38%-48% of the 1990 level. The measures taken at the policy or national level start before the Paris Climate agreement. It started in the year 2011 and is in progress. Though every industry is responsible for reducing CO_2 emissions, the responsibility falls under the Ministry of Infrastructure and Environment. Apart from this, the Ministry of Economic Affairs and Climate policy also plays a major role in mitigating the emission issues in the Netherlands.

The measures taken in the infrastructure domain mostly suit this thesis's context and hence will focus on them. Multiple measures have been executed in the AEC industry regarding the material change, sustainable materials, circular materials, etc. These are adopted in the industry at a growing pace. Another measure was introducing the MKI (MillieuKostindicator) for implementing a tax on CO_2 emissions in every industry. This is one of the significant measures taken for the AEC industry as they are one of the biggest sources of emissions in every country. Although efforts are taken in the forward direction, a slight paradigm shift must consider the thousands of infrastructures built in the past 70 to 100 years. These structures were never considered an emission source at the time of their construction. However, these structures reaching their lifetime and combating the CO_2 emission are two crucial factors to be considered to decide on the future. This decision needs to consider that there will be many replacements, demolition, and maintenance of assets. A single municipality has hundreds of assets. The impact these activities bring on the environment is enormous; hence, this thesis will use this as one of the needs of society, and the other needs will be mentioned in the problem description.

In the Netherlands, there are about 344 municipalities (Centraal Bureau voor de Statistiek, 2023). Each Dutch Municipality consists of hundreds or thousands of infrastructural assets. These assets are of different types, which can be small or large, and are made of different materials. These assets were built more than half a century ago. Most of these assets have crossed or reached their intended lifetime ("Service life of concrete structures | TNO", n.d.) and hence need to be maintained regularly or replaced at the right time to provide less disrupted service to the residents of the Municipality. Such activities planned by the Municipality are based on cost, risk, service life, inspections, and the number of intervals per cycle. These activities are a significant source of CO_2 emission, and it is repetitive throughout their lifetime (Ma et al., 2021) (Seo & Kim, 2013a)(Seo & Kim, 2013b). This CO_2 emission is recognized as one of the reasons for climate change (Choi, 2019).

The Netherlands has made some commitments as a nation and a member country of the EU to the Paris Climate Agreement to minimize emissions. Apart from the policies, most of those commitments are mainly up to the municipalities and private organizations to carry out (B. C. Zoeteman, 2013). Efforts are taken both on a global scale as well as on a local scale to reduce emissions in all possible ways. One of the ongoing efforts to reduce CO_2 emissions is the project called URBCON, which is funded by the EU and executed by and in the Northwestern countries of Europe. This project aims to reduce the use of default raw materials, thereby reducing emissions from the construction and maintenance of buildings and infrastructure in cities(Interreg). Based on the current Interreg program from 2021 - 2027, the main aim is to "Promote a green, smart and just transition for all North West European territories to support a balanced development and make all regions more resilient." In the asset management domain, the physical assets located in the Municipality are one emission source from their construction, maintenance, and replacement activities (Ma et al., 2021). The LCC applications like Dubocalc already address the emission data of materials and emissions during construction, operation, and demolition. However, the emissions are mostly related to the material emissions and activity during the construction, operation, and demolition process, not the activity involved in the maintenance phase. Due to the need of the industry and the commitment to cut down the CO_2 emission. An information model is needed, which contains all the necessary information about the maintenance works(Kuntswerk) for every type of asset, each of those maintenance works has to be decomposed into more minor activities and their emission details, cost details, etc. This model contains all the available data that are crucial for the asset management plan, and hence it can be utilized for all the required quantifying comparison and assessment purposes. Using this model, the CO_2 emission can be considered an essential factor in selecting alternate materials for the assets or in deciding the strategy for asset maintenance planning. This information model can be helpful to asset managers and municipalities in making decisions on the maintenance strategies of assets.

1.1. Sweco & Obsurv

1.1.1. Sustainability in Sweco

The climate goals of the world nations and sustainability goals of the Netherlands are recognized by Sweco as an organization and a stakeholder in many Governmental projects. They believe that sustainability is essential to tackle the current situation. In most of the infrastructure and construction projects provided by the company, both cost and emission are regarded as equivalent criteria. There is always a consideration of using environmentally friendly materials in their projects or minimizing material or energy consumption. Further, Sweco implements sustainable design and life cycle analyses for its projects. Using circular materials in the project is one way of achieving it.

1.1.2. Company's interest and needs:

This graduation thesis will be in cooperation with Sweco Netherlands. It is a multi-faceted firm who are well established in many European countries. They provide consultation, engineering, and other services to firms, the Government organization that are active in architecture, construction, and asset management. In Sweco NL, Obsurv is one such team focused on the portfolio management of the assets of Municipalities. They are responsible for managing the assets of the Municipality through web-based software called Obsurv. This application/software is the first-of-a-kind integrated management system for public spaces, which considers planning and budgeting in a single process. They consult municipalities on asset management and maintenance matters of the assets by planning their maintenance activities for a given period or during their lifetime. Sweco NL needs to implement sustainability in its services as an industry leader in this asset management domain. This need and witnessing of routine maintenance activities as an emission-causing factor lead to the requirement of building an information model for all the maintenance activities of the assets in a municipality and connecting them with their corresponding CO_2 emission. Due to the needs of society and the environment, the company and the team have decided to create this information model, which can help the Municipality to understand the effects of maintenance activities by providing them with the necessary emission details and the costs for all the assets. Providing such information can give the customer (Municipality) more options to weigh the scenario based on essential criteria like the emission and the costs.

1.2. Problem description

In reality, reactive maintenance strategies are still followed in most organizations despite the ongoing advancement in technology and learning from maintenance management (de Souza et al., 2021). This means very minimal measures are taken in the policy-making phase before constructing an asset or multiple assets in a given area. Government organizations operating and maintaining the infrastructure assets do consider a trade-off between environmental protection and economic development (Jin et al., 2018); however, this does not include the maintenance activities carried out throughout the lifetime of the assets and are an essential source of CO_2 emission. There is considerable research conducted in other domains where the CO_2 emission from maintenance activities has been recognized. E.g., maintenance in the building sector (Ahmed Ali et al., 2020), railway resurfacing maintenance (Krezo et al., 2018), and maintenance of asphalt pavement maintenance (Yu et al., 2018). There are instances where the emission is considered for single bridge maintenance (Gokasar et al., 2022) but not for multiple assets. In the Netherlands, the Government and other organizations utilize quantitative tools like Dubocalc and CO_2 ladder to assess environmental impact throughout the life cycle of projects/assets. However, neither policymakers nor product developers currently have the tools to monitor the effects of the various innovations in road infrastructure construction, maintenance, or management techniques (Keijzer et al., 2015). This is the case for other types of civil infrastructures as well. The initial point of the research problem starts from the industrial and global need to reduce CO_2 emissions. Despite considering CO_2 emission in the production and construction phases, the focus on CO_2 emission during the maintenance phase of the assets needs to be improved. The commitment to minimize CO_2 emission has yet to be achieved in the asset management & maintenance of civil structures, which are a part of the construction industry. Asset management and maintenance involve making complex decisions on the appropriate strategies throughout the life cycle of the assets. The computer-based Decision Support Systems (DSS) can solve and enhance the decision-making processes in complex systems by reducing uncertainties, and human errors (Velmurugan & Dhingra, 2021). Hence an information model has to be developed to solve the problem quantitatively and provide data/indicators for the decision makers like the Municipality and asset managers involved in the asset management and maintenance of civil structures.

1.3. Research gap

The current tools used in the Netherlands to quantify the CO_2 emission are Dubocalc, Madaster, CO_2 ladder., etc. The Dubocalc considers the CO_2 emission throughout the project's lifetime, from manufacturing to demolition. During the manufacturing and construction phases, it considers all the minor activities involved, like transportation, installation, etc. However, for the maintenance phase, the quantity of emission is given for the whole operation and maintenance phase and does not consider the minor activities involved. As this phase is the longest and has multiple maintenance activities throughout it, it should consider the emission from all such minor activities involved in the maintenance phase. The existing emission database focuses more on material and construction phase emissions. For example, Madaster and Dubocalc focus more on material emissions throughout their life cycle. However, the sub-activities like transportation and machinery emissions involved during routine maintenance are not considered(Heisel & Rau-Oberhuber, 2020) (dos Santos et al., 2017).
The research gap is that numerous research focuses on the CO_2 emissions from materials manufacturing, using materials during the construction process, emission during the operation phase of the assets, and the demolition process. Nevertheless, during the operation of the asset, every asset goes through routine maintenance. These maintenance activities include more minor activities like material usage, installation, transportation, etc. The emission data related to the maintenance phase of the assets are mainly under the assumption and are not verified (Krezo et al., 2018). Since the maintenance activities are not predictable and are based on the asset structure's condition, it is hardly evaluated in the existing applications. This is identified as the research gap and will be used for this thesis.

1.4. Research Objective

Based on the problem description and the research gap, the initial objective is to create an information model that considers all the assets in a municipality and connects them with their maintenance activities and sub-activities. The next objective of the research is to connect these significant activities and sub-activities with their emission details. Currently, the MKI(environmental costs) is used as the indicator for the emission of CO_2 (Choi, 2019). The final objective is to develop an indicator that the stakeholders, like the Municipality, can use to compare and analyze if the asset is built with a different material and how the emission will be. This indicator will be helpful for the users as it can aid in comparing and assessing the emission situation for many assets with a large number of maintenance activities. By developing such an indicator, the Municipality's decision-making process can be based on the emission details, costs, and other factors.

1.5. Research questions

Main Research Question
"How can the CO_2 emission from maintenance activities of a large number of physical assets be quantified and used as an indicator by the municipality in the decision-making of an asset management plan?"

Sub-Research Questions:

1. How can the major Maintenance activities of each type of asset be breakdown into sub-activities?
2. How can the emission data be linked to all the sub-activities of the maintenance works?
3. How can the information model be built using the relevant data?
4. How can the information model be adopted in the asset management plan of Municipalities?
5. How can the information model aid in making decisions on maintenance strategies for the Municipality?

1.6. Research Outcome

There is an industrial need for such a maintenance emission information model. It is because the existing software(Dubocalc) is time-consuming and tedious to quantify the emission data for a large number of physical assets with n number of maintenance activities. The outcome of this research shall simplify this process by establishing an indicator that can be used to quantify the emission from maintenance activities for all the assets. The indicator for each type of material that can be used for the construction, maintenance, or replacement of the asset. This emission index or indicator provides the following:

1. Comparison between the emission data if the assets are maintained/replaced with different materials.
2. Provides insight into how maintenance activity and the emission differ based on the material selection for the asset.
3. Decisions can be made using this model focusing on cost and the quantified emission data.

2
Literature Study

This chapter elaborates on the literature findings. It begins with the current Dutch standards, regulations, and strategies for maintaining the infrastructure. From the regulations and strategies, we gather information about the breakdown structures and why they are necessary for the final output of the research. The next part focuses on the emission details from the activities involved in maintaining these infrastructures within a municipality. With the findings from the breakdown structures and the emission data, information models are studied to create a new model that contains the relevant factors for this thesis. The final part of the literature study focuses on adopting the created information model in planning maintenance activities and how they can be used to make decisions on the maintenance strategies of the Municipality.

2.1. Dutch Asset Management and Maintenance Regulations

In the Netherlands, the Government organization Rijkswaterstaat(RWS) under the Ministry of Infrastructure and Water Management is the central responsible organization for all the main infrastructure facilities. Their function is to design, construct, manage and maintain all these infrastructure facilities through various organizations under them or contractors.

Asset management is considered an overall system, whereas the maintenance management of assets from a particular portfolio is regarded as a sub-system. Further, this can be categorized into civil assets, Buildings, and industrial assets. All these can finally be categorized into their elements and components. For this research, only the maintenance management of the assets in a particular portfolio is considered. Hence the regulations of those will be studied in detail. The primary asset management standards followed in the Netherlands are ISO 55000, ISO 55001, and ISO 55001.

- ISO 55000 - Overview, Principles, and Terminology
- ISO 55001 - Management systems
- ISO 55001 - Guidelines and application of ISO 55001

For the system that borders both asset and maintenance management, the standards followed are EN 16646 and prEN 17666

- EN 166646 - Maintenance within physical Asset Management
- prEN 17666 - Maintenance of Engineering Requirements

Similarly, for the sub-system of the Maintenance of assets, the standards followed are EN 17007, EN 16991, EN 15341, EN 13460, and prEN17666.

- EN 17007 - Maintenance process and associated indicators
- EN 16991 - Risk-based inspection framework
- EN 15341 - Maintenance Key Performance Indicators
- EN 13460 - Documentation of Maintenance
- EN 15628 - Qualification of Maintenance Personnel

2.2. Key Concepts & Explanations

To further focus on the research topic in detail, the primary terms and definitions are necessary to understand the concept. As per (Hastings, 2015), Asset management is "the coordinated activity of an organization to realize value from assets". Similarly, as per NEN-EN 17485, the term maintenance management is defined as "All the activities of the management that determine the maintenance objectives, strategies, and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics."

The final output of this research can be helpful for maintenance strategies. These strategies identify the tactics and tools required to execute the maintenance plan of the assets.

According to the International Infrastructure Maintenance Manual (Institute of Public Works Engineering Australia & Association of Local Government Engineers of New Zealand, 2015), maintenance activities are planned and unplanned activities to minimize the degradation of the assets to maintain their serviceability against failures.

In the Netherlands, for the Maintenance of infrastructures/assets, there are three hierarchical levels of the system. They are, namely,

- Network (Eg: Highway)
- Structures (Eg: Bridges, Roads, Tunnels)
- Components (Eg: Foundation, Joints, Deck)

Our goal is to focus on the Municipality at the network level and the Municipality's assets and elements at the structures and components level, respectively. Maintenance strategy in the Netherlands is mainly based on the risk (Wessels et al., 2019). FMECA (Failure mode, effect, and criticality analysis) is essential for risk-based maintenance strategies. Though these strategies focus much on the critical factors of the structure, the less critical components are also crucial for the considered network, which is the Municipality.

2.3. Breakdown structures

The system we deal with in this research is the infrastructure system. Every Municipality owns a certain amount of infrastructure within its boundary, and the Municipality regulates these infrastructures. Such an infrastructure system consists of various structures like bridges, roads, railroads, sewers, duikers, etc. (INCOSE & Wiley, 2015). Due to the large number of assets, such infrastructure systems are complex and unique and deal with multiple interfaces in the system. They cannot be standardized and differ according to various municipalities. To approach such complex systems, it is essential to retrieve all the information from the top of the system until the minor activities involved in the maintenance cause the emission. One way to categorize and decompose them is through breakdown structures. System Breakdown Structures(SBS) give a hierarchical representation of a system with the necessary system breakdown without the possible interfaces and the changing dynamics of the system.

Breakdown structures are regarded as an essential tool for an extensive project/system which has multiple sub-projects or sub-systems in it. The purpose of breakdown structure is to give an overview of the project or the system hierarchically into workable sub-systems, parts, or elements. This way, all the sub-systems, elements, works, and activities related to the project are captured. It will help plan, estimate the cost, or understand how the project/system works. Breakdown structures were first developed from the Work Breakdown Structure (WBS) and eventually got developed into multiple types of breakdown structures per the requirements and the users needs. The various types of breakdown structures are System Breakdown Structure (SBS), Requirement Breakdown Structure (RBS), Project Breakdown Structure (PBS), Activity Breakdown Structure (ABS), Building Breakdown Structure (BBS), etc. These breakdown structures are also designed not to lose any crucial information about the project and to connect every element involved so that time, cost, and risk factors can all be estimated accurately.

For this thesis, the Municipality is considered a system of system (SoS) as per (Blanchard & Blyler, 2016) as it consists of multiple independent systems that can function independently. To set up a clear boundary for this thesis research, only the infrastructures existing in the Municipality are considered. This alone acts as a separate system. To gather the necessary information from the infrastructures and the maintenance activities, it is vital to decompose the infrastructures into the type of infrastructures.

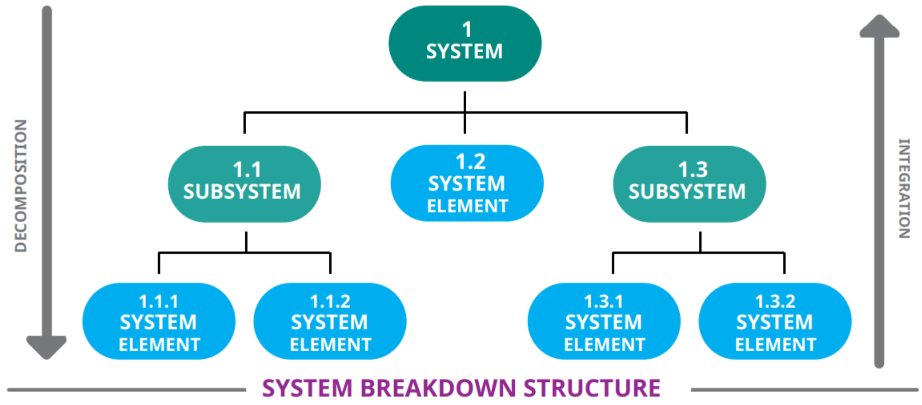


Figure 2.1: System Breakdown structure (de Souza et al., 2021)

This Maintenance of the assets is recognized as a system, and a System Breakdown structure is derived from it. The next step will be decomposing the type of assets into their elements which are considered sub-systems. These sub-systems are decomposed into their elements and can only be connected to the work breakdown structure as the maintenance activities are based on the elements or as an entire asset. Each of those elements is decomposed into its type of maintenance activities, which are further broken into their respective activities.

Two breakdown structures can be modeled together to incorporate the information on one layer into another (Camilo et al., 2012). The outcome can be utilized for the next stage, where we connect them to the emission data. In this information model, we are incorporating three varieties of breakdown structures: the system breakdown structure, the work breakdown structure, and the activity breakdown structure.

2.3.1. System & System Breakdown structure

The Municipality in the Netherlands has multiple systems under them. The considered system for this thesis is the infrastructure system. The ultimate goal of this research is to implement the final deliverable, which is the sustainable indicator in the decision-making strategies of the Municipality in terms of asset maintenance. Any sustainable goal in a municipality needs to have a collaborative approach with stakeholders like citizens, business organizations, etc (K. Zoeteman et al., 2016). This approach is vital for most of the sustainability and society-related measures that must be implemented on a large scale as it gets input from the critical stakeholders involved in the process. The Municipality, asset management consultants, contractors, and sub-contractors are the primary stakeholders responsible for managing and maintaining the infrastructure so that a reliable and safe service is provided to the users in the community (Kruithof, 2014). Most of the infrastructure existing in the Municipality are constructed 60 to 70 years ago. These structures are either reaching their lifetime or requiring an upgrade to prolong their lifetime and continue providing the service. The prolonging of the lifetime of infrastructures can be done by managing & maintaining the structures, strengthening, replacing elements, repairing, etc. Executing all these measures will cost 11 billion Euros every year (Bleijenberg & TNO, 2021) for the Government. This situation means that a regular stream of Maintenance is mandatory for almost all the infrastructures existing in the Municipality.

An asset is defined as an entity that has an actual value to an organization or an individual and provides a service to the users (Maring & Blauw, 2018). The Municipality manages all the assets from the design phase until demolition and disposal. The longest phase in the life-cycle of these assets is the operation & maintenance phase. The Municipality, with the help of consultants like Sweco NL, plans on the Maintenance of these assets. The maintenance planning and monitoring of the assets currently are more focused on the factors like cost, specifications of the assets, priority of the assets, and the ambition level of the Municipality. Out of the mentioned factors, the crucial one is ambition level.This is similar or in par with the other standards like NEN2767-t, NEN2767-c, CROW-t, CROW-c, beeldkwaliteit and SHV. This ambition level has six scales: Prachtig, Mooi, Degelijk, Sober, Veilig, and Onveilig. Prachtig is the well-maintained and safest standard of assets, and Onveilig is the least maintained and unsafe standard of assets.

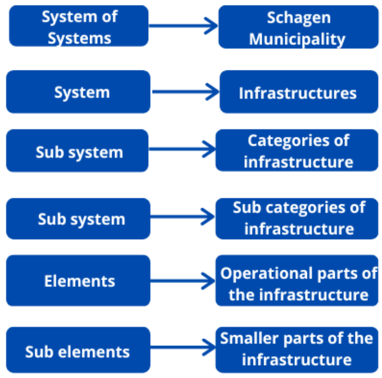


Figure 2.2: Breakdown structures

Based on the available ambition level, there are three categories.

- Alleen Onderhoud (only Maintenance)
- Onderhoud + Vervanging (Maintenance + Replacement)
- Onderhoud + Vervanging + Gevolgschade (Maintenance + Replacement + Consequential damage)

The costs for the three categories are determined based on the ambition level for a year. Depending on these cost figures, the Municipality is expected to make some decisions regarding the maintenance strategies of the assets.

Another type of classification of maintenance activities is based on the time of maintenance activities which is often mentioned as Periodic Maintenance or Time-Based Maintenance(TBM).

- Routine maintenance - Inspection/ cleaning
- Yearly Maintenance - Maintenance activities per year
- Fixed Maintenance - Maintenance activities every five year
- Replacement of Objects

From past research, it is evident that Asset Management(AM) is complex and many municipalities and Governmental organizations find AM and maintenance planning difficult (Pham, n.d.). Most of the existing forms of AM focus more on minimizing costs and improving the efficiency of maintenance planning. The starting point for the inclusion of CO_2 emission as a criterion for decision-making in AM or maintenance strategies has to be from the asset owner (Municipality). It has to be determined whether the objective can fit the organization on a strategic level. The starting point is the breakdown structure to utilize CO_2 emission as the indicator for the Municipality's decision-making.

The breakdown structure starts from the Municipality and decomposes into the last activity based on the Maintenance works for each structure or object. The breakdown structure starts from the system breakdown structure and ends with the Activity breakdown structure. The decomposition is not an outcome but a tool and a starting point for estimating CO_2 emissions and a holistic view of the maintenance process. This way, it is possible to have an overview of the vast system of the Municipality and

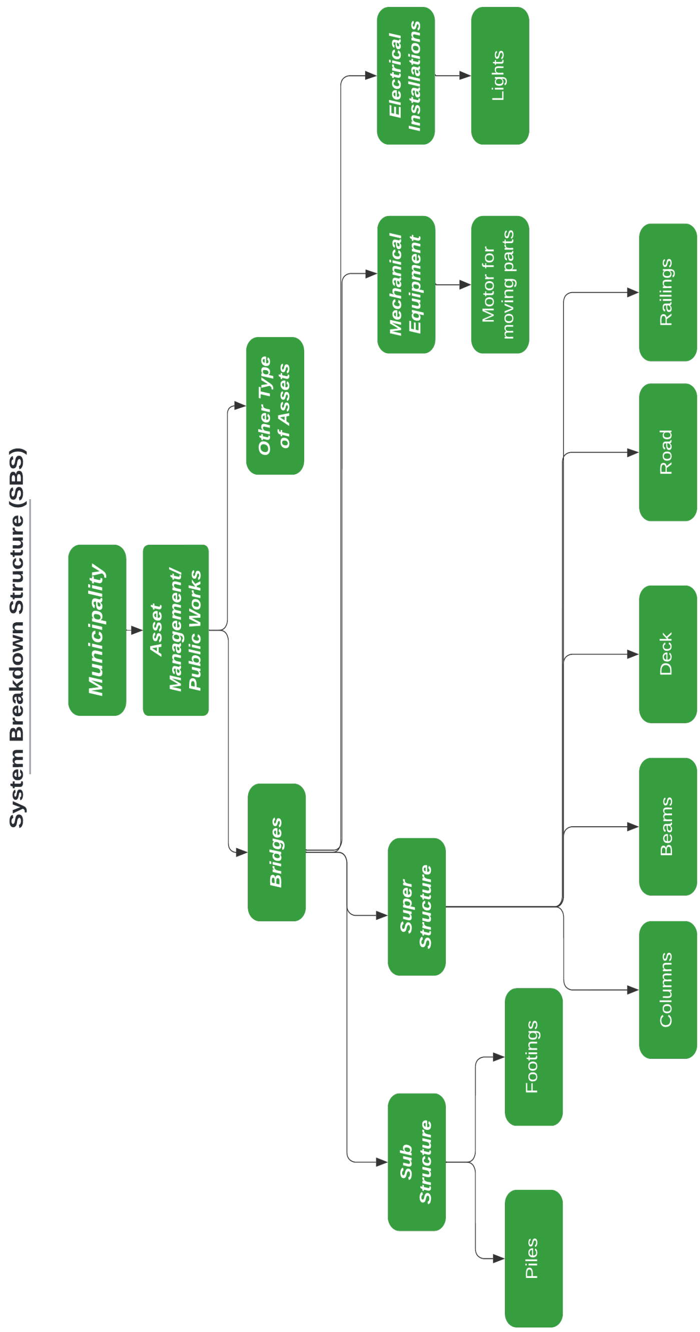


Figure 2.3: System Breakdown Structure of a bridge

NORM	Omschrijvingen per ambitiniveau						Disciplines
NEN2767-t	Uitstekend	Goed	Redelijk	Matig	Slecht	Zeer slecht	Gebouwen, kunstwerken
NEN2767-c	1	2	3	4	5	6	Gebouwen, kunstwerken
CROW-t	A+ Uitstekend	A Goed	B Redelijk	C Matig	D Slecht		Wegen
CROW-c	A+	A	B	C	D	E	Wegen
beeldkwaliteit	A+ Prachtig	A Goed	B Redelijk	C Matig	D Slecht		Wegen, Groen, Meubiliar
Ambitie	Prachtig	Mooi	Degelijk	Sober	Veilig	Onveilig	Algemeen
SHV		Schoon	Heel	Veilig			Algemeen

Figure 2.4: Types of Standard used by the Municipality

connect the system and sub-systems with their respective activities. These activities can be linked with their emission details in the next phase of the research.

2.4. Emission Data

The emission data required for such activities are to be collected and analyzed to connect the activity with the emission data. Then it has to be tailored to the needs of an information model. Since emission data is also vast and vague, it is necessary to determine the boundary for this emission data.

Emission Boundaries

The emission data that must be collected for the information model must be provided with a boundary. This is to create a decisive data structure, not an open-end data structure where all data seems relevant to the model. The boundary in terms of the phases considering the different phases of Maintenance also includes and excludes some in and out of the emission data scope. Only the gebruiktsfase (operation & Maintenance phase) is focused. In this phase, the operation phase is common and natural for every asset. The other four are scenarios (B2, B3, B4, B5). These might or might not occur during the lifetime of the asset. They are,

- B1 - Gebruik (operation)
- B2 - Onderhoud (Maintenance)
- B3 - Vervangingen (Replacements)
- B4 - Reparities (Repairs)
- B5 - Verbouwingen (Changes)

There are three types of GHG emission scopes, direct emission (Scope 1), Indirect emission from machinery and equipment usage (Scope 2), and indirect emission from electricity usage (scope 3) (Schmitz et al., 2004). For this research, scope one and scope two emissions are only considered. That is, the emission from the maintenance activities, emission from the material used for the Maintenance, and emission from the transportation of the materials are within the scope of this research. Emissions caused apart from the maintenance phase like production, construction, and demolition; disposal is out of scope for this research. The greenhouse gas emissions include CO_2, SF_6, CH_4, N_2O, HFCs, and PFCs. Among them, the type of emission in this research's scope is CO_2 emission. Other emissions shall be considered in the case of the absence of CO_2 emission and the availability of other emission data. On the whole, CO_2 emission is the focus of the research. To further clarify emissions estimation, double counting at various interfaces has to be identified and avoided. As mentioned by (Sandanayake et al., 2018), there are three types of emission, and these are the primary focus of the research.

- Emission from the material
- Emission from the machinery usage(transportation & operation emission)
- Emission from the equipment usage

Dutch & Sweco Practices

In the Netherlands, a system called the Environmental Performance system (Milieu-prestatie-systeem) is used to determine the environmental performance of a structure. This system combines a set of methods, databases, and calculation tools. Organizations use various applications to determine the environmental impact of their projects, systems, scenarios, etc. Some of them are GPR material, One Click LCA, Dubocalc, MRPI-MPG tool, etc. These applications or calculators are based on the National

Milieu Database (NMD). Dubocalc is one of the calculators devised by the Government organization Rijkswaterstaat.

In Sweco, self-developed Carbon Cost Management service and Dubocalc are used for the sustainability analysis and Life Cycle Analysis (LCA) in their projects. Most of these applications are based on projects or structures. Due to that, the accuracy in certain phases could be better as the focus on the processes involved is neglected. Though it is beneficial for a project setup, estimating the total emission from the maintenance activities of all the assets in the Municipality is time-consuming. Hence a different approach is needed to make decisions based on the emission data. For this reason, this research considers all the activities involved in the Maintenance and their respective emissions. This way, the data acquired can be used for a small-scale and larger-scale estimation of the emission.

2.4.1. Norms of Emission Estimation

The GHG protocol (Schmitz et al., 2004) suggests that estimating GHG emissions has five crucial steps. The steps are as follows.

- Step 1 - Identify sources
- Step 2 - Select the method of calculation
- Step 3 - Collect Necessary data and select the emission factors
- Step 4 - Utilize Calculation tools
- Step 5 - Finalized data to be used

Application	CO_2 (kilotons)	% of the total
Road surfacing (asphalt and road foundations)	197	28%
Coastline and navigation channel maintenance	191	27%
Structures (steel and concrete structures, excluding construction sites)	154	22%
Construction sites (earth-moving and other mobile equipment)	74	10%
Electricity (road lighting, traffic management etc.)	52	7%
Government Shipping Company	35	5%
Vehicle fleet (road inspectors etc.)	9	1%
Total for RWS, excluding buildings and mobility	712	100%

Figure 2.5: CO_2 Emission details by RWS (Ministry of I&W, 2020c;2019)

The above picture is an example of how much emissions are caused by road construction and activities related to that. Similarly, this can be done for all the maintenance activities and used for the following research stage. Similarly, maintenance activities related to the type of asset have their emissions. These emissions are from different sources as well. To identify emission sources, the different types of sources or scopes are to be identified and differentiated. The direct emission sources are first identified and followed by the identification of the indirect emission sources.

Direct Sources : Emission from the construction materials used for the replacement or repair works of the structure/asset. From the Work breakdown structure, the activities related to every maintenance measure (maatregel) are allocated. All these activities will be analyzed and studied for the type of emission, whether they are the direct source of emissions or indirect source of emissions.

Indirect Sources : Transportation of materials & machinery to the construction site for maintenance activities is considered an indirect emission source.

Method of Calculation

The calculation method for this research has to cater to all the activities and their relevant emission. All these activities are currently not monitored for emissions. Hence, the better way to calculate the emission is by using commonly available data like fuel use, emission factor, etc. Most emission databases, like the IPCC (Intergovernmental Panel on Climate control), provide various emission factors for various materials. Such databases and common factors can be used to calculate the emission data. These databases' accuracy and their values must be ensured throughout the process.

Life Cycle Analysis

As per the standards of ISO 14040, LCA is a cradle-to-grave approach that examines the environmental impacts of a material, product, process, or service during its lifetime either continuously or by independent phases (Kamali et al., 2019). It accounts for the emission from the extraction of the materials or the production of those materials, emission from the transportation of those materials, emission from their usage during construction, emission during operation and Maintenance, emission during demolition, and emission during disposal. LCA have different approaches, and they can be modified per the system's need. The different types of LCA are a) conceptual LCA - Life Cycle thinking, b) Simplified LCA c) Detailed LCA. In the Netherlands, LCA is considered necessary for circular and green procurement. The Dutch construction sector is adapting to use these LCA to become more circular. Applications like Dubocalc uses detailed LCA as it is used for real-life projects which need accuracy to a certain extent. The emission for the materials used in the replacement of the components of an asset is obtained from Dubocalc. Most of the LCA applications start from the data collection about the raw materials, products, processes, and energy used to extract or manufacture the product in question. Then the evaluation and estimation of emissions caused by the input materials/products are done. Then the emissions are categorized into different impact categories like Global Warming Potential (GWP), biodegradability, toxicity, etc. The final step involves the impact scores being weighed using the shadow price method and combined. This is done to convert the impact into a comparable number like MKI, which is expressed in Euros. Such Life cycle analyses or Life cycle cost analyses are done in most companies, primarily in the construction sector to become more sustainable and circular.

2.4.2. Emission from the material

The materials used during the Maintenance are only for the repairs and replacement of elements or components of the asset. The type of material used for such repairs & replacement depends on the type of asset and its composition. For example, a bridge can be constructed using concrete, steel, wood, etc. Similarly, the ground barrier can be made of different types of materials. The CO_2 emission has to be collected from the Dubocalc and other available sources for the materials. Since the material has to go through all the stages of its life, the embodied carbon emission of the materials is considered. The operational carbon emission from the maintenance activities is calculated using different methods, explained in the next part. The carbon dioxide (CO_2) or greenhouse gas (GHG) emissions associated with manufacturing and using a product or service are referred to as embodied carbon. In the case of construction materials, this refers to the CO_2 or GHG emissions associated with the extraction, manufacturing, transportation, installation, Maintenance, and disposal of construction materials and products (Cao, 2017). In the maintenance phase of an asset, the damaged materials and components that are to be replaced are taken into account for their emissions. To consider the emission from the materials, every asset in the Municipality is to be assessed. This assessment determines the components of every asset and the materials used for their construction.

The material emission for the elements and components of every type of asset is collected based on various sources. The emission is for unit dimensions of the respective materials. This emission quantity will be used for the overall research in quantifying the material emission. Along with this material emission, the transportation emission from the maintenance activities and the machinery & equipment emission from the activities together will give us the overall emission.

2.4.3. Emission from the machinery usage

The emission of all greenhouse gases from transportation activities can be derived based on the example given by (Sandanayake et al., 2018). The same can be utilized for calculating transportation emissions from maintenance activities.

$$E_{T_GHG} = \frac{Q_j * EC_j * EF_j}{1000}$$

Where,

$$E_T(GHG) = CO_2\ emission\ from\ transportation$$

$$Q_j = Quantity\ of\ fuel\ type\ (j)\ in\ kL$$

$$EC_j = Energy\ content\ factor\ or\ the\ heating\ value\ for\ fuel\ type\ (j)\ in\ GJ/kL$$

$$EF_j = CO_2\ emission\ factor\ for\ fuel\ type\ (j)\ in\ kgCO_2 - eq/GJ$$

To verify this with the Dutch standard, (Swertz et al., 2017) has also given a similar formula for calculating CO_2 emission from mobile sources in the Netherlands. This is the standard also followed by Statistics Netherlands(CBS).

$$Emission(kg) = \sum type\ of\ fuel\ sales\ (kg) * heating\ value\ (MJ/kg) * Emission\ factor\ (kg/MJ)$$

The quantity or fuel type is determined based on the vehicle and the activity. The respective fuel type's energy content or the heating value is derived from the CBS. For petrol, it is estimated at 43.0 MJ/kg; for diesel, it is estimated at 43.1 MJ/kg. Similarly, the carbon content or the emission factor is estimated from the CBS. For petrol, it is 3140 g/kg, and for diesel, it is 3130 g/kg. The above formula determines the emission from transportation-related activities during the maintenance phase of an asset life cycle. For every activity that involves transportation, the distance traveled by the vehicle, the type of vehicle, fuel consumption, heating value, and emission factor is collected and utilized for the CO_2 emission for every activity. Similarly, for every machinery operation, the working hours of the machinery, the type of machinery, fuel type, and fuel consumption data are collected and used for the CO_2 emission from the operation. Therefore, the transportation of the machinery from location A to the site and machinery operating at the site contribute to CO_2 emission. Suppose this is estimated for every activity considering unit dimensions and specifications. In that case, the outcome can be used for the overall emission calculation from the machinery and transportation involved during the asset maintenance.

2.4.4. Emission from the equipment usage

Besides the transportation emission, the other significant emission is from the equipment used for the maintenance activities of an asset. This research focuses only on the operation & maintenance phase of the assets. So the equipment's production and end phases are out of scope. Also, the machinery or equipment breakdowns, repairs, and changing of parts are out of the scope of this research. According to the ERA research report, three vital factors must be considered to estimate the CO_2 emission from the equipment. These factors are

- Hours per year (Usage)
- Transport during use
- Fuel Consumption

To estimate the CO_2 emission from the equipment used, specific data are needed like the weight of the equipment(Kg), Load capacity of the truck/ Trailer that is used for the transportation of the machinery from point A to the site and back to point A, truckload capacity factor (%), the distance over which the equipment is transported to the working site (Km), Average number of jobs, total operating hours during the maintenance phase, Average energy consumption of the equipment(fuel or electricity), Share of bio-fuels in for fuel or country of use for electricity, motor oil consumption (l/year).

To get the overall emission from the equipment, The breakdown structures will be helpful. It should be initiated from the equipment used in the minor activities of Maintenance of every component in an asset. Suppose the equipment's usage is collected for every type of asset and their minor maintenance activities, along with the usage hours and power consumption. In that case, it will be easier to calculate the overall emission from the equipment.

Data Collection

The data regarding the assets are collected from the Municipality using the software OBSURV which is one of the own built products of Sweco. All the necessary data regarding the assets are gathered from this source. The data regarding the minor activities of Maintenance, their respective emission, transportation activities, machinery usage, equipment usage, and their emissions are only partially gathered from the primary source as neither Sweco nor Municipality have that information. Hence these data are collected from the available literature and various database.

Calculation tools

There are various methods and tools to calculate the emission of Greenhouse gases like CO_2. Some of the commonly available calculators are Dubocalc, GHG protocol tools, etc. Various online calculators are also available to estimate CO_2 for activities like transportation from point A to point B.

2.5. Information Model

The available amount of data is humongous today in every field. The amount of data we deal with for a municipality is similarly significant. An information model needs to structure the available data in the desired manner to use it for the various purposes of the users. Creating an information model avoids all discrepancies related to data. These information models are crucial for any organization as the data collected is used for the purposes like cost estimation, risk estimation, Life cycle analysis, etc. An Information model is " an organizational framework you use to categorize your information resources Without such an information model, the tendency to lose data, collection & storage of unnecessary data, and retrieval of erroneous data are all inevitable". Information models are a combination of multiple data models. The difference between a data model and an information model is that the information model is more about managing organizations and objects at a conceptual level. Whereas data models are at an abstraction level (Schonwalder, 2017). Further information models are primarily in Unified Modeling Language (UML) while the data models are not (Schonwalder, 2017). For this research, the information model will also be based on UML.

2.5.1. Unified Modelling Language (UML)

The information model is to be developed from the assets' database in the Municipality. The emission data will be the digital representation of the real-world structures. Most of the infrastructure-related information models use UML as their essential tool of modeling (Jetlund et al., 2020). UML is a well-known information modeling language that is widespread for information systems and models. Also, the dynamic nature of the assets in the Municipality can be better handled through this UML (Veitaite & Lopata, 2022). The purpose of using UML for this research is that it can be used in the future for advanced information models like BIM and can be collaborated with the existing IFC standards that are common in most Building information models (Jetlund et al., 2020).

UML can be used for various purposes like software solutions, business processes, information models, information systems, systems behavior & structure, etc. There are varieties of UML diagrams that can be utilized according to the type of usage. The two main types of UML diagrams are structured and behavioral diagrams. Structured diagrams are mainly used to depict the objects and elements present in the system. At the same time, behavioral diagrams are to describe the functioning of the objects present in the system with each other.

UML Diagrams

In the structured type of UML diagrams, there are wide varieties like class diagrams, object diagrams, composite structure diagrams, etc. Our focus is on the class diagrams for this research. Class diagrams are influential for any object-oriented system. It gives a clear representation of the various classes present inside a system along with their attributes and a clear depiction of the relationship among the different classes, and subclasses.

There are varieties of layouts and symbols used for the class diagrams. A simple class consists of three parts: the name at the top of the class, attributes at the center, and methods or operations performed at the bottom. The relationship between the classes is explained using the varieties of arrows and their orientation among the classes.

The essential elements of a class diagram are the classes, objects, attributes, operations, entities, relationships, etc.

- **class**: A class can be defined as a system, object, or a collection of objects which come under a common structure and pattern. A class can be defined using the different attributes and their operations.
- **Subclass**: It is a class that inherits certain attributes and operations.
- **Objects**: Objects are elements that represent the classes in the UML.
- **Attributes**: The characteristics of the class are described by these attributes.
- **Method or Operations**: It is the function or usage of an object or class.
- **Relationships**: This defines the connection between the various classes and subclasses in the class diagram.

3 Research Design

This chapter describes the research methodology of this thesis in detail. The first part, section 3.1, explains the data collection, and the second part, 3.2, explains the scope of the research. 3.3 gives a piece of detailed information on the research methodology. The last part, 3.4, gives a summary of this chapter.

3.1. Data collection

For this research, the two inputs needed are the breakdown structures and the emission data. Only some data is collected for the information model based on the available literature. The data unavailable in the research papers are collected through the technical reports of the various municipalities, Government organizations like TNO and Pianoo. The data regarding the maintenance activities are collected through the websites of the various maintenance contractors.

The data required for this research are collected through various sources. The research objective of this thesis is approached using a mixed method of qualitative and quantitative research methods. The required data can be collected through a qualitative approach using literature studies from multiple sources and quantitative approaches like estimation for the CO_2 emission. Similarly, the data collected and the information model formed can be verified quantitatively and validated qualitatively. Pictures 3-1 in the research methodology section show how data is collected for every research question and the methods used.

For this thesis, a particular municipality (Schagen) will be chosen as a case study. Apart from the required data from the assets located, maintenance activities data, costs details, and ambition details are collected. These are the available data at the initial phase of the thesis.

3.1.1. Breakdown structures

The breakdown structure for the Municipality is initiated with the literature studies and the data collected from the company, which shows the existing projects and how maintenance activities are planned for various municipalities. These data consist of all the relevant data for the Municipality regarding infrastructure specifications, cost, and planning.

The next step of data collection is decomposing the maintenance activities into more minor activities until the emission quantification is accurate. This decomposition is done by the literature studies and some relevant data available from the company. In case of unavailability of required data, it is to be collected through technical reports of the asset management plan of various municipalities.

3.1.2. Emission Data

Further, other data required for the thesis is collected from the literature studies. For example, the emission data for activities involved in the maintenance program and the emission data related to the materials used or the installation process are collected through literature studies.

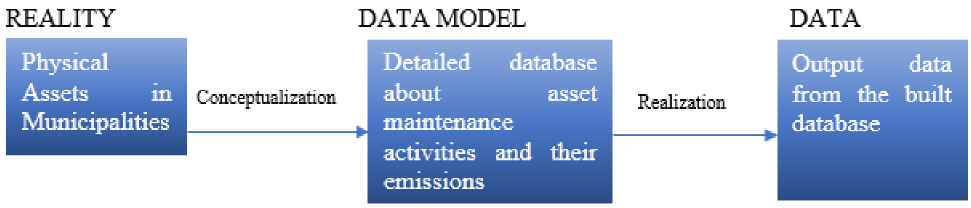


Figure 3.1: Information Model

Material Emission : Various available databases like Dubocalc and ICE database will be used for this emission. For the material emission, the embodied CO_2 is taken into account.

Transportation emission : It is estimated based on the available literature on transportation emissions and according to the location of the Municipality. Some of the data used for this emission are based on assumptions. For example, the distance to be traveled from point A to point B by the contractor for the maintenance work.

Equipment & machinery emission : These emissions are again estimated based on the literature studies. This estimation considers the machinery usage, fuel usage, and emission factors. Some of the data, like the working hours, are generally assumed.

3.1.3. Information model- UML

The details about the information modeling requirements and methodology are collected through literature studies. Due to the large size and complexity of the input information, it is necessary to categorize the required data and out-of-scope data needed to quantify the CO_2 emission details. Through data modeling, this can be done and will be helpful for future purposes (Koch & König, 2018). This information can help analyze, compare, and assess the data for further planning and decision-making scenarios.

Once the modeling method is chosen, per the norms of the Unified Markup Language (UML), the first step is to use the inputs and form the object-oriented models (OOM) through structured diagrams. This process can be done by recognizing the entity (objects), their attributes, associates, and inheritance. For example, re-painting is a physical activity existing in reality that is defined as an entity. There are many entity types(Classes)for an asset like cleaning, inspection, replacement, etc. In comparison, the geometric properties, functionality, material type, shape, etc., are considered as their attributes. These attributes have their name and can be of different types. When these entities, entity classes, and their attributes are well defined, the data model will be well structured and can be further developed based on future needs.

3.2. Scope of the research

This section clarifies the scope of the research using the boundaries set for the research.

Included in the research 1. Breakdown structure: This includes all the breakdown structures from the System breakdown structure to the Activity breakdown structure. 2. CO_2 emissions: This includes the material emission for which the embodied CO_2 is considered. For transportation emissions, material transportation and labour transportation are taken into account. For the machinery & equipment emission, only those that use the fuel are considered. Also, only the use phase of the machinery & equipment is mainly taken into account. 3. Information Model: This includes using UML for the assets and their types. The boundary is set until the asset types only for the information model.

Excluded from the research 1. CO_2 emissions: The CO_2 emission from the energy supply, water supply, and electrical equipment is out of the scope of this research. For the machinery & equipment, the emission from their raw materials, manufacturing, and disposal are out of the scope of this research. 2. Information model: Due to the data size of the maintenance activities for each type of asset, the UML model is excluded from the maintenance activities.

3.3. Methodology

The sub-research questions are to be solved to achieve the final research outcome. The research process is split into four phases. The first phase involves the literature study and data collection. In contrast, the second phase involves the decomposition of the Municipality using the breakdown structures and connecting the assets with their maintenance activities and corresponding emission details. The third phase involves building the information model based on the data collected. The final phase involves the verification and validation of the information model.

3.3.1. Phase 1: Problem Analysis & Data collection

The research methodology is categorized into different phases according to the sub-research questions. In the first phase of the research, the research problem is analyzed, and sufficient data is collected to initiate the primary steps to obtain the information model. The data required are collected through the literature studies, and some generic data are collected through various technical reports, maintenance contractor's websites, etc. Using the acquired information, the next steps of the research are devised.

The following data on CO_2 emission is collected from the literature studies. The emission from maintenance activities is categorized into three types of emissions, namely material emissions, transportation emissions, and machinery & equipment emissions.

Total CO_2 emission = Material emission + transportation emission + Machinery & equipment emission

Material emission : This emission is mostly obtained from available sources like Dubocalc, One click, etc. It takes the embodied CO_2 into account for the respective materials used.

Transportation emission: This emission is obtained using the formula obtained from the CBS stats and Research paper (Sandanayake et al., 2018).

$$E_{T_GHG} = \frac{Q_j * EC_j * EF_j}{1000}$$

Where,

$$E_T(GHG) = CO_2\ emission\ from\ transportation$$

$$Q_j = Quantity\ of\ fuel\ type\ (j)\ in\ kL$$

$$EC_j = Energy\ content\ factor\ or\ the\ heating\ value\ for\ fuel\ type\ (j)\ in\ GJ/kL$$

$$EF_j = CO_2\ emission\ factor\ for\ fuel\ type\ (j)\ in\ kgCO_2 - eq/GJ$$

This emission includes the repetitive transportation from the maintenance activities using the materials and transportation of the machinery to the construction site. There are some assumptions about this transportation emission, like the point of origin and ending of the travel or the distance traveled. Since this depends on the contractor and for every contractor, this distance will vary. The quantity of fuel depends on the distance traveled. The values of the other two factors are obtained from available sources like CBS.

Machinery & equipment emission: To estimate the emissions from the machinery & the equipment, the data regarding the usage of every machinery for the maintenance activity is necessary. Once this data is available, the usage of the machinery is figured. Another factor is the amount of transportation of the machinery. For the handheld equipment, this is not required. Based on this, fuel consumption is derived. Based on the type of fuel used, the emission for that fuel can be derived from the NMD or CBS. These three factors are essential in collecting the CO_2 emission from the machinery & equipment.

Machinery & Equipment emission = Hours per year (Usage) * Transport or distance traveled during use * Fuel Consumption * Emission factor

3.3.2. Phase 2: Building the Information Model

The first step in phase 2 deals with the creation of breakdown structures. The connection from the Municipality level to the minor maintenance activities is established through this breakdown structure. The purpose of this breakdown structure is to decompose the Municipality's assets in a detailed manner to estimate the maintenance emissions for every maintenance activity associated with the assets, and overall, this can aid in understanding which type of asset is made with which type of materials are responsible for the amount of CO_2 emissions. The second step deals with the UML class diagrams, which provide a schematic map for the users to connect the assets with emission data and details on the type of data needed to be collected for the emission estimation.

3.3.3. Phase 3: Diagnosis of the Information Model

The information model is built according to the research objectives and the outputs obtained from the breakdown structure and the UML class diagram. Once the structuring part is finalized, the emission data of the maintenance activities for the entire Municipality is estimated. Then this data is adapted as per the UML structure. The final step of this phase will be the information model with all the necessary data.

Verification: The third phase deals with verifying and validating the built information model. The verification process can be done by verifying that the requirements of every single component, like the breakdown structure, UML class diagrams, and the information model, on the whole, are met. Further, the results of the information model are also to be compared with the available or existing LCA applications like Dubocalc. This comparison can ensure the difference in emission values between the existing and the created information model.

Validation: Numerous methods can do the validation. In this research, the information model is to be validated by using the model to estimate the CO_2 emission for similar assets with similar maintenance measures from other Municipalities. This way, the output ensures that the model works provided the database for the maintenance measures are updated.

Dashboard: To present the information model interactively. The developed information model will be transformed into an interactive dashboard. (A.6) & (A.7) represents a sample structure of the dashboard to be developed.

3.3.4. Phase 4: Output & application of the information model

The final phase deals with the application of the information model effectively in the decision-making of maintenance planning and strategies. This phase also consists of the research conclusions and future recommendations. From the dashboard, the implementation of this information model and the overall conclusions of this research are explained in the final phase. After the conclusions, the limitations of this research and matters that can be approached for future research are provided.

3.3.5. Output

Using this built-up information model and the final dashboard, the emission data can be quantified for each activity related to the assets. Using the same principle, the CO_2 emission for assets made of certain materials can be witnessed. This result is used as an indicator for that particular type of material. The emission details are calculated for the various materials used for every type of asset. Based on the CO_2 emission indicator obtained for the type of material, the Municipality can use it for the portfolio management of the assets and their maintenance activities.

3.4. Summary

The process mentioned above is the research design for this thesis. The outcomes from the process will be used to answer the sub-research questions and the main research question.

4

Maintenance Measures and their Emissions

This chapter will start with the basic structure of the Municipality concerning the civil structures and their maintenance in section 4.1. Then, Section 4.2 will elaborate on the maintenance measures at a municipality level in detail. Section 4.3 is focused on the estimation of emissions from the maintenance measures. The following subsections will explain the emission from the materials and emissions from the maintenance activities in detail. For explanation purposes, a particular type of object, i.e., a Bridge, in this case, is taken as an example to explain the process of maintenance activities and how the emissions are derived from the material and activities. The rest of the details can be found in the information model with the necessary data.

4.1. Municipality and civil infrastructure management

Every Nation depends on its well-functioning infrastructures for its economy. These civil infrastructures are generally expensive and have multiple stages in their lifetime. Most of these structures are constructed for 50 - 100 years or more. In preserving the value and prolonging the life of these infrastructures, maintenance plays a crucial role (Gelderman et al., 2019). The Municipality which is taken as an example for this research is Schagen Municipality. The picture below shows the type of civil structures in this Municipality based on the collected data.

Though we have multiple objects apart from the civil structures, only the civil structures are considered for this study. Also, the responsibilities and duties of the Municipality are more than the maintenance activities. Usually, the operations & maintenance are considered as a bundle together which is managed by one of the departments of the Municipality. Based on the research focus and the research boundary, only the maintenance activities are focused on.

According to the Ministry of infrastructure and water management, Rijkswaterstaat is the primary agency responsible for the Dutch primary road network, waterway network, primary water systems, and the environment they are located. However, the Municipalities are the tier of Government with multiple responsibilities in providing direct services to the citizens. They are also responsible for building, managing, and maintaining large and smaller infrastructures, civil assets, and other objects within their boundary and under their control. The Municipality has multiple divisions in its organizational structure. The research focuses on the Municipality's civil assets, and the department responsible for the maintenance is the city management (Stadsbeheer) (Goldbohm, n.d.). They handle all the management and maintenance of municipal civil infrastructures. New construction or development projects are not under this department's control.

The maintenance approach differs for each Municipality. These approaches are aimed at satisfying the Government's national and local goals. Based on these goals or objectives, the management and maintenance of the various structures located in the city are carried out. as mentioned in the literature, the standards of these maintenance activities are primarily based on the CROW and NEN regulations. Also, the main stakeholders involved in the research process are the Municipality which is considered as the asset owners and the asset owners (department of city management) (van Riel et al., 2014),

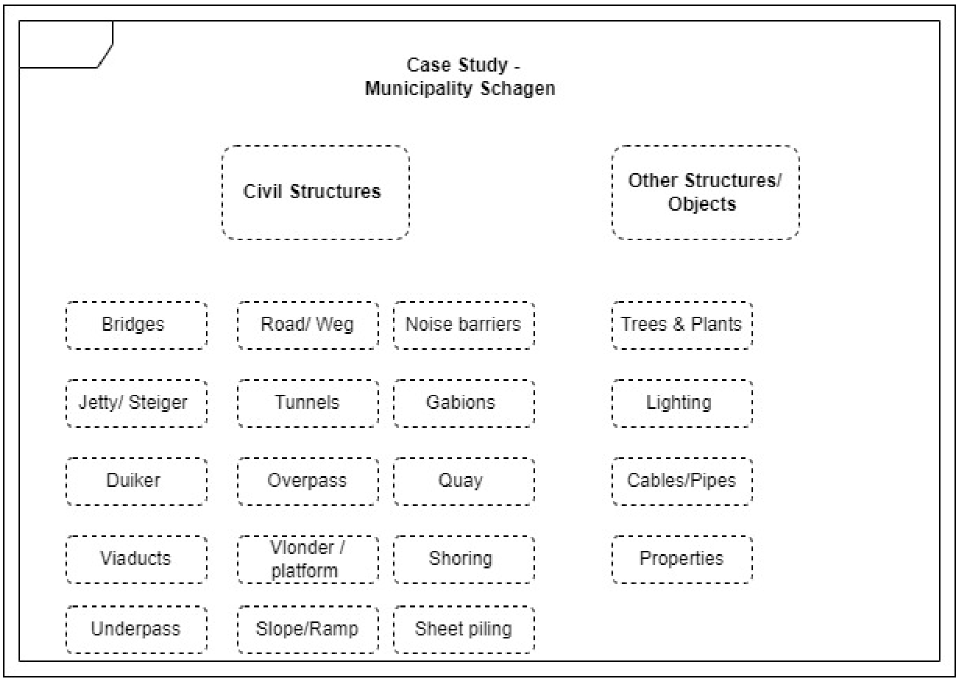


Figure 4.1: Schagen Municipality

Sweco (Obsurv), who are the consultants who have the client relationship with these municipalities. In this scenario, the contractor firm is responsible for the execution part of these maintenance activities. They are the service providers who tend to agree with the Municipality (Asset managers). All these stakeholders work in unison to provide safe and uninterrupted service to their citizens to utilize the public infrastructures.

4.2. Maintenance Measures

The Netherlands' municipalities manage civil infrastructures and provide periodic maintenance to keep the structures functional and safe for their usage. Apart from the maintenance, they are also expected to do inspections. These inspections are crucial for the maintenance measures done to prolong the life of the civil structure. There are three types of inspections for civil structures. They are condition inspection, technical inspection, and conservation/ maintenance inspection. The condition inspections are based on the NEN2767-4. In contrast, the conservation inspections are based on the CUR 72 (class 1.2), and the technical inspections depend on the structure's type or the structure's material (Institute of Public Works Engineering Australia & Association of Local Government Engineers of New Zealand, 2015). In the Netherlands, Based on ISO 55000 and NEN 2767, there are three categories of maintenance measures (Onderhoudmaatregelen). They are,

1. **Major maintenance measures :** Major maintenance measures aim to ensure the structure's functionality and preservation. Through these measures, the civil object is restored to its necessary condition. The decisions to go for repair or replacement are based on the defects' severity and extent. Depending on the severity and extent of the defects, a decision must be made about whether repair and replacement of the parts are necessary. Based on the size of the work, it is mostly outsourced to external maintenance contractors. Some examples of major maintenance measures are concrete repair works, masonry works, repair or renewal of decks, railings, etc.
2. **Minor Maintenance measures :** Minor maintenance ensures risk liability and compliance with the needed image quality. It includes minor maintenance, such as simple (manual) repair measures, and fixed maintenance (cleaning activities). These measures do not need complex aiding structures like scaffolding to be built, and the obstruction caused by such activity is minimum to the users. These measures entail uncomplicated and cheaper operations to reinstate the civil object back to its good condition. These minor maintenance measures, if performed periodically,

the major maintenance measures can be postponed to their original schedule. This performance of the minor maintenance activity helps reduce costs and provide undisturbed service to the users. Some examples of minor maintenance measures are cleaning objects, painting, and minor repairs on the pavement, etc.

3. **Replacement of objects :** Replacements are intended to make required structural changes. It is due to the reason that the object may be ideal for serving its function. Alternatively, the entire object may not be ideal or safer anymore to be used. Replacements are mandatory when major maintenance can no longer restore the structure to the desired condition. Replacements of smaller components are usually avoided, and mostly complete functional parts like the deck or the whole structure are replaced (Gemeentewet met betrekking tot Besluit Begroting en Verantwoording provincies en gemeentes BBV).

The maintenance type for every civil object at the municipality level is almost the same. This type is based on the frequency and the functions involved. Some other maintenance classifications include preventive type, corrective type, etc. The four major categories of maintenance type followed by most of the municipalities in the Netherlands and relevant to this research are :

- Maintenance/ Conservation (Instandhoudingsinspectie)
- Technical Inspection
- Cleaning Object
- Replacement of objects

4.2.1. Maintenance/ Conservation
The maintenance/conservation inspection or the instanhoudingsinpectie is based on the NEN 2767. These types of inspections are focused on the safety and the future of civil objects. The main aim of these inspections is to gather data for the MJOP (Multi Jaar Onderhoud Plan) and a safety plan. Often, these inspections are initiated when the outcome of the conditional inspection of the entire object or an element could be more satisfying. The frequency of these inspections is about one year for small-sized assets and 5 to 6 years for medium and large-sized assets.

4.2.2. Technical Inspection
These technical inspections are mainly done for every asset at a one-year interval for smaller objects and five years for large-sized assets. The emission from this type of maintenance measure will be from the transportation of the vehicles and the usage of machinery to inspect significant assets.

4.2.3. Cleaning Object
These maintenance measures are performed in shorter duration for most of the assets. It can also be done as per the weather conditions sometimes. The frequency of cleaning the assets is higher than other maintenance measures.

4.2.4. Replacement of objects
These maintenance measures are one of the significant sources of CO_2 emission in the maintenance phase of the asset. Though the interval is very high between the two replacement activities, the usage of machinery, transportation of materials, and machinery cause the maximum emission, among other maintenance measures.

4.3. Maintenance Activities and emission estimation

From the Major maintenance categories, the major maintenance activities are provided based on the records of the Municipality. These major maintenance activities involve,

- Maintenance or Conservation inspection
- Object replacement wooden bridge
- Replacement of planks <5cm
- Replacing wooden handrail

- Replacing wear layer on wooden deck (Asphalt)
- Cleaning object

The minor maintenance activities are framed based on the above major maintenance activities. For a different type of asset, like a tunnel, there will be necessary changes in both the major and the minor maintenance activities. These minor activities consist of various tasks inside them. For example, cleaning a bridge (reinigen object) has multiple smaller tasks inside of it, from transportation to using machinery, disposal, etc. Hence we need to figure out these smaller tasks to estimate the overall emission from the cleaning activity.

4.4. Type of Civil structures

In the Municipality of Schagen, the maximum number of assets are fixed bridges; hence, these bridges are focused in detail compared to the other type of assets.

Bridges

According to (of Transportation & Program, 1997), this type of maintenance is done routinely; it is done to remove; clear the components of an asset to be free from dust, dirt, vegetation, debris, etc. The scuppers, joint areas, and drains are also cleaned during this routine maintenance. This routine maintenance ensures the proper functioning of the assets by preventing the blockages of drains, corrosion, vegetation growth, etc.

All the activities involved in cleaning the objects need manual labour and certainly dedicated types of equipment to achieve the objective. The equipment needed is a water trailer, sewer snake, long-handle scrapers, square-pint shovels, brush clippers & saw.

The activities that can cause CO_2 emissions are listed below. They are

1. Transportation of the machinery & equipment to the site - The distance traveled, and the fuel used for that travel contribute to the CO_2 emission.
2. Cleaning/washing using the water jet/compressor - The cleaning/washing requires an air compressor. Most of the time, it uses fuel as its power source, leading to their respective emissions. The number of equipment used, the type of fuel used, and the number of hours of usage all contribute to CO_2 emissions.
3. Collection and disposal of waste from the asset location to the destination. This transportation, from the travel distance and fuel consumption, contributes to CO_2 emission.
4. All these works are done after making temporary traffic arrangements. These works can lead to some CO_2 emissions beyond our scope.

Apart from the activities mentioned above, the rest involve only manual labour and do not contribute much to the emissions.

Tunnels & Viaducts

The cleaning of the tunnels & viaducts involves the cleaning of emergency exit doors, gutters, gullies, etc. Manual operations are performed to carry out the activities of cleanings for smaller-sized tunnels. Machines like ZOAG are used to clean the walls, ceiling, and roads using vacuum and pressurized water for larger tunnels. This vehicle is considered an emission source due to its usage for longer hours and fuel consumption during that time.

4.5. Material Emission

The materials used for the construction of civil structures are one of the emission sources. Though the research focuses on the maintenance phase, the replacement of elements or objects will induce activities like transporting the materials and products from the factory to the respective construction site. The installation of that certain elements or objects on the construction site follows this. Hence, this emission information model considers the emission from this transportation and the installation process. A method is devised to estimate the overall emission from the construction materials used for the replacement activities. Every civil structure has multiple components and is not composed of the same materials. It is always a combination of various materials to build the entire structure. For the emission estimation, there are some accurate details from the Municipality and details regarding the emission from various databases like MLD, ICE v3, etc. Finally, there are certain assumptions are followed. They are :

1. Due to the variety of every material type, the emission data are collected for the most common type of material used. For example, Concrete of grade 40 Mpa is used as a base to collect the necessary data like emission factor, material density, conversion factor, etc.
2. Wood or timber used for the construction of civil structures like brick are assumed to be Angelim Vermelho and Azobe with 12% moisture content for the sheet piles, bridge decks, sawn piles, walkway deck, sheet pile horizontal railings, etc.; Karri with 12% moisture content is mainly used for the noise barriers. Based on the information from (Database, 2022) and (hout co2 calculator, 2022), these are the standard most used wood for the construction purposes civil structures in waterworks.
3. The dimensions of the overall civil object are accurate. However, the dimensions of some of the elements are assumed as the database is not focused on minor details like thickness or diameter.
4. Objects like noise barriers are assumed to be of certain heights, and the estimation is calculated on the type of material.

4.6. Transportation & Equipment emission

Calculation For material Replacement																
				Dimensions							activity into GHG emissions					
	Components	No of Components	Material used	length (m)	Breadth (m)	thickness (m)	Specifications	Volume	Density kg/m3	Mass	Unit Emission tCO2e/t	Conversion factor	Emission	Frequency	Overall emission over remaining lifetime	Source / Reference
Fixed - Girder Bridge - menisweg	Beam	3	Wood	10.3	2.34	0.25	Piquia - 12% moisture content	18.0765	800	14461.2	0.263	0.01428385	0.054325704			Ice v3.1
	Ramp	1	Wood	2	2.34	0.25	Piquia - 12% moisture content ; 1 in 12 slope	0.585	800	468	0.263	0.01428385	0.001758113	20.6	0.137132845	Ice v3.1
	Handrail	2	Wood	10.3	0.05	0.025	Piquia - 12% moisture content	0.02575	800	20.6	0.263	0.01428385	7.7387E-05	20.6	0.006036189	Ice v3.1
	Wear layer	1	Asphalt	10.3	2.34	0.01	Distributor road - General asphalt	0.0234	2300	53.82	0.053	1	0.00285246	23.69	0.22249188	https://www.him.nl/en/wearing-course-versus-asphalt-costs-and-benefits/#:~:text=Asphalt%20has%20a%20layer%20thickness,is%20only%207%2D10%20mm.
	Abutment	2	Concrete	2	2.34	2	Grade 40 - 50 Mpa	18.72	2400	44928	0.159	2.4	17.1445248			Ice v3.1
	Column	1	Wood	3	0.3	0.3	Piquia - 12% moisture content	0.27	800	216	0.263	0.01428385	0.000811437			Ice v3.1
															0.365660914	Ice v3.1

Figure 4.2: Material emission from the replacement of the object

	Activities associated														
	Generic activities														
	Transportation	Type of Vehicle	Vehicle Name	Travel Distanc	Travel type	Type of Maintenance	Frequency	Per Years	Year of demolition	Fuel Consumption	Emission Factor	Unit	Conversion factor	Overall emission	Source / Reference
		Van	Ford transit connect	20	1 way	routine	1		2021		5.8E-04	$tCO_2e/t.km$		1.2E-02	
		Hgv	Goods vehicle	20	1 way	routine	1		2021		1.0E-04	$tCO_2e/t.km$		2.1E-03	
		Car	Passenger type	20	1 way	routine	1		2021		0.17067	$kgCO_2e/km$	0.001	3.4E+00	
	Cleaning/washing	Equipment	Type	Specification	Power/Fuel	Full tank capacity (l)	Usage of 40 litres (hrs)	usage of 1 litre(hrs)			Emission Factor	Conversion factor			
		Generator (2011 ArcGen Powermaker 6DV (Z482) 6kVA Diesel Generator)	Portable	0-10kva; 110v	Diesel	40	12.5	3.2				2.54603		8.147296	https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020

Figure 4.3: Transportation & Equipment emission

5
UML Design

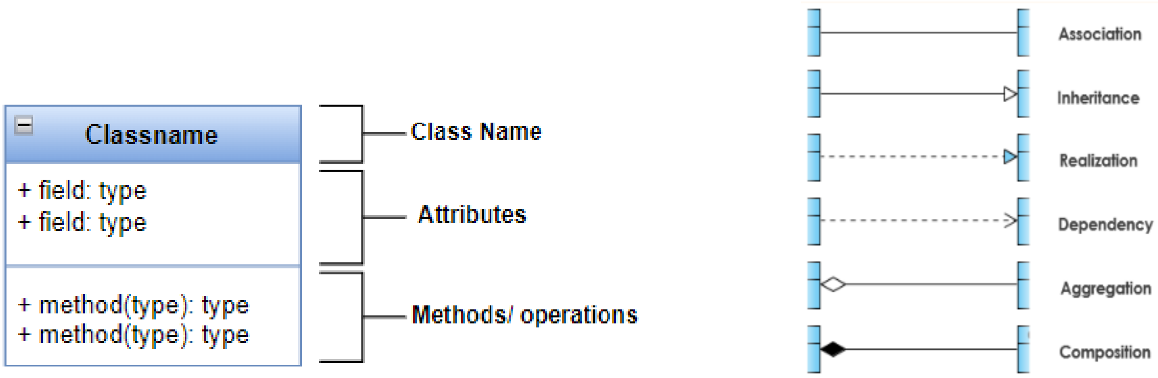
5.1. Information model requirements

Based on the objective of the information model, the UML diagram requires providing a schematic or a map of how the model works, how the elements in the model are connected, how the information flows, etc. This requirement is necessary to validate the model built and confirm that it serves the objective. Below are the listed requirements of the information model that is developed.

1. To explain the information model to the user and how the information model works.
2. Identify all the major and minor assets/ objects in the Municipality being investigated or analyzed.
3. To provide a clear breakdown structure for the Municipality from the level of the whole Municipality to the level of the minor maintenance activities.
4. To provide a definite explanation of how each of the class, sub-class, attributes are related in every breakdown structure
5. To provide a clear distinction between the classes and sub-classes.
6. To provide explicit content on the attributes of every object/asset and proper specifications of each attribute in the Municipality.
7. To provide a distinction between the major and minor maintenance activities of all the assets.
8. To elaborate on what maintenance activities are carried out for a particular type of asset.
9. To include proper emission details like the emission factor, conversion factor, fuel consumption, type of material, source, etc., for the overall emission calculation of the maintenance activities.
10. To provide an example of the estimation of CO_2e emission from the maintenance activities of a particular asset.
11. Though this model is focused on CO_2e emission, provision to consider other emissions, as well as CO_2e emission, have to be provided in the model.
12. To include the emission-related data sources in the information model developed.
13. To provide the option for the users to add new assets/objects in the model for future purposes.
14. To allows adding objects/assets apart from the civil structures.
15. To provide the users an option to change the emission factors due to the updated data.
16. To provide an option for the users to add custom emission-related data to the model for new scope of emissions.

5.2. UML Model

The purpose of using the UML model for this research is to provide a schematic map for the information model and to use the model for future purposes to be built into an application or to be made as a feature in the application. UML is a commonly used modeling language to define, illustrate, build and document the elements of a software system or any system in general (Rumbaugh et al., 2023). Most



(a) UML class entity **(b)** UML Class Relationship types

Figure 5.1: Basics of UML Class Diagram

systems have complex and complicated structures, relationships, and operations. For this reason, UML is utilized to aid users in understanding a system's static structure and dynamic behaviour. The diagrams created with UML can be translated into various programming languages like Java, python, etc. It is common to use UML for databases (Rumbaugh et al., 2023). Hence, for the research purpose, it is deemed necessary. The end goal of using UML for this research is to provide a simple visualization of all the systems, sub-systems, elements, and components in the overall Municipality (System of Systems) and their possible relationships.

There are multiple types of UML diagrams. For this research, UML class diagrams are used as they can provide a static graphical representation of the system using the model elements like class, sub-classes and portray the relationships between them. UML class diagrams have some advantages and disadvantages.

Advantages: The advantages are that it gives a definite visual representation of the crucial entities of the system and provides the data like attributes and operations of each class and sub-class. Finally, the relationship between the entities and the dependencies is distinguished.

Disadvantages: The disadvantages of the UML class diagram are that it does not provide a procedure to resolve a problem. The dynamic nature of systems cannot be implemented in UML class diagrams but only using other types of UML diagrams.

The approach of using this UML class diagram for the research is to provide a guideline for the users on the operations and functions of the final information model or the Dashboard. This comprehensive research-oriented and detailed approach can be more beneficial for the users in understanding the whole model.

5.2.1. Class Diagram

A class is the basic entity of the UML class diagram, which provides the name of the actual entity of the system, its attributes, and the operations of that entity. Apart from the relationships between various classes, dependencies are provided using these classes.

- Class Name: It denotes the generic term of the elements that belong to that class.
- Attributes: It denotes the character related to the respective class.
- Methods or Operations: It denotes how different classes interact with each other.

5.2.2. Terms and Definitions of UML Class Diagrams

Relationships

The relations are the key factors in these Class diagrams. There are different types of relationships among the classes like association, inheritance, dependency, aggregation, composition, etc.,

- **Inheritance:** This type of relationship refers to the subclass inheriting certain attributes from the Super class regardless of having their attributes.
- **Dependence:** This type of relationship shows that the classes are directly related to each other

- **Composition:** This type of relationship shows a class has strongly associated with another class; without it, it cannot exist. It is a stronger association type of relationship.
- **Aggregation:** This type of relationship denotes that one of the classes is a part of the other class, and they have similar functions.

5.2.3. UML Class Diagram - Fixed Bridge

The original class diagram can be found at Appendix (A.5)

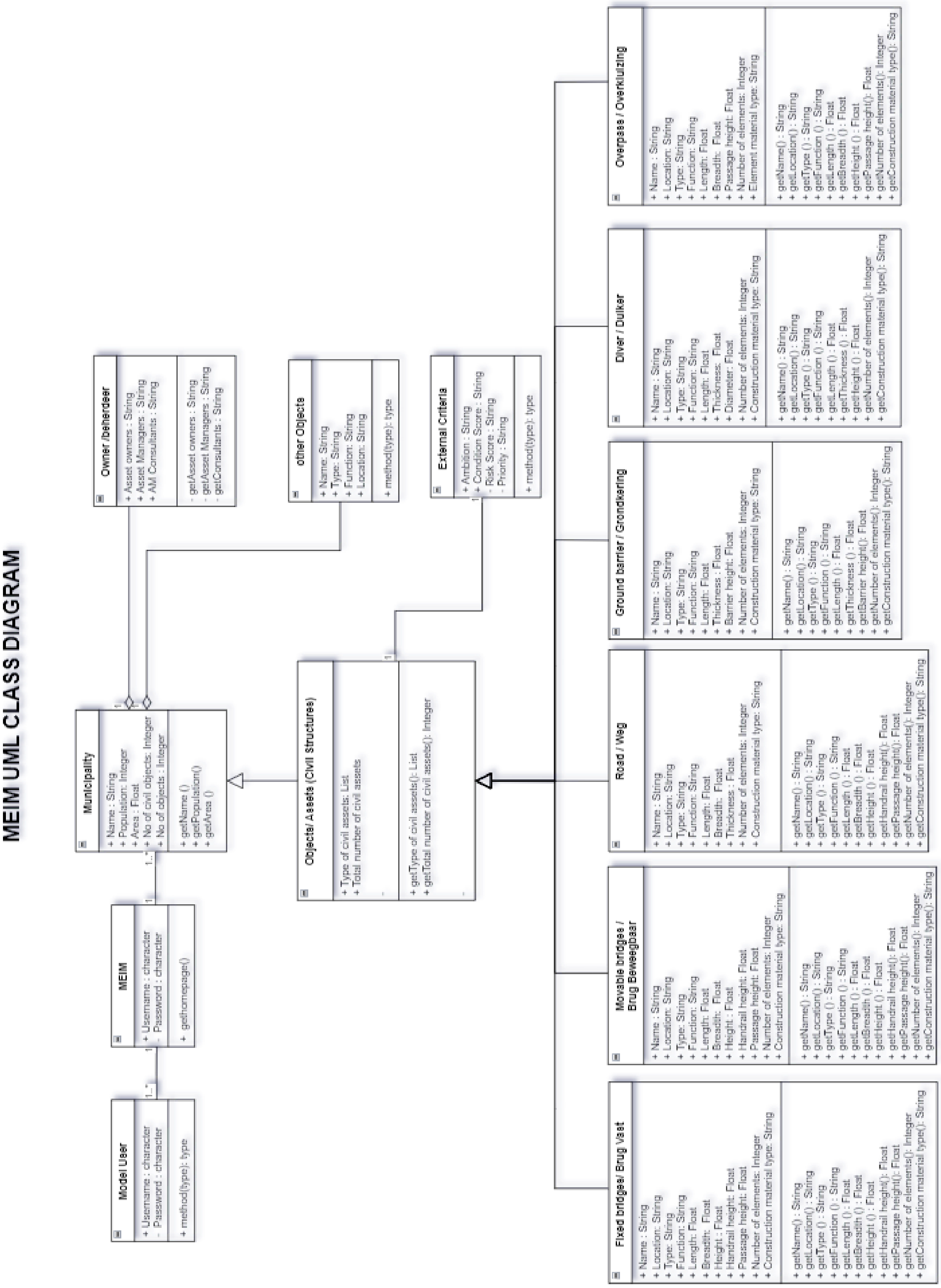


Figure 5.2: UML class diagram of Municipality

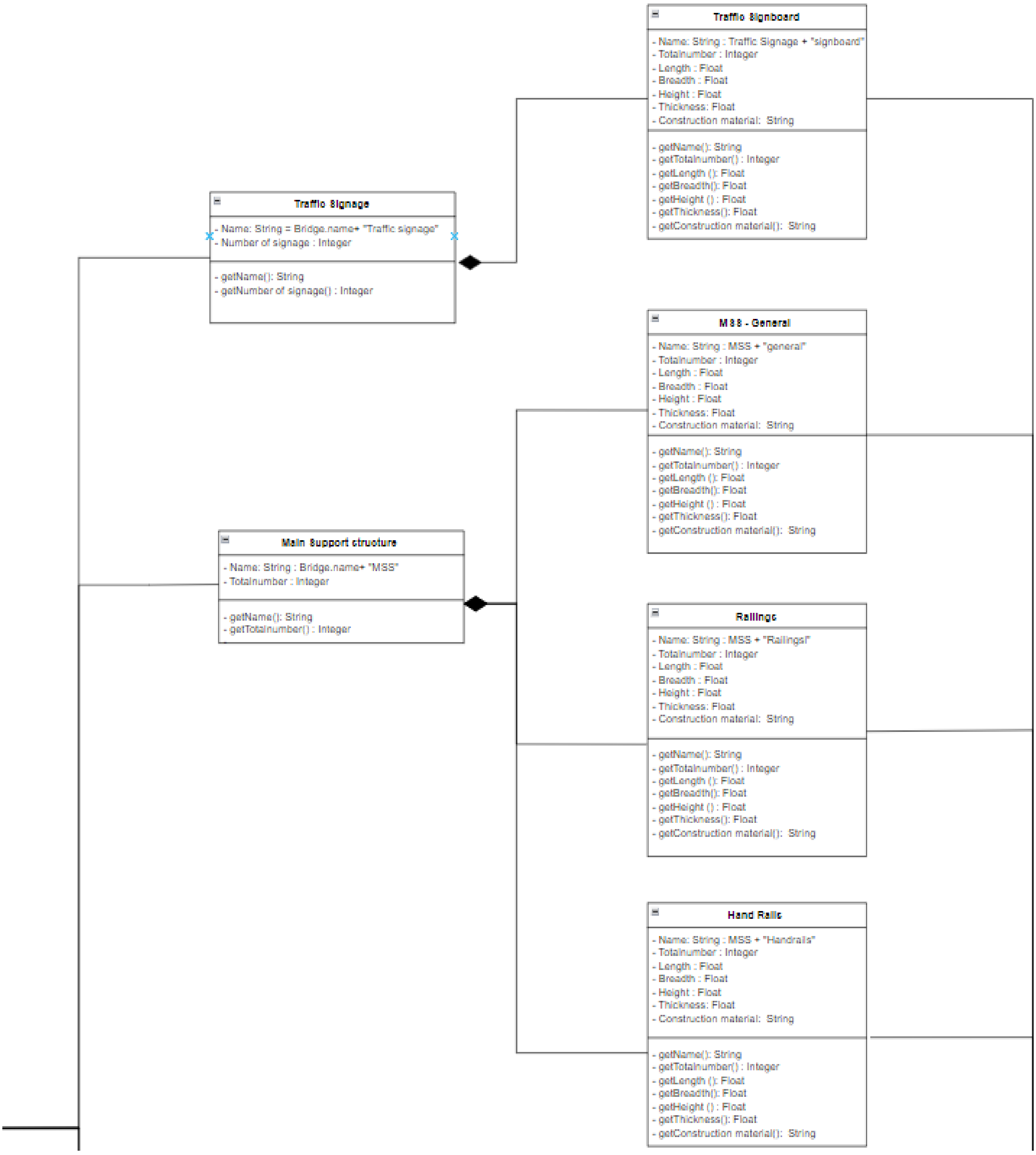


Figure 5.3: UML class diagram - Fixed bridge (part 1)

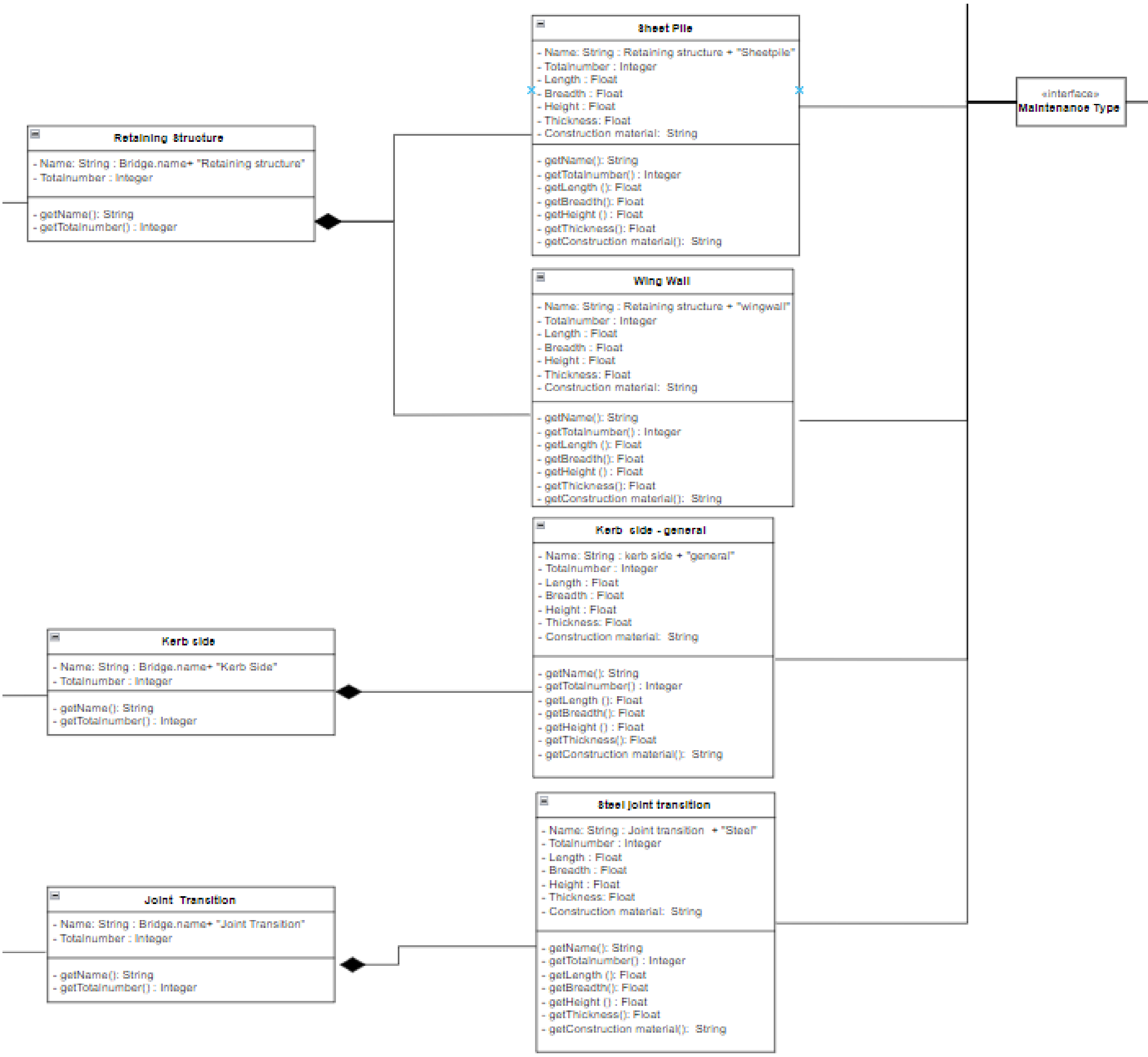


Figure 5.4: UML class diagram - Fixed bridge (part 2)

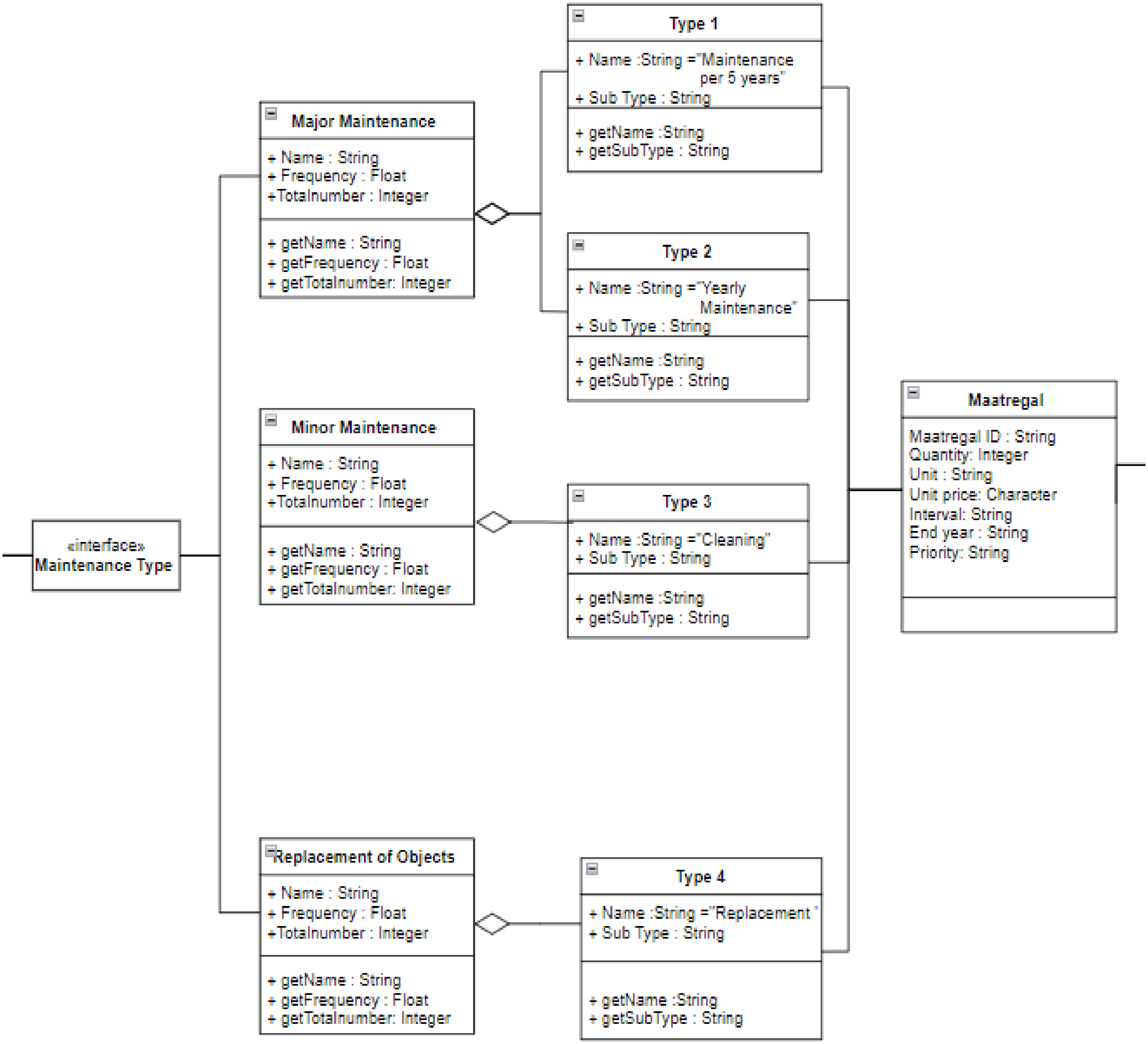


Figure 5.5: UML class diagram - Fixed bridge (part 3)

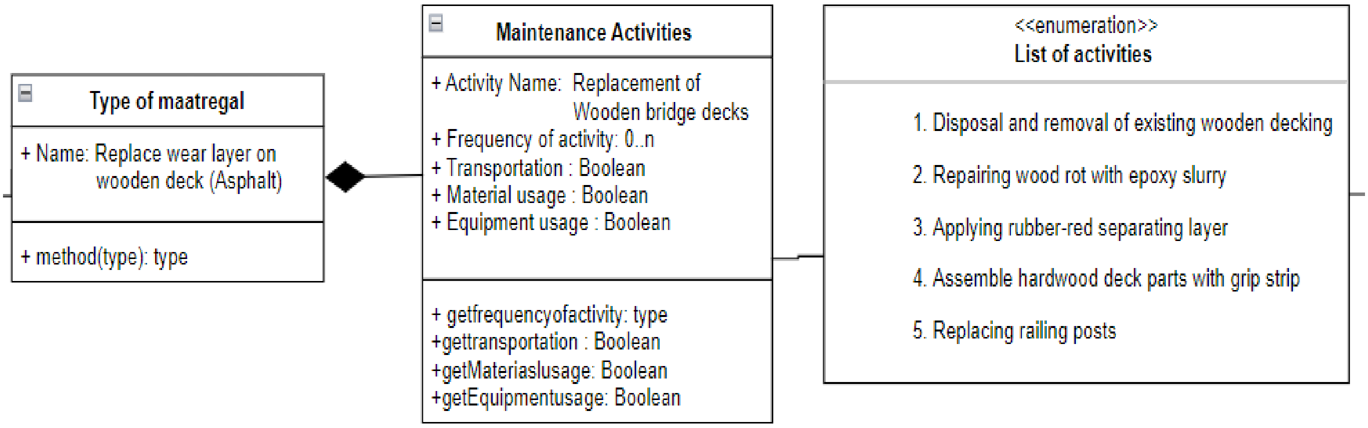


Figure 5.6: UML class diagram - Fixed bridge (part 4)

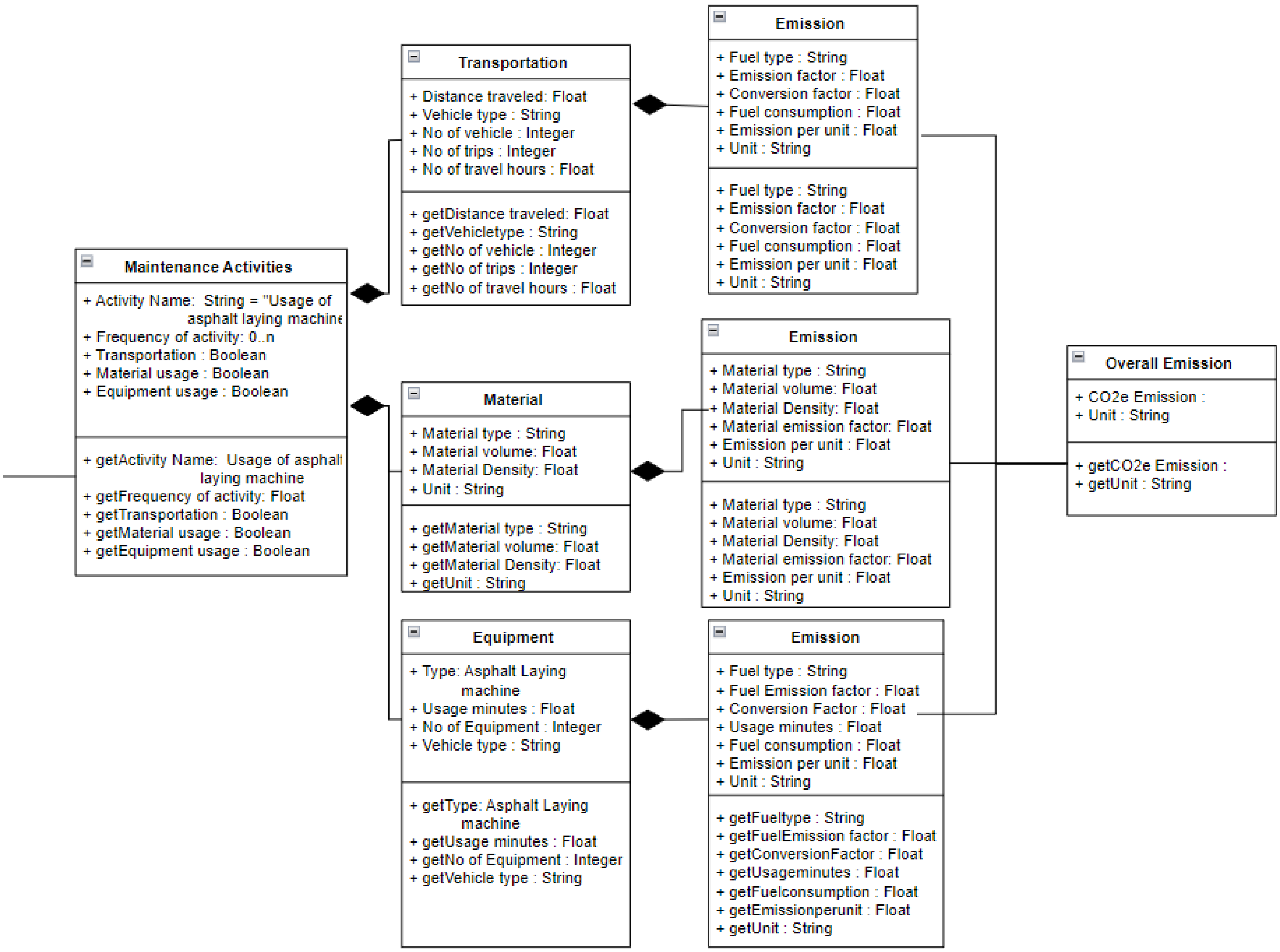


Figure 5.7: UML class diagram - Fixed bridge (part 5)

6
Information Model

This chapter describes the functioning of the information model. The first part, section 6.1, introduces the information model and explains its basic structure. The second part, 6.2, explains the scope of this information model. Section 6.3 deals with the data collection process and sorting of the data. Section 6.4 deals with the information model's usage and how the information model's output can be utilized. The last part, 6.5, gives an overall summary of the information model.

6.1. Structure of the Information Model

6.1.1. Introduction

This information model is developed to initiate the CO_2e emission database from the maintenance activities of the civil infrastructures. These maintenance activities are sometimes overlooked and must be definite in the estimation process. Due to this reason, a separate information model focussing on the CO_2e emission only from the maintenance activities of the infrastructures belonging to a municipality is necessary. Pertaining to that, this information model was developed to create an informative database of CO_2e emission of the maintenance measures (maatregel) and how to quantify the emissions for all types of assets with various maintenance measures.

This information model is a combination of static and dynamic models. The reason is that the input sheets consist of certain cells that have to be given by the user, and these cells are enabled to retrieve information according to the user's input. This way, the model is interactive for the user.

6.1.2. Overview

The 6.1 represent the overview of the excel based information model and the key functioning of the model.

File Type

This information model is developed as an excel file with the inbuilt features like macros utilized inside the model. The file extension of this model is .xlsm, which is the extension for excel files with macros enabled.

6.1.3. Structure of the Model

The three major blocks of the information model are the model's input, database, and output. Each of these blocks consists of multiple sheets - about 18 sheets, some of which can be edited, while the remaining are only for info. The excel sheets containing vital data about the assets, emission database, etc., are protected with a password shared within the team Obsurv and other users. This protection avoids adding unwanted data to the model and keeps the database and other vital sheets unaltered and protected. The input block consists of eight sheets: Homepage, Read-me, Municipality, Index,

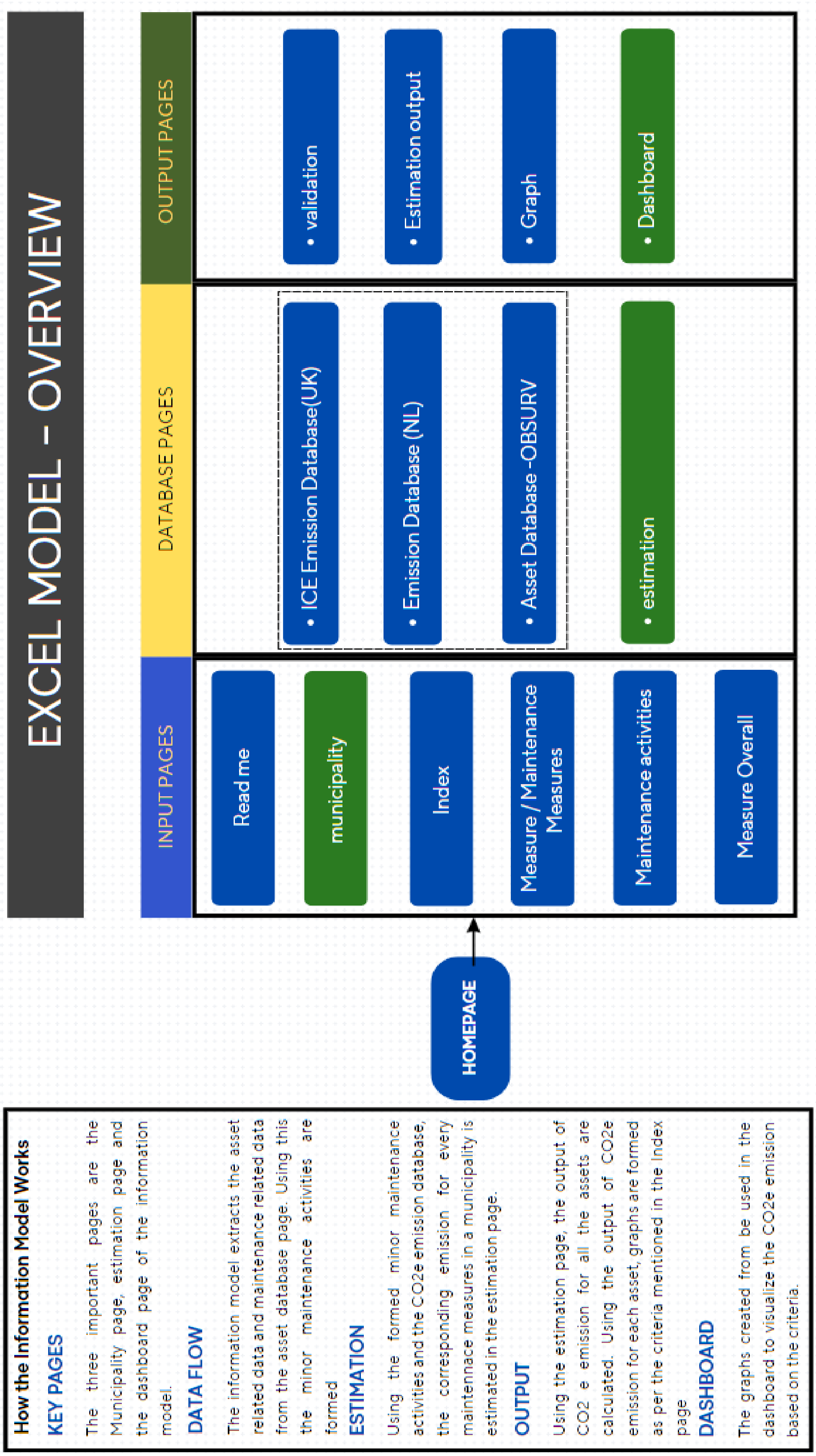


Figure 6.1: Information model - Overview

maatregel, maatregel overall, activities, and overall activities. At the same time, the database block consists of inventory, Calculation, Emission database - ICE, Emission database- Dutch, and Asset Details. Finally, the output block consists of the graph and dashboard sheets. This dashboard sheet can be exported into a report/pdf file.

Input Components

Homepage: This is the first sheet of the information model. This sheet provides brief information about the model. Apart from the information, the navigation buttons to the various sheets that can be used to retrieve necessary information are provided.

Read-me : This sheet contains information on how to use the information model and a flowchart of how the model works. Apart from this, what is in the scope of the model and out of the scope of the model is also provided.

Municipality : It is the important sheet where crucial details are provided for the user, and the user will have options to select. The user can select a single type of asset or use the municipality's overall assets. Also, the user can select the various categories available to see the variations in CO_2e emissions according to different categories. This sheet will also have navigation buttons to various sheets that can be edited.

Index: This sheet is used for categorizing the assets as per the requirements. The assets are categorized based on various criteria like the size of the assets, location of assets, heavy machinery usage of the assets, assets based on the construction materials used, etc. This sheet is half protected to preserve the existing categories, and the remaining part can be used to create different categories based on other criteria.

Maatregel: This sheet provides information about a particular asset the user wants to analyze. Once the user inputs the Kuntswerk Code (KW), their corresponding maatregel is retrieved. From this page, the user can go to the activities sheet, which ensembles the minor maintenance activities of every maatregel performed for that particular asset.

Activities : As mentioned, this sheet is focused on a single asset and its minor maintenance activities. From this sheet, the estimation of CO_2e emission from each of the minor activities.

Maatregel Overall : This sheet contains the maatregel and the necessary specifications, like the frequency of maatregel. Start year and end year of the maatregel that are required to calculate emissions for a lifetime. In this sheet, some important data on the CO_2e emission from every maatregel is retrieved from the calculation sheet. Overall, the CO_2e emission from the asset is the sum of CO_2e emission from every maatregel performed. With this data, along with the frequency, start year, and end year of maatregel, the user gets the data on the overall CO_2e emission from a single asset during its lifetime. This emission corresponds only to the maintenance activities.

Overall Activities : This sheet retrieves the minor activities of every maatregel corresponding to a single asset. Minor maintenance activities of every asset are obtained, which is easier to quantify the emissions for each maatregel.

Database Components

Inventory : This sheet contains information relevant to the machinery and equipment utilized. This sheet contains useful data like the fuel consumption of various machinery, equipment, etc. The data from this sheet is useful for the emission estimation of different maatregel.

Estimation : This sheet is where the estimation of every minor maintenance activity connected to a maatregel is done. This sheet provides important data required for the overall output of the information model.

Emission database - ICE : This sheet contains data obtained from the ICE database. It provides the CO_2e emissions for various construction activities, machinery usage, fuel consumption, disposal activities, etc. Further, it also provides information about the density of various construction materials used. The database provided by ICE is utilized in the National Highways of the UK Department for CO_2e emission (Lokesh et al., 2022).

Emission : This sheet contains retrieved information on the emission data and their corresponding assets. This sheet does not have any usage and is only for info.

Asset Details : This sheet contains the database of the assets and their respective details collected from the OBSURV platform of Sweco. Most of the sheets in the input utilize the data from this sheet.

Emission Database : This sheet also contains a database of the CO_2e emission from fuels, electricity, and other power sources. This database is more Dutch-oriented and recognized by many Dutch organizations and Government agencies.

Output Components

Dashboard : The output from the CO_2e emissions of each maatregel concerning every asset is shown collectively in various categories using different graphs. This graph gives a visual representation of which construction material causes more or less emission and which assets located in a particular location give more or less emission.

Graph : All the data related to the dashboard graphs are given as input in this sheet.

6.2. Scope of Information Model

Assets : The scope of this information model is limited to the maintenance measures (maatregel) performed for civil infrastructures. This database of assets can be extended to numerous municipalities. However, the information model now consists of data only related to a particular municipality of Schagen.

Emission :

- The emission from the materials used for the maintenance activities like the replacement of an object or a component are taken into account. The CO_2e from the material is embodied carbon. The CO_2e emission from the transportation of the materials is taken into account; however, it is from the supplier to the construction site. The prior emission from these materials on how the supplier acquired these materials or other material processing is out of scope.
- The emission from the transportation of the labour to the construction site, emission from the transportation of the machinery and equipment to the site. As mentioned earlier, material transportation will also be included in the scope of the information model.
- Though the disposal activities are used in the breakdown structures, and the minor maintenance activities, the emission corresponding to the disposal activities is out of scope.
- The types of construction materials used in the assets are considered for the emissions. However, the materials used to conserve various components of an asset are not considered. As these materials are particular, it is not easy to estimate the emission for such materials.
- The vehicles used, like the van for manual transportation, truck/trailers for material transportation, and off-road machinery used for construction activities, are taken into account in the information model.
- The fuel types used for transportation and machinery usage considers most of the fuel available in the Netherlands.

Machinery :

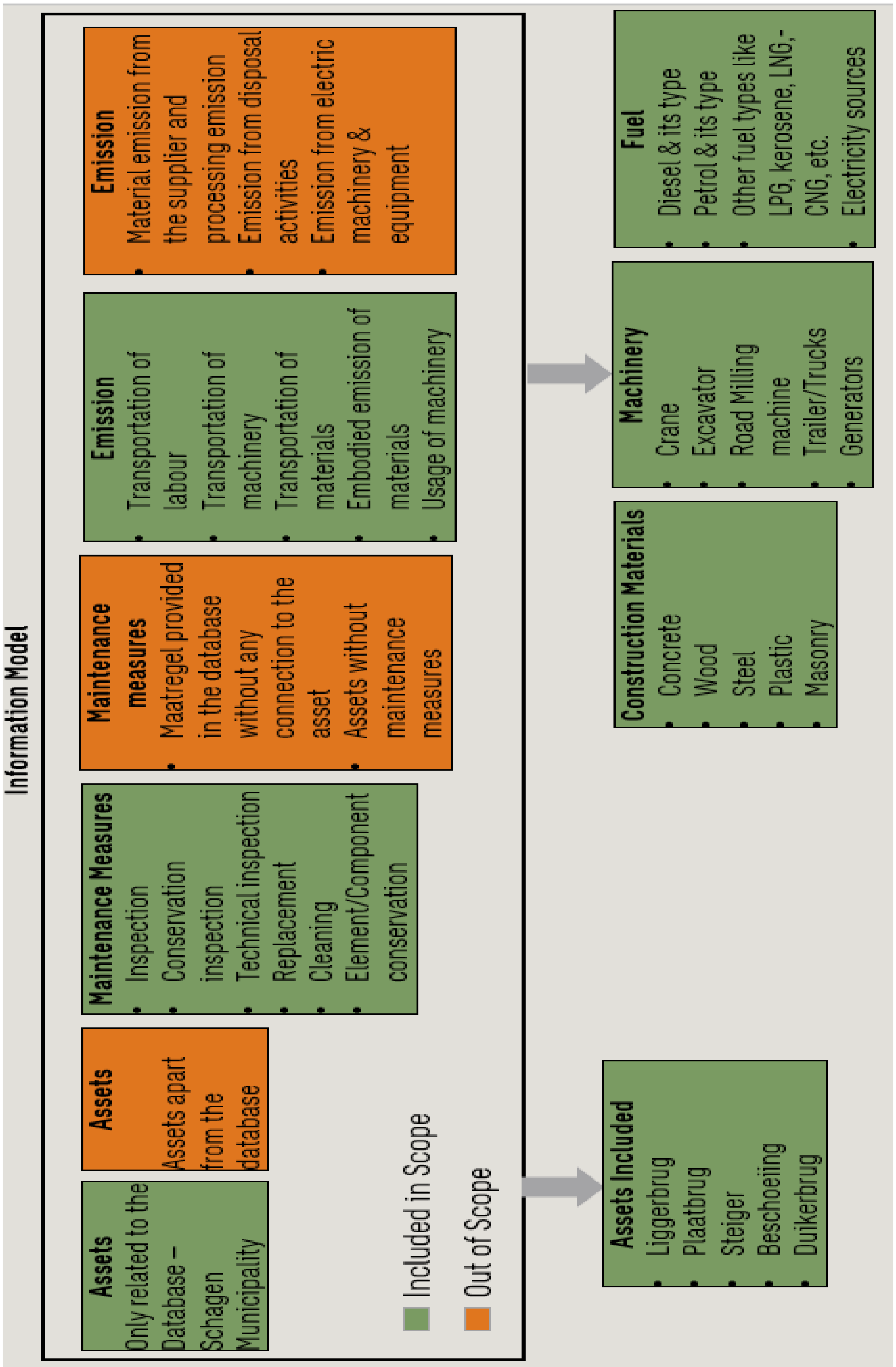


Figure 6.2: Information model - Scope

- The machinery used for maintenance activities is included in this information model. These machineries are one of the major emission sources as they are used regularly to maintain these civil structures. These machinery include excavators, cranes, generators used in the construction site, etc. Most of these machinery currently use diesel as their fuel for operation. At this point, only selective machinery is considered for this information model however it can be expanded to other machinery. All the types of machinery and their important information related to fuel consumption, type of machine, engine power consumption, etc, are provided in the inventory sheet of the model.
- Any addition to the inventory list of machinery can be done. The usage of such machinery must also be updated in the maatregel sheet. This way, the user can link the data from the inventory to the maatregel, which can be used for the overall estimation of emissions for the maatregel related to all the assets.
- In recent times, there has been a change in utilizing electric-powered machinery for construction activities. These latest sources can be added as a power source in the future for this information model.

6.3. Data Collection & Sorting

The data necessary to be collected for the required output is determined from the first step of the research. From the breakdown structures, it was clear about the assets and their decomposition. From this, the UML class diagrams were made to sketch a framework for the data type needed to get the desired outcome. Most of the data collected was based on the UML class diagram. On the other hand, some data was deemed necessary in the UML class diagrams but needed to be obtained for the emission estimation. These data are not crucial but can improve the accuracy of the overall estimation of CO_2e. Examples of such data are the dimensions of minor components, elements of a civil structure, and exact activities performed for every maatregel. The level of detail of the acquired data is at the initial level. The data relating to the assets and their essential details like dimensions, lifetime, frequency of maintenance activities, and other relevant details are obtained from the OBSURV online platform. The data relating to the minor maintenance activities are collected from various sources like the websites of the various contractors, research papers, and guidelines of Rijkswaterstaat, EU, etc. For the data related to the emission from the various fuel sources, construction activities are obtained from the two vital databases, which are the ICE database (Institute of Civil Engineers) for the CO_2e emission and the greener company & CO_2e emissiefactoren database which is recognized and promoted by milieu central, Stichting Klimaatvriendelijk Aanbesteden & ondernemen(SKAO), Rijksoverheid.

6.3.1. Data categories

The user of this information model can select to view the emission of any single asset within the municipality or to overview the emission of all the assets in the municipality. This information model has various data categories. They are listed below.

The user needs to provide input from the asset database or select the type of asset they want to investigate. Other inputs are based on their requirement to select the type of emission they want to view and which asset they want to view the maintenance measures, their corresponding minor activities, and emissions from these minor activities.

6.3.2. Data edition & updation

The obtained data related to the assets can be categorized as per the user's needs in the information model's index sheet. Initially, the default categories are based on the criteria like construction materials, location of the assets, size of the assets, and machinery usage of the assets. This type of sorting can be helpful for output generation and visualizing the emission according to the required criteria.

6.4. Usage of the Information Model

The Flowchart mentioned below explains how to use the information model to obtain the relevant data and output from it. Using this information model, we can arrive at the dashboard, the final sheet that

Data Categories			
Assets	**Maintenance measures**	**Estimation**	**Database**
Maintenance work (Kuntswerk Code)	Maintenance measure ID (Maatregel ID)	Type of vehicle	Material
Maintenance Name (Kuntswerk Name)	Frequency (Hoevelheid)	Travel distance	Material Density
Asset owner (Eigenaar)	Start year of the maintenance measure	Mileage	Units
Asset Manager (Beheerder)	Interval	Usage in hours	Material type
Type of civil structure (beheerobjectsoort)	End year for the maintenance measure	type of fuel	Carbon Factor
Maintenance work type (Kunstwerktype)	Priority (Prioriteit)	Emission factor	Carbon factor units
Construction material (Boumaterial)		Conversion factor	Source of fuel
Dimensions - Length, breadth, height		Total Number of Vehicle/Machinery	Unit
Railing height (leuninghoogte)		Total CO_2e emission	Well to Tank
Passage height (Doorvarhoogte)			Tank To Wheel
Construction year (Aanlegjaar)			Well To Wheel
Asset function (Gebruiksfunctie)			
Ambition (Ambitieniv)			
Street (Straat)			
Location (Woonplaats)			
Demolition year			
Residual life			

Table 6.1: Types of Data

displays visualizations of the emissions of different assets based on criteria like location, size, etc. This sheet is read-only. The user has the option to add a new criterion to the available data and get the visualization of emission data according to that. This operation can be done in the graph sheet where a separate location is provided for the new criteria addition.

6.5. Overall Summary of the Information Model

The information model is focused on a particular set of assets. The necessary sheets are the homepage sheet (B.1)which can be used to navigate the various sheets. The Municipality sheet is the critical input page where the user has to provide input or select the type of data they want to retrieve from the information model.

Step 1: The first step to using the information model is to enable the macros in the excel file. For the recent versions of MS-Excel, this option comes on the first display screen with a warning in yellow. The older versions have the option to enable editing. If the older versions of MS-Excel are not macros enabled, it can be manually enabled from the Menu > file > options > Macro settings.

Step 2: The second step is for the user to decide on the buttons on the homepage to navigate to the desired sheet. The selected cells or the coloured cell in the Municipality sheet (B.2) are the desired cells to provide the input information from the user. The remaining cells are protected and cannot be edited

Step 3: The user has two options to select. 1. To look at the overview of maintenance measures, minor maintenance activities, and the emission related to those minor maintenance activities. 2. To view the overall assets and the CO_2e emissions from the maintenance measures of all the assets. In this option, the user can decide between the various categories to select the type of emissions needed.

Step 4: Based on selecting a single asset or the overall assets of the municipality, the desired maintenance measures (maatregel) can be viewed using the respective buttons.

Step 5: Based on the selection in steps three & four, this step is allocated to view the minor maintenance activities involved in every maatregel. In this step, the emission corresponding to the maatregel is also obtained and can be seen. Maatregel sheet(B.4), Overall Maatregel sheet(B.5), Overall Activities sheet(B.6), Estimation sheet (B.9)

Step 6: After the overview of the minor maintenance activity and their emissions, the navigation button can take the user directly to the dashboard sheet (B.11) output. This sheet provides the graphs of various emissions according to the criteria set as default in the index sheet.

Those were the main steps involved in the information model. Apart from that, other sheets can be used as a read-only page to view the data collected and how the emission estimation for each activity is made.

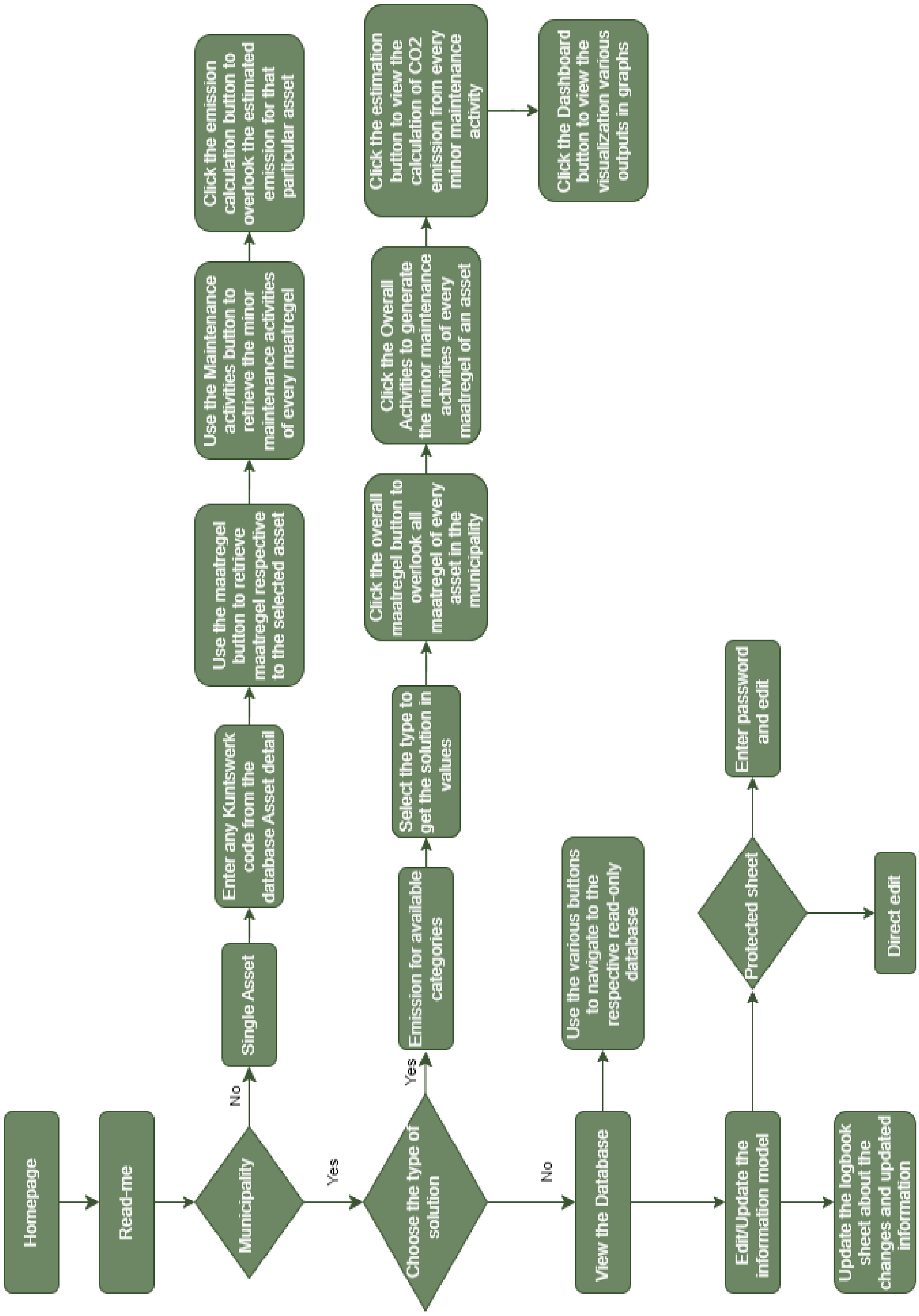


Figure 6.3: Flowchart on how to use the Information model

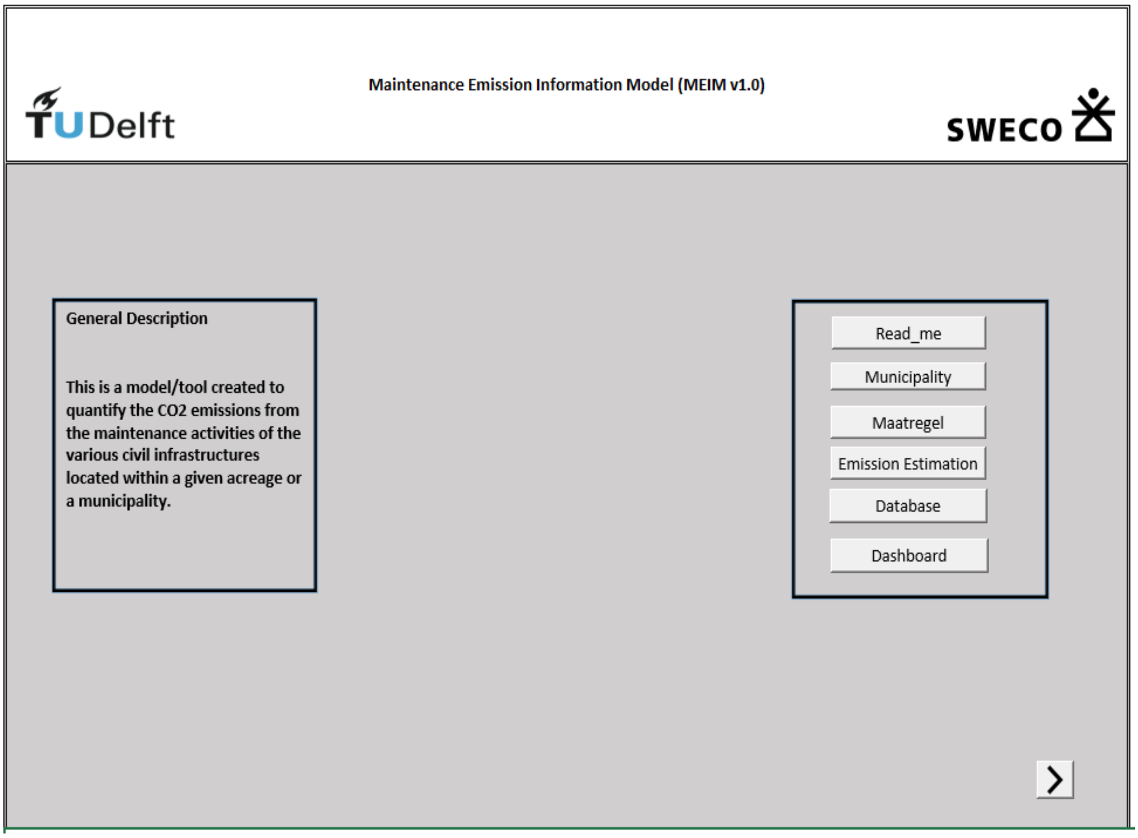


Figure 6.4: Homepage

7

Verification & Validation

The information model was explained in detail in the previous chapter. This chapter focuses on verifying and validating the developed information model. This chapter consists of two sections. The first section, 7.1, focuses on verifying the information, and the second section, 7.2, focuses on validating the model.

7.1. Verification

The verification process in system engineering is done to check if the system has been built as per the needs or requirements (Mclucas et al., 2012). The information model is verified by verifying the individual components of this research. The information model was the output of the research's first two components, the breakdown structure, and the UML class diagrams. The three individual components are as follows

1. Breakdown structure
2. Unified Modelling Language (UML)
3. Information model

7.1.1. Breakdown Structure

Requirements : The breakdown structure is required to decompose the Municipality into its assets. Then the assets are decomposed into their respective components. Each of these assets is connected to their major maintenance works and then decomposes the major maintenance works. Finally, each of these major maintenance works is breakdown into minor maintenance activities.

Verification : The breakdown structures used in this research are of three types. The first system breakdown structure involves the Municipality, in concern, a system of systems. The municipality organization consists of multiple systems, among which the required system of civil infrastructures/asset management system is to be decomposed. This requirement is verified by decomposing the assets into different types based on criteria like functionality, construction material, type of asset, etc. All these assets/civil infrastructures have their major maintenance works. The work breakdown structure realizes the relationship between the assets and their major maintenance works, then decomposes the major maintenance works that verify the requirement. The last breakdown structure, called the activity breakdown structure, consists of decomposing every major maintenance work into minor maintenance activity. Through this, the overall requirement of the breakdown structure of decomposing the Municipality assets into their minor maintenance is achieved and verified.

7.1.2. UML class diagram

Requirements : The UML diagram requires establishing the connection between the breakdown structure and the information model. UML class diagrams in this research are required to connect the minor maintenance activities (outcome of the breakdown structures) with the emission data relevant to each minor maintenance activity. Apart from this, the class diagram is required to provide the connection or relationship between the components of an asset, asset types with the overall municipality system, and the overall information model. The last requirement is for the user to recognize what type of data is needed for estimating CO_2e emission from the maintenance activities of the assets.

Verification : Every requirement mentioned for the UML class diagram can be verified using the class diagrams provided in Appendix b. The class diagrams satisfy the requirement of connecting the breakdown structure and the information model by providing a clear structure or schematic from the user's point of view of operating the information model until the CO_2e emission of a minor maintenance activity. Through the diagram, the type of relationship between the various classes (components) can be verified by the type of arrows/lines used. Each component in the breakdown structure is translated into classes and sub-classes in the UML class diagram. Every class and sub-classes is provided with their respective attributes and functions. These attributes and functions are crucial for the user to recognize the type of data needed for the estimation of CO_2e emission from the maintenance activities of an asset and multiple assets in a given acreage or Municipality.

7.1.3. Information model

Requirements : The overall requirement of the information model is to create a model/tool to quantify the CO_2e emissions from maintenance activities for a large number of assets. Other requirements are focused on the output of the emissions obtained. To create a dashboard of the CO_2e emissions data using various graphs to compare the data according to criteria like size, machinery usage, location of the assets in the different parts of the Municipality, construction materials, etc. The last requirement was to utilize this information model for the Obsurv platform in the future for the respective clients from different municipalities.

Verification : The requirement to quantify the emissions is done using the information model in the excel file under the estimation sheet. The requirement to use the output emission data to compare with different criteria and to visualize in the form of graphs is verified in the dashboard sheet of the file. The final output of the emission data can also be retrieved as a report or as a separate .csv file, which can easily be used in any software environment.

7.1.4. Verification results

The verification of the information model has mostly favourable outcomes from each of the steps. The breakdown structures, the UML class diagram and the information model individually and on the whole satisfies all the requirements of the research.

7.2. Validation

In system engineering, validation is defined as a process that is performed to check the developed system, product whether it has been created as per the intended objectives (Mclucas et al., 2012). This validation process is to be performed at every stage as well as the completion of the product/design, i.e., the validation can be performed for the individual systems or for the entire artefact created (Honour, 2013).

7.2.1. Validation method

There are numerous methods of performing the validation process. Initially, the developed information model was planned to be validated using interviews with experts. These experts belong to the Municipality asset managers, maintenance contractors, sustainability experts in Sweco NL. Using this type of validation, the developed information model can be shown to the mentioned stakeholders and required feedback can be collected from different perspectives from different stakeholders. Necessary preparations were done for this purpose and the corresponding stakeholders were reached out for the expert validation. However, due to unforeseen circumstances and time restrictions, this method of validation turned out to be infeasible.

Hence, it was decided to validate the information model by another method. Another efficient method to validate such information model was to testing it with different Municipalities. For this method of Validation, Initially the Zuidplas Municipality was selected and tested. Zuidplas is a municipality which

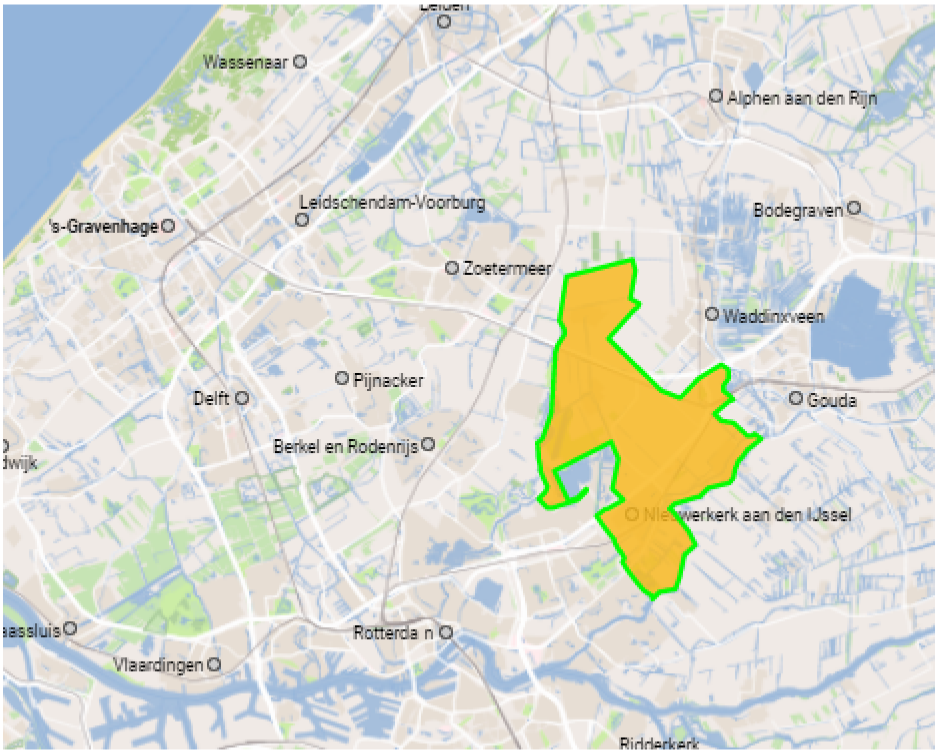


Figure 7.1: Zuidplas Municipality

consists of number of villages within it. It comes under the province of South Holland. It has an area of 58 km^2 and a population of 45000. The area of this municipality is comparatively lesser compare to Schagen but on the population level it is similar in rage.

The validation process of the information model will be based on three different parameters. These are 1) Level of Accuracy, 2) Applicability, and 3) Usability. This results of the validation for few number of assets can be found in the appendix (B.9).

7.2.2. Level of Accuracy

The data obtained from the obsurv platform has the most accuracy in the information model as they are directly obtained from the Municipality. The obtained data includes all the asset-related data and maintenance measures (maatregel data). Apart from that, the database used for the CO_2e emission from the different materials or energy sources is equally accurate as the former. The source of this emission database is highly validated and recognized around the world. The first database, ICE, is based on the UK construction industry, and the second database is more relevant to the Netherlands construction industry. The data with less accuracy is the minor maintenance activities concerning every maintenance measure and their respective emission. The reason is that these data are based on multiple literature sources rather than a single source. The data related to the transportation of vehicles and machinery usage also consists of some assumed values. Such assumptions bring down the level of accuracy in this data category. Regardless, the emission values obtained from this information model are compared with Dubocalc, the most used application for the emission and Millieukostenindicator(MKI) or Environmental Cost Indicator (8.1). Though some minor differences exist in the values obtained, the values are primarily in the nearby range.

7.2.3. Applicability

The developed information model is based on the asset database of Schagen Municipality. However, the information model can be applied to other municipalities since most asset types built are similar in numerous specifications and might have similar maintenance activities. The core of this information model is the database and the emission calculation sheet. Suppose the asset database and their respective maintenance measures of most types of assets are obtained. In that case, the emission estimation for all such activities can be done following the procedure mentioned. This way, the information model can be utilized for numerous municipalities.

7.2.4. Usability

Most users can utilize the information model after reading the basic instructions provided in the read-me sheet of the model. Though the intended users are the Obsurv team in Sweco, this information model can also be used by the contractors who are directly involved in the execution of the maintenance activities. The UK Department of Transportation has been collecting CO_2e emissions directly from users like contractors. Such input can improve the accuracy of the data collected and benefit the contractors and other stakeholders involved in the process. Similarly, this information model can be used by the Municipality and the maintenance contractors to update the database and retrieve the necessary information from the model. The model is also easier to update, edit or add new information to the database.

7.2.5. Validation results

The validation of the information model by testing it in a different municipality had both favourable and unfavourable results. The favourable part is that numerous maintenance measures (maatregel) of the Zuidplas municipality were recognised and were able to retrieve the CO_2e emission for all those measures. The critical note is that, all the assets having similar maintenance measures as the mentioned ones from information model were recognised. CO_2e emission for these maintenance measures can be retrieved however, there were also other maintenance measures apart from the ones used in the model. It is impractical to retrieve emission data for those new maintenance measures. The conclusion is that, this information model can be developed into a bigger version taking into account of all maintenance measures of every municipality. This way, the usability and applicability of the model can be extended to a maximum level.

Thus the information model has been verified and validated by using the methods mentioned above. The information model created has successfully achieved its overall objective per the research needs.

8 Discussion

This chapter deals with the final results obtained from the research and its discussion. The first part focuses on the interpretation of the results obtained from the information model; the second part focuses on the research contributions to the scientific side; the third part focuses on the practical contribution of the research, and the final part focuses on the limitations of the research.

8.1. Interpretation of the Results

The research objective is to create an information model/tool that focuses only on the maintenance activities of the civil infrastructures belonging to a given area or Municipality. The objective was achieved through a procedure that started from the breakdown structure, then proceeded to the UML class diagram, and ended in the information model, which is the final output of the research.

The results obtained using the developed information model showed differences with the default CO_2e emission application Dubocalc. The results obtained from the model are analyzed, and a set of selective assets are chosen to be compared with a similar asset from other widely used applications like Dubocalc.

A set of 3 bridges of length 11m - 13m from the Municipality of Schagen was taken as an example to be compared. These three bridges are compared against three similar bridges of 12m in length from the Dubocalc application. The graph (8.1) shows the differences in the CO_2e emission values of assets of similar types and dimensions.

It was observed that in the Dubocalc application, numerous assets where given very minimum CO2e emissions during the usage & the maintenance phase in their life cycle. For some assets it was even given nil emission for their maintenance activities. This shows that, the focus of the Dubocalc application is on the construction and other phases compared to the usage and maintenance phase. This explains that it takes the CO2e emission from the materials usage, material transportation into account whereas the transportation activities involved or the machinery usage phase are not taken into account. The emission values from the Dubocalc application can be found in the appendix (A.8) , (A.9), (A.10)

From the Dubocalc application, it was evident that based on the construction material used, the assets constructed using wood have more emission in the B phase of the entire life cycle, which is the usage & maintenance phase. The reason is that the frequency or the interval of the maintenance activities is more for the wooden infrastructures than other materials like concrete, steel, etc. The wooden infrastructures can be structurally efficient and have a longer service life only when they are well designed and subjected to regular maintenance with more frequency (Asdrubali et al., 2017). However, the information model proves that the CO_2e emission from the concrete bridge is more from the maintenance activities performed throughout their lifetime than similar steel and wooden bridges.

There are two reasons observed from the results,

1. Though the frequency of maintenance activities is higher than for concrete or steel structures, the number of maintenance measures or maatregel is less for wooden civil structures. Due to this reason,

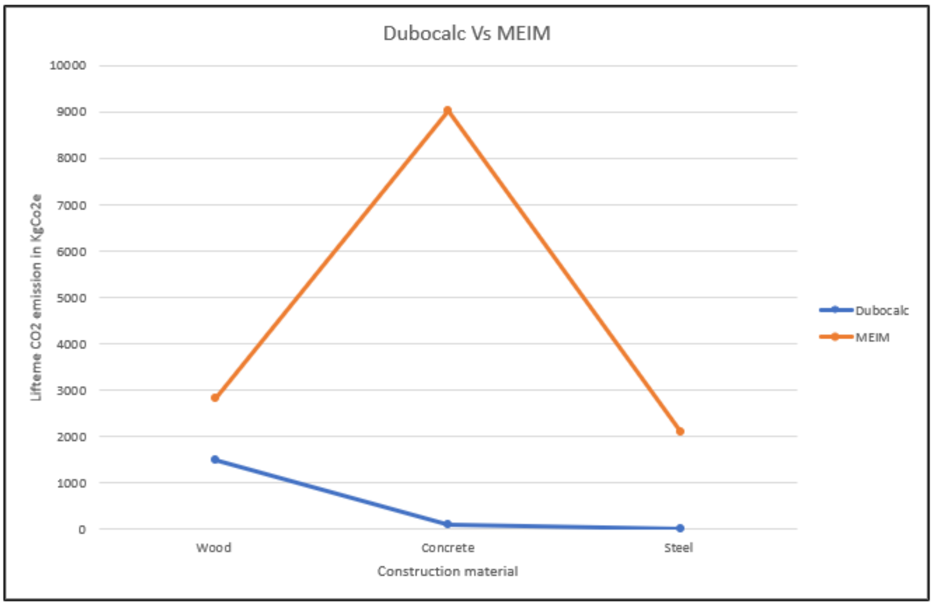


Figure 8.1: Emission Data comparison with the information model and Dubocalc

the minor activities for every maatregel are less overall.
2. For wooden civil structures, due to the fewer maintenance measures, the usage of heavy machinery, and the emission concerning the vehicles, trucks are also less comparatively. Also, these wooden structures do not require heavy cranes or excavators due to their size and weight in nature.

The obtained results from the information model, the estimated emission data for the entire Municipality or every asset, can be used per the user's needs. Based on the criteria given by the user, their respective output can be retrieved in the dashboard as output.

8.2. Scientific Contribution

The developed information model has added value to the literature concerning the emission from maintenance activities. Currently, though multiple literature studies are available on the information model focusing on the emission from the construction of buildings, civil infrastructures, etc, the literature focusing on information models, applications targeting on the maintenance activities and their emissions is few. Such model can add value to the asset management literature, as the main focus is on the maintenance of the assets.

The CO_2e emissions from the maintenance of civil structures are only considered in the life cycle analysis an application like Dubocalc. Such applications determine the emissions and MKI for assets right from the initial stage of the production phase until the demolition phase of the asset. Due to the detailed study of the asset/material throughout its lifetime, the maintenance and usage phase of the asset only focuses on some of the maintenance measures involved in the real-life scenario. This issue is addressed using the information model, focusing mainly on maintenance activities. It can add value to the life cycle analysis performed for civil infrastructures.

Further, the research gap identified is that the maintenance or usage phase does not take the inspection performed or the machinery usage into account, and not only the materials used for the maintenance activity and the transportation of the materials are usually taken into account for the life cycle analysis. This information model fills this research gap as both crucial factors are considered for estimating CO_2e emission. The points mentioned above denote the added value or contribution to the scientific field.

8.3. Practical Contribution

The essential requirements were identified using the literature study to achieve the research objective. Each component of the research, like the breakdown structure, the UML class diagrams, and the information model, can be used individually by any user to achieve a similar objective as the research. The developed information model can be practically used by the Obsurv team or stakeholders involved in the management and maintenance of the civil infrastructures within a given municipality. The emission data obtained can be used in the existing obsurv platform. The CO_2e emission data corresponding to every single asset can be added to the obsurv platform together with the other specifications of the assets. This way, the clients(Municipality) can use the overall emissions to create new sustainability goals or amend the existing sustainability goals related to the asset management department.

8.4. Limitations of the research

It is essential to take the limitations of this research into account. This way, further or future research can be enhanced and improvised. The limitations of this research are explained in detail below.

Data source and accuracy of data :
Though the central part of the data collected is from trusted and recognized sources, the data related to the minor maintenance activities concerning every maintenance measure of the civil structure is collected from multiple sources. These sources include Beherdeer plan/ kuntswerken plan for various municipalities like Delft (Delft, 2011), Meppel (Meppel, 2018), Geetruidenberg (Hoogterp, 2018),Lingewaard (Zijlmans, 2021) various websites of maintenance works contractors like Batec bv (NL, 2019), De Vries werkendam BV ("Kranen - Aannemingsbedrijf de Vries Werkendam B.V. | Werkendam", 2021), Sluisdeuren("Sluisdeuren", 2021) , Koninklijke oosterhofholman ("Succesvolle vervanging historische vloeddeuren Haarlemmerschutsluis", 2018), MRS waterbouw (Waterbouw, 2020), etc. Due to the multiple data sources, there are some disadvantages like conflict in the data, redundancy, and Data authenticity as the data collection method will be different for the different sources.

The data accuracy limitations are witnessed only in the values used or assumed for the transportation of the vehicles, machinery, and the usage hours of the machinery. This assumption is because the transportation details of the contractors to the construction site might vary, and it is not a fixed value. However, these transportation values were to be recognized; hence, these values are assumed for the estimation.

Limited database:
The database of the maintenance measures(maatregel) is in terms with the assets located in the Municipality of Schagen and their nearby areas. The CO_2e emission estimation is purely focused on these maintenance measures. Hence, the suitability or usability of the information model is limited and can be used only if the assets have similar maintenance measures as the collected data. Due to this reason, the validation of the information model is also limited to only certain assets of the other Municipality in concern (Zuidplas)

9
Conclusion & Recommendations

This chapter deals with the conclusion and future recommendations of this research. The first section deals with detailed answers for each sub-research question. The following section deals with answering the main research question and how the research objective is achieved. The last part focuses on the future recommendations of the research.

9.1. Sub-Research Question

1. How can the major Maintenance activities of each type of asset breakdown into sub-activities?

The literature review conveys that the system of civil infrastructures in a municipality is a complex system that consists of multiple types of assets, and they are interconnected with each other (INCOSE & Wiley, 2015). Hence to arrive at the sub-maintenance or minor maintenance activities, the literature suggested that breakdown structures can be utilized to ensure efficient decomposition of the Municipality in terms of the asset management system. It is used in most industries and for much more complex systems.

The breakdown structure was devised to be simple for the users to understand. So the three types of breakdown structures were used for the research. They are,

1. System Breakdown Structure (SBS) - This breakdown structure decomposes the Municipality into its assets and assets into their respective components and elements.
2. Work Breakdown Structure (WBS) - This breakdown structure breakdown the assets & their components into major maintenance works.
3. Activity Breakdown Structure (ABS) - This breakdown structure decomposes each major maintenance work into its respective minor maintenance activities.

Hence using the three different breakdown structures which can be modeled together (Camilo et al., 2012), the outcome of this sub-research question is achieved.

2. How can the emission data be linked to all the sub-activities of the maintenance works?

From the literature studies, the data and type of data necessary to estimate the CO_2e emission from the maintenance activities of civil infrastructures are obtained using the various research papers (Sandanayake et al., 2018), (Swertz et al., 2017). Since the objective was to develop an information model about the infrastructures, the research by (Jetlund et al., 2020) suggests one way to approach the information model is using the Unified Modelling Language (UML) as it is commonly used in the most infrastructure-related information model.

The UML class diagrams transform the breakdown structure components into classes and sub classes. The data required to estimate the CO_2e emission are connected to these classes and subclasses. Further, the relationship between the assets and their maintenance activities is also defined clearly using this UML class diagram. These UML class diagrams of bridge type of assets (5.1), (5.2), (5.3), (5.4), (5.5).

The UML class diagram aids in acquiring the data required for the CO_2e emission estimation, the relationship between the assets and their maintenance activity, and maintenance activity and their emission. Hence, the outcome of this sub-research question is achieved using the UML class diagram.

3. How can the information model be built using the relevant data?

The information model required three components which are the input components, database components, and output components. The output, collected from the breakdown structure and the UML class diagram, provided one of the inputs for developing the information model. The information model's database components are obtained from trusted and recognized platforms. The asset database is from the OBSURV software; the emission database is from the ICE database, which is used in the UK; the other emission database is from the CO_2e emissiefactoren, which is used mainly in the Netherlands. The output component of the information model gives the model's objective, which is the CO_2e emission from the maintenance activities for a large number of assets for a particular municipality.

4. How can the information model be adopted in the asset management plan of Municipalities?

The OBSURV software is a web-based platform, and various municipalities currently use it to manage and maintain their respective assets. The software is currently utilized for various criteria like intelligent planning and budgeting of the management and maintenance activities of all the assets in the Municipality and administrating the daily maintenance of various objects. It allows the users and clients to perform strategic and tactical asset management and maintenance planning. It has a dashboard environment that can be useful for visualizing critical data. Since the current software is used for the asset management of the municipalities, the output of the information model, which gives the CO_2e emission from the maintenance activities for every single asset, can be used as data to be added to the Obsurv platform. This added data on CO_2e emission can ensure the users consider sustainability as a criterion in the asset management plan/ multi-year maintenance plans, along with the cost and time criteria that are usually used.

5. How can the information model aid in making decisions on maintenance strategies for the Municipality?

As per the various references from technical reports of Municipality's management & maintenance plan (Zijlmans, 2021) (Pianoo, 2017), the management and maintenance plan of a civil structure is provided when their construction is completed and delivered to the asset owner. At this stage, a decision has to be made by the asset manager and asset owners to plan what type of maintenance measures(maatregel) are needed for the asset. The decision includes the control measures, type of maintenance activity, quantity, frequency of inspection activities for the asset, methods of performing the maintenance activities, estimate on the number of man hours, secondary activities linked to the primary maintenance activity, etc. The information model's output of the CO_2e emission details can be used at this stage for the decision-making in determining the methods to perform the maintenance activities which can reduce the emissions from the transportation or the usage of the machinery. Also, the emission can be used as a criterion even before the construction of the asset when decisions can be based on the sustainability criteria to build the civil structure using which construction material. The output from the dashboard shows that specific materials tend to have more CO_2e emissions than others. Together with the other requirements like the cost, life period, and function of the assets, the emission data can also be used to compare different materials before the construction process.

9.2. Main Research Question

"How can the CO_2 emission from maintenance activities of a large number of physical assets be quantified and used as an indicator by the Municipality in decision making of an asset management plan?"

The research follows a logical and practical research design to achieve the research objective. Using the literature studies and following the guidelines from the breakdown structures and the UML class diagram, the information model was built, realizing the research objective of quantifying the CO_2e

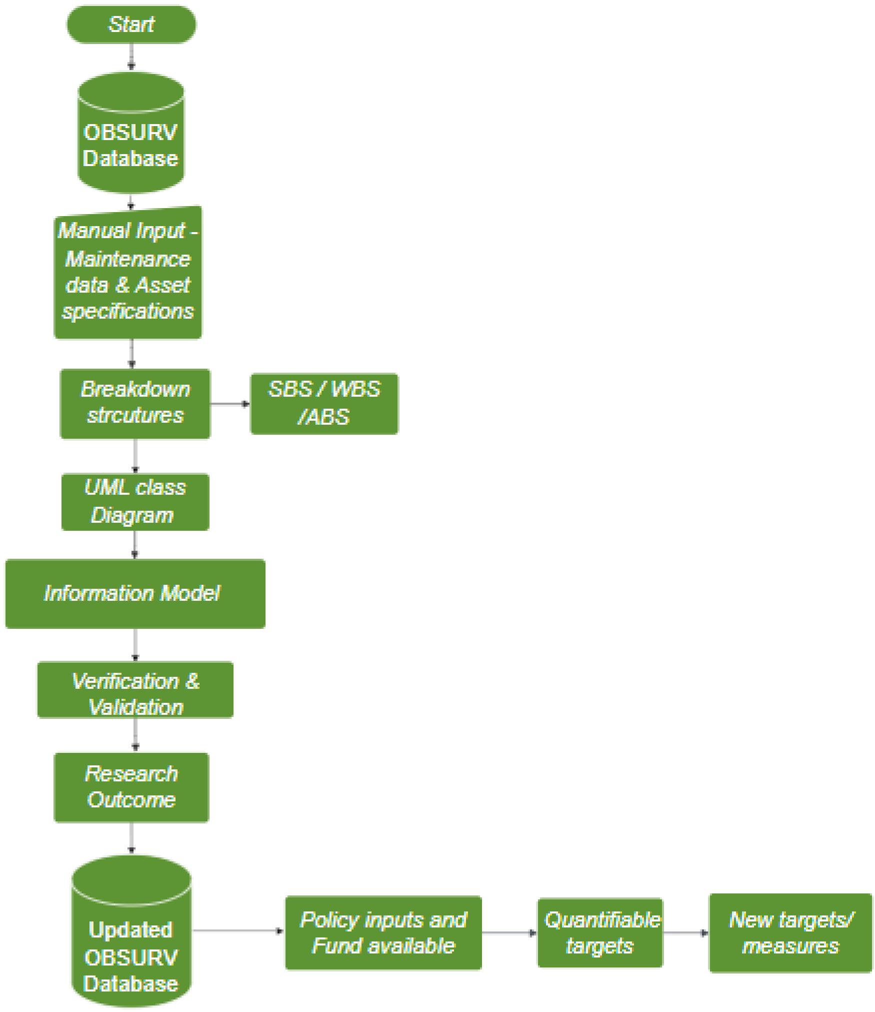


Figure 9.1: Process flow for Decision making on Maintenance strategies

emissions for numerous assets. The results are verified and validated for practical application of the information model in the industry.

The main research question is answered using the answers obtained from the sub-research questions and the developed information model. This model consists of multiple databases which are interconnected with each other in order to quantify the CO_2 emissions from the maintenance activities of every single asset. The asset database, which consists of all the data related to the assets, are designed to work with the CO_2 emission database to obtain the final results of overall emission data. The MS-Excel based model is designed so that the user can utilize it to calculate the CO_2 emission for a single asset or assets grouped based on specific criteria. The developed model provides data for the emission for every asset located in the given acreage or Municipality. This data acts as an indicator for the stakeholders involved in the decision-making. The model provides the users, visually and through the data, with how much emissions are obtained from every type of asset based on criteria like construction material, size, usage of heavy machinery, etc. Though there are some limitations in the developed information model, it adds value to the field of research in terms of redefining the estimation of CO_2e emission of maintenance activities compared to the LCA applications like Dubocalc. The data from the information model can improve the estimation of the CO_2e emission in the LCA applications for a particular phase (Phase B - usage and maintenance) of the civil infrastructure during their lifetime. This information model can also be used for other municipalities, provided their respective assets data are obtained.

9.3. Recommendations

9.3.1. Practical Recommendations

The stakeholders involved in the asset management and maintenance can utilize the information model for the assets.Due to the reason that this information model covers more than the Dubocalc during the maintenance phase of civil infrastructures, this model has an upper hand for the maintenance phase CO_2e emission estimation. Using the estimation method applied in the information model, a central database consisting of all kinds of maintenance measures(maatregel) based on all the municipalities can be created. This created database can aid the information model to become an much better version and can replace other applications like Dubocalc for the CO_2e emission during maintenance phase of the civil infrastructures.This information model can be utilized by most municipalities for the emission quantification of the maintenance activities provided that all the maatregel are decomposed into their minor maintenance activities and their required emission data is quantified accordingly. Hence Municipalities can use this model instead of Dubocalc to gain information about the CO_2e emission from the maintenance activities of civil infrastructure. This information model can add value to the existing life cycle applications like Dubocalc since the maintenance or the usage phase emission is redefined and the necessary scope for maintenance is added to the existing scope. The consultants, asset owners/managers can monitor the CO_2e emission from the maintenance activities specifically and can take any measures with the output data available from the information model.

9.3.2. Future Research Recommendations

The data relating to the minor maintenance activities are collected from multiple sources, and some values, like the distance traveled by the contractors and machinery usage hours, are assumed. This data can be improved in quality if collected from direct sources like the contractors performing the maintenance activities. The information model is currently based on MS-Excel. It can be transformed into Power BI application to enhance data visualization and have multiple criteria indexing without much effort. The user interface can also be improved compared to the excel model if it is transformed into Power BI application. The current information model does need some input from the users to operate. It can be improved by automating multiple processes within the model using python. This information model currently quantifies the CO_2e emission from the minor maintenance activities of the assets in a municipality. With this information, the next step can lead to optimizing the CO_2e emission with other criteria like time and cost for the entire Municipality. These are the future research recommendations.

10 Personal Reflection

10.1. Thesis Process

At the beginning of the thesis process, I had two criteria for my thesis. 1. A challenging and quantitative research 2. Thesis with a company. With these criteria in mind, I delved into various domains and topics that were related to CME and my specialization E§. As a result of this process, I decided to do research in asset management and optimization. During the initial stages of preparing the research proposal, I also got an opportunity to do my thesis with Sweco Netherlands. The research domain that I was interested in also coincided with the company's interest. The thesis process initially was more concentrated on asset management and optimization and I had to work for three months on this topic and to develop a prototype for the thesis kickoff. Eventually, things did not go as per the plan as I could build only a part of the prototype. Further, during the first kickoff of my thesis, the requirements of the company and my thesis committee were found to be different. This caused a huge setback in the graduation process and caused a 3 months delay. It was decided to change my thesis committee and modify the thesis topic as per the requirements of the company and the University. With the new research topic, I was able to form a new committee after explaining my topic and research details. In August, I was able to have my kickoff for a new research topic of developing an information model for maintenance activities successfully and began my thesis officially.

Since the kickoff, it was a gradual learning process for me with proper inputs and direction from the thesis committee. At moments, I felt the topic was too broad, considering the scope of CO2e emissions. With some guidance from the committee members, I was able to figure out the necessary scope of the thesis and the scope of the information model as well. Throughout the process, there were some back-and-forth activities in framing the research methodology and eventually changing it when some of it could not be worked out. For example, the initial research methodology was to conduct interviews with the asset managers from the municipality and contractors who execute the maintenance activities for the municipality. However, due to poor response from both municipality and the contractors, it was decided to collect information from the available sources. The same happened for the validation process as well.

After creating about two to three working information models in excel, I felt all of them were chaotic and overloaded with too much data, figure out a way to make the model user-friendly was a hard task and it happened after months of working. The findings from the breakdown structure and the UML class diagrams provided some necessary insight for the development of the information model. When the skeleton of the information model was developed after a long time, that was when I realized this is something that can be useful for the university as well as the company. Until then the whole process was a bit vague. This was one of the milestones of the graduation process.

The two progress meetings that I had was essential for the information model. Though I could not provide much development during both progress meetings, I was able to get valuable feedback from the committee members on what their expectations were. This helped a lot in the enhancement of the information model and in improvising the operation of the model. Most of the actual findings from my research happened between the second progress meeting and the green light meeting. The information model was developed as per the mentioned scope of the research. It was both verified and validated after the development. Though I had some concrete findings, I was a bit skeptical about whether this would satisfy the committee or not. Using the obtained results, presentation, and report, the thesis committee was satisfied and agreed to give me a green light for the final defense. This was the other key milestone of my graduation process.

10.2. Personal learning

1. There was a lot of learning personally throughout this graduation thesis. Right from the beginning being clueless about the thesis until reaching a stage where I get the green light was a slow but steady learning curve for me. Though I had a lot of personal struggles both with my thesis and personally, what mattered was I did not give up. This quality has to be embraced in the future as well.
2. There were situations during the process that could have been maneuvered easily with the help of committee members if I had sought their help. Due to my hesitation, I was not able to do so. This is one of the things that could have helped me during the thesis. I want to learn and change myself in asking for help.
3. It was quite difficult for me as the whole thesis process itself is an individualistic and self-learning process. Some of the choices I made for the research could have been better if they had been taken after in-depth scrutiny.
4. The time factor also played a critical role in my research process. Some of the research areas can be improved if I had more time for the data collection and the development of the information model.
5. The balancing of thesis work and life was a bit poor as I was mostly occupied with the thesis work. This was fruitful at times but caused other issues as well. With the help of my efforts, I was able to overcome the problems caused by the imbalance.

10.3. Suggestions for Future Students

- Select a research topic that is really interesting and you are passionate about that topic.
- Do proper research for the kickoff that will be helpful for the research and will not obstruct your work during the process.
- Believe in yourself and the research process. It might not be evident at the beginning but eventually, you will arrive at the research objective.
- Structure your thesis technically as well as how it fits in your life. This structuring can be really helpful when you are going through the process and facing some obstacles. This routine structuring can be helpful.
- Try to communicate with your committee and friends to get some feedback regularly. Since your focus is too narrow, this feedback can provide you with relevant direction sometimes. This can improve the thesis work overall.
- Keep a proper balance between thesis work and your life. This has an impact on the work that you are producing.

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A
Input

A.1. Breakdown Structures

The three Breakdown structures that are used for the research are the System Breakdown Structure (SBS), Work Breakdown Structure (WBS) and the Activity Breakdown Structure (ABS). The purpose of using three Breakdown structures is to be coherent as well as distinctive about the decomposition of the system, sub-system and elements involved.

SBS: This deals with the decomposition of the municipality into their asset, asset types and finally into their components & elements. The picture (A.1) is the example of Schagen Municipality, where the asset type of bridges are used. Here the system is the Asset management department, from there it is decomposed into various assets which are the sub systems.

WBS: This deals with the decomposition of the assets major maintenance works and the types of maintenance works. (A.2) is the example of Schagen Municipality, where the asset type of bridges are used. Here the system is the Asset management department, from there it is decomposed into various assets which are the sub systems.

ABS: The major maintenance works are decomposed into the maintenance measures and finally into their minor maintenance activities. (A.3) is the example of Schagen Municipality, where the asset type of bridges are used. Here the system is the Asset management department, from there it is decomposed into various assets which are the sub systems and various elements.

A.2. UML Design

The UML Class diagram is a graphical notation used to construct and visualize object oriented systems. A class diagram in the Unified Modeling Language (UML) is a type of static structure diagram that describes the structure of a system by visual representation. (A.4) is the basic class diagram for the municipality which was developed initially during the research process. It provides detail on the asset types.

(A.5) provides the detailed overview of the UML class diagram of a municipality with respect to the information model.

Every asset type can be developed further into its own UML class diagram. All these can be connected to the overall class diagram of the municipality.

A.3. Dashboard Model

(A.6 & A.7) are the preliminary model of dashboard that was to be developed as a result of the information model. This contains all the necessary details about the municipality, the number of assets they own, type of assets and their respective numbers. Using this data and the emissions that are estimated, the output information like which assets are responsible for more emissions, what type of materials used are causing more CO_2 emissions can be determined. Also the overall emissions from the maintenance activities is also given for the asset owners. Such dashboards can provide interactive information. This can allow the user to select the type of asset, mention their specifications and estimate their emissions and compare them with different materials.

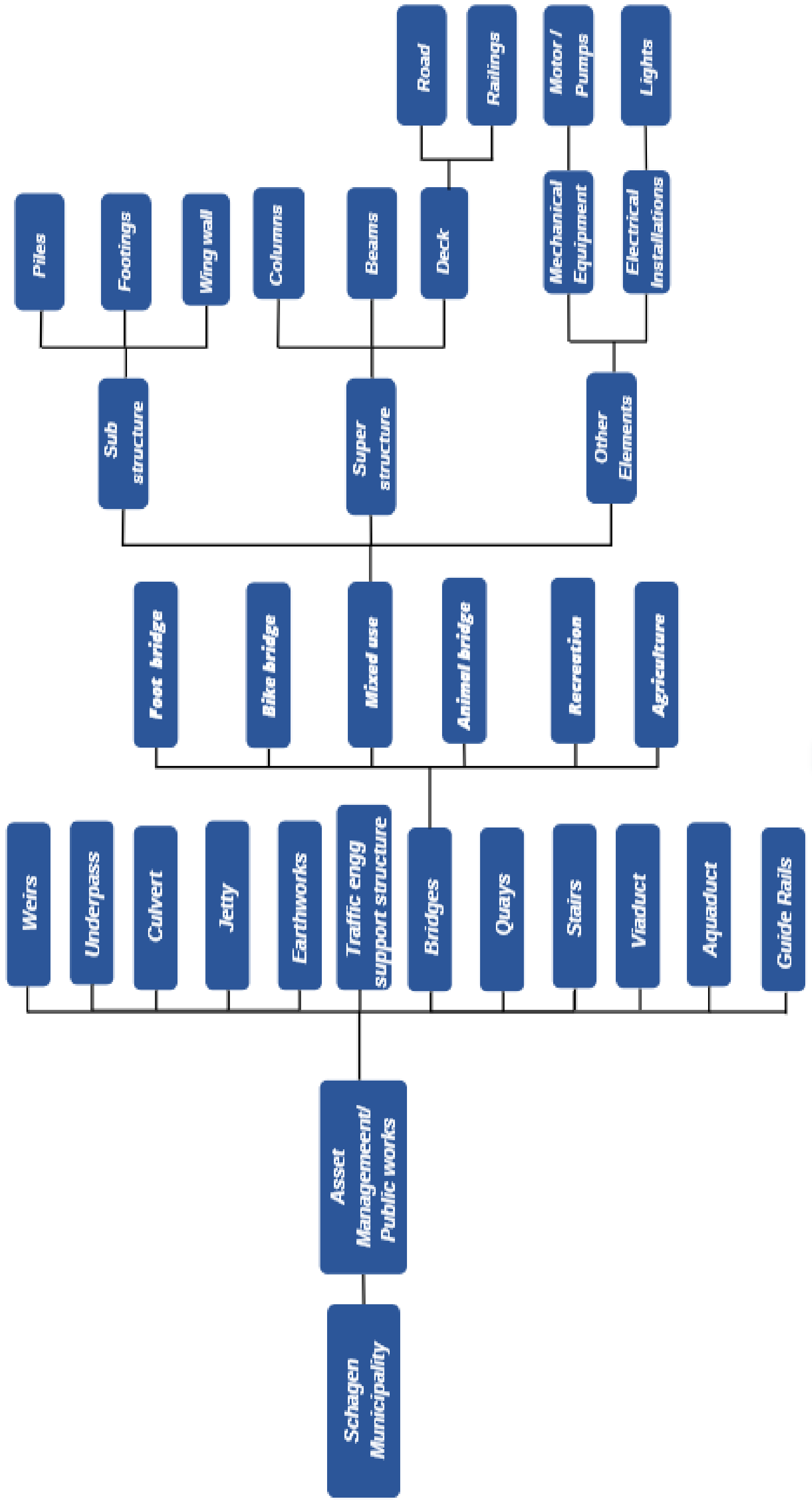


Figure A.1: System Breakdown Structure of a Bridge

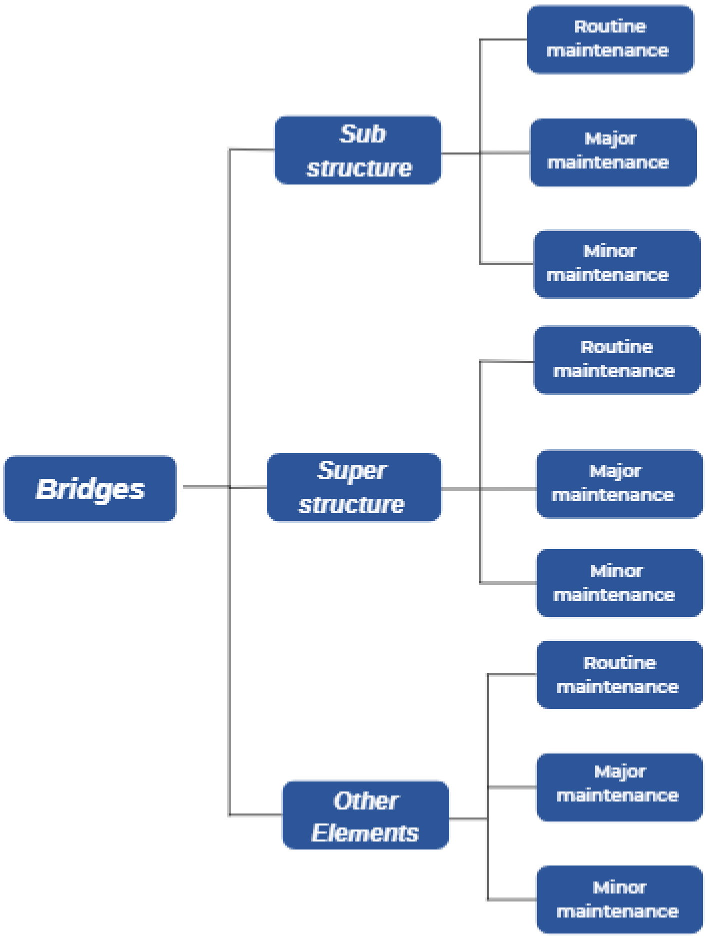


Figure A.2: Work Breakdown Structure of a Bridge

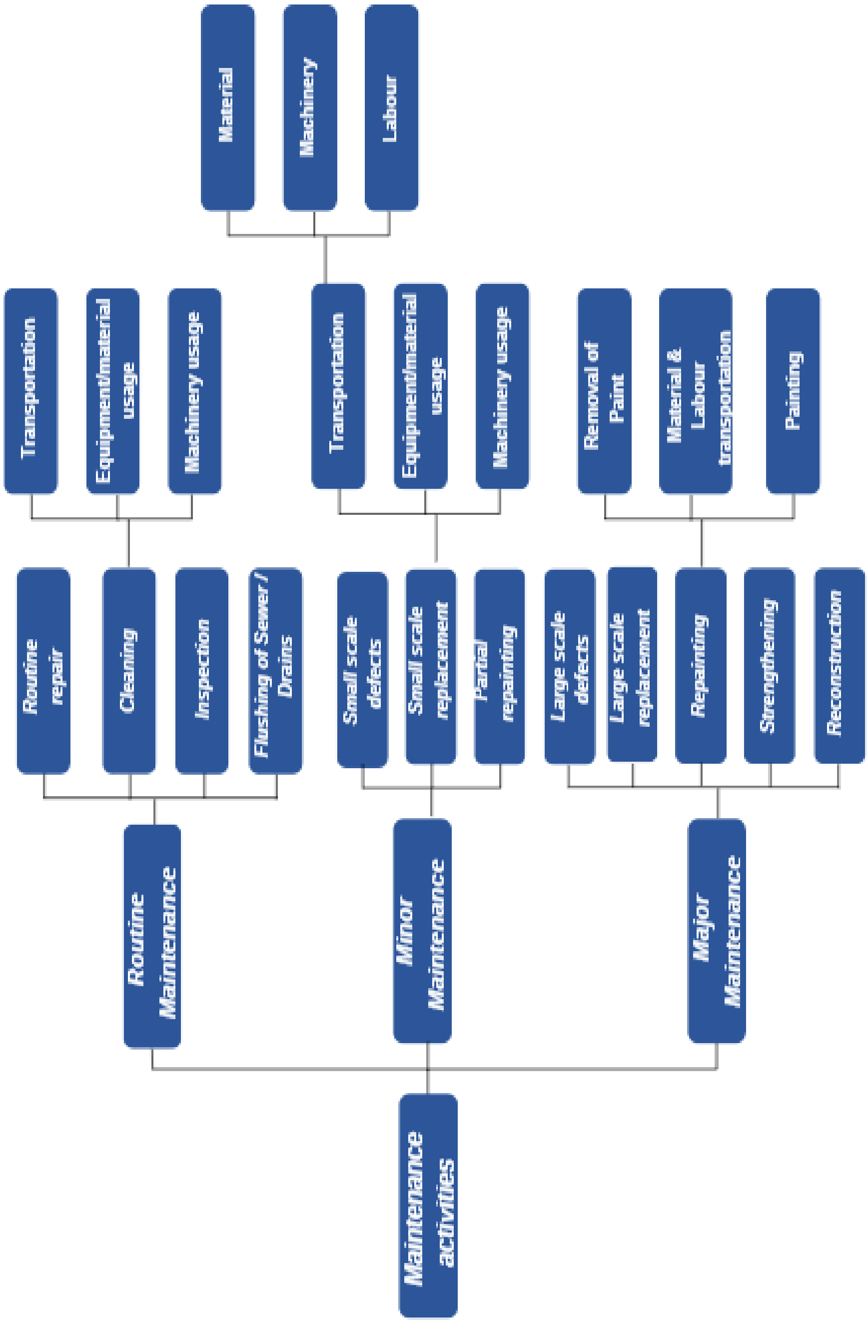


Figure A.3: Activity Breakdown structure of a bridge

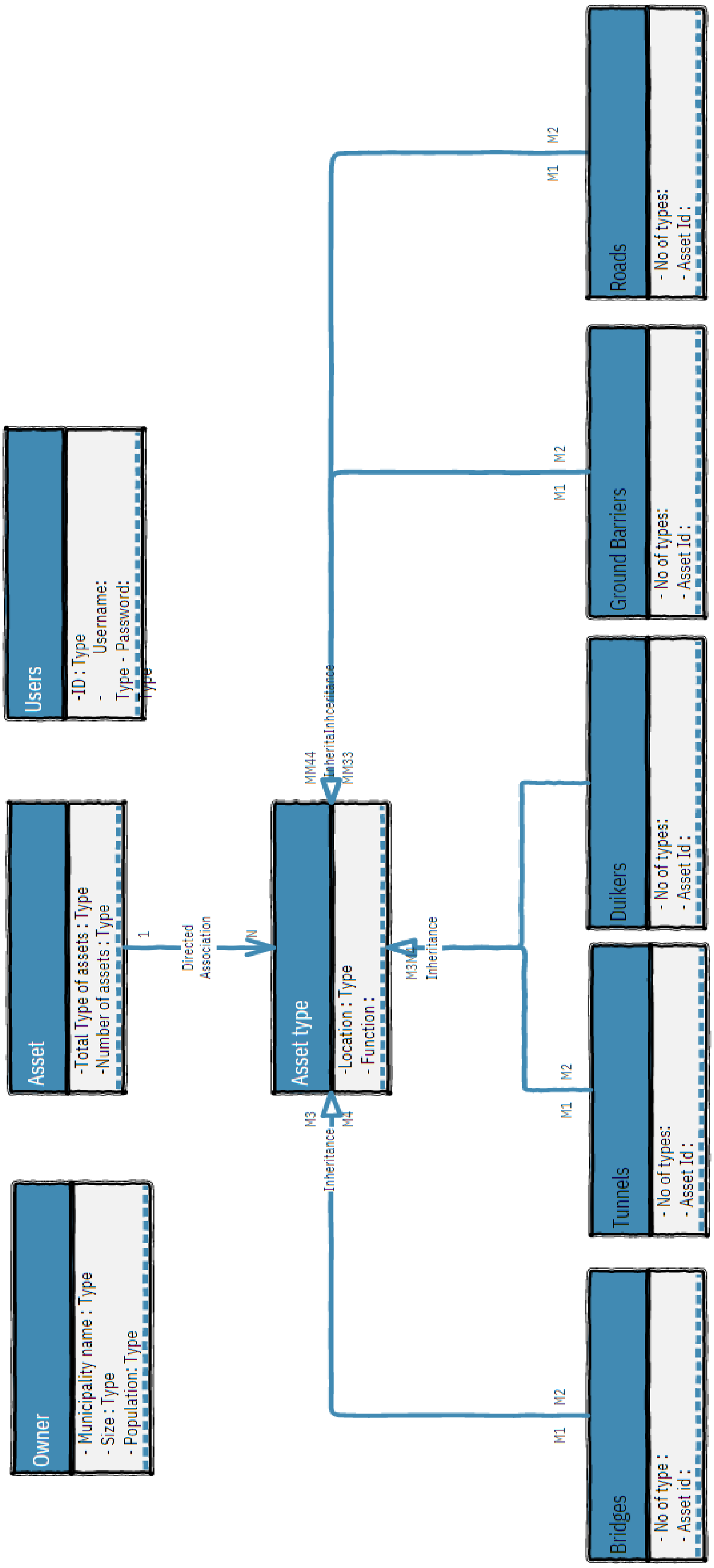


Figure A.4: Initial UML Class Diagram

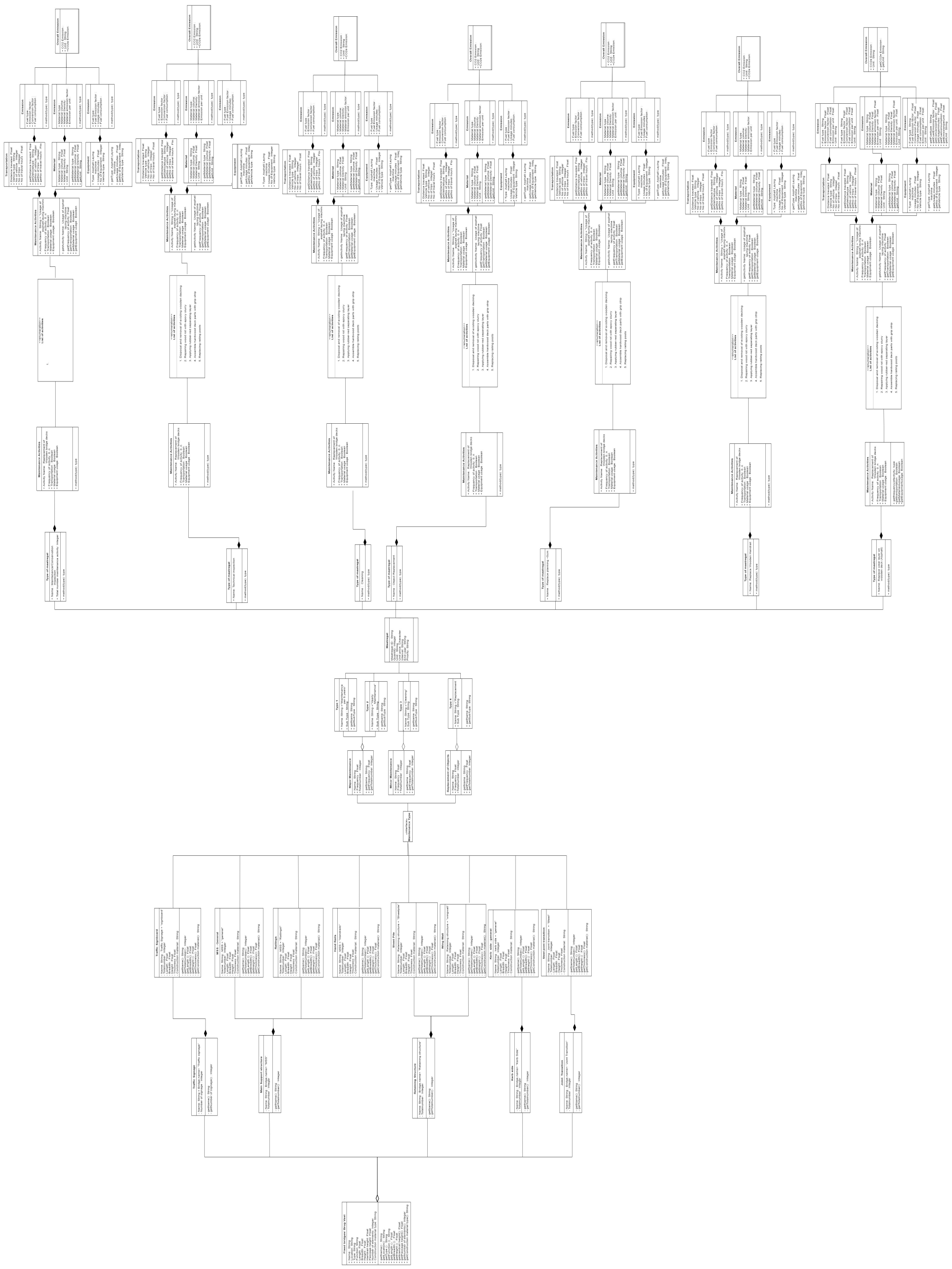


Figure A.5: Final - UML Class Diagram

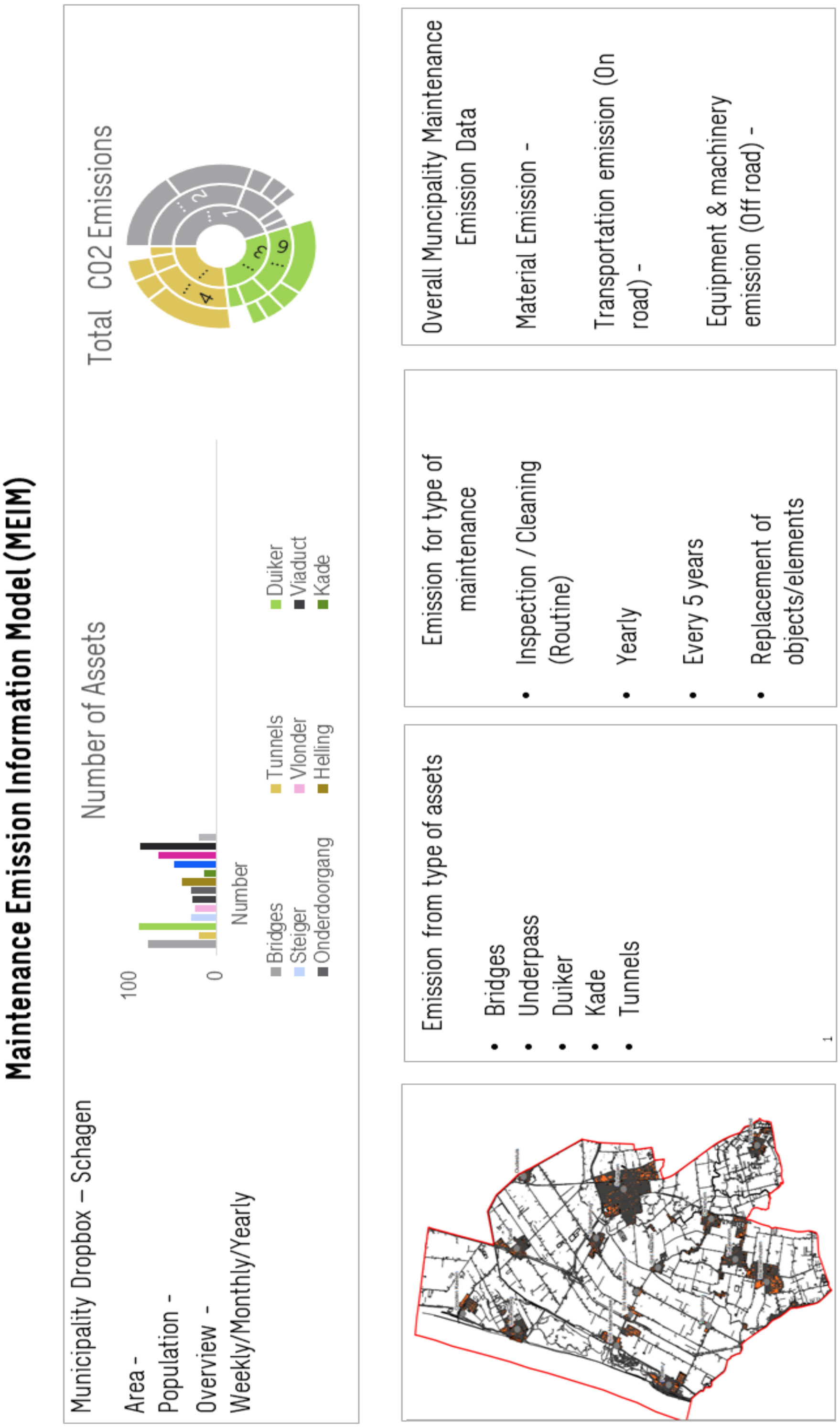


Figure A.6: Dashboard page 1

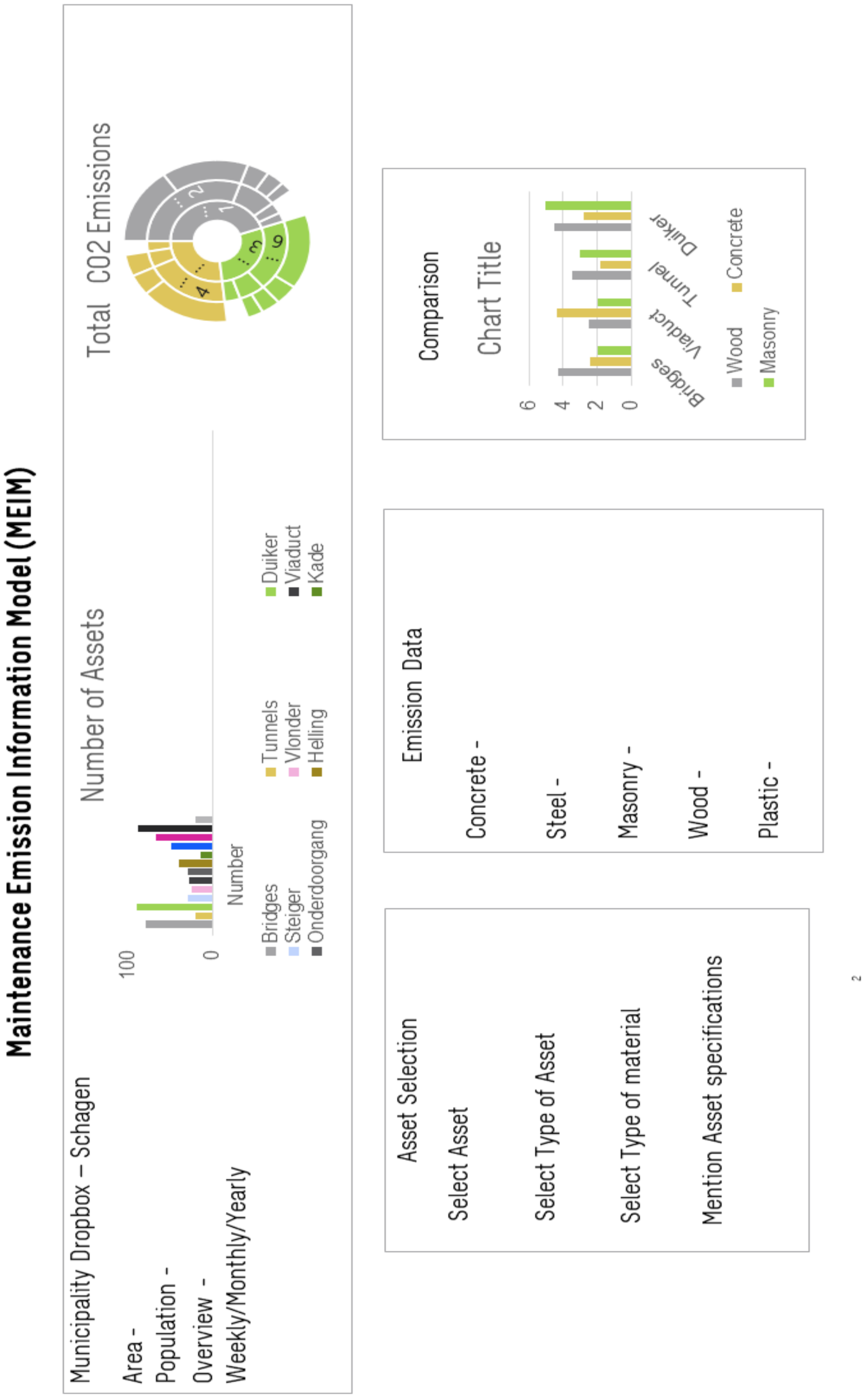


Figure A.7: Dashboard Page 2

A.4. Dubocalc vs MEIM

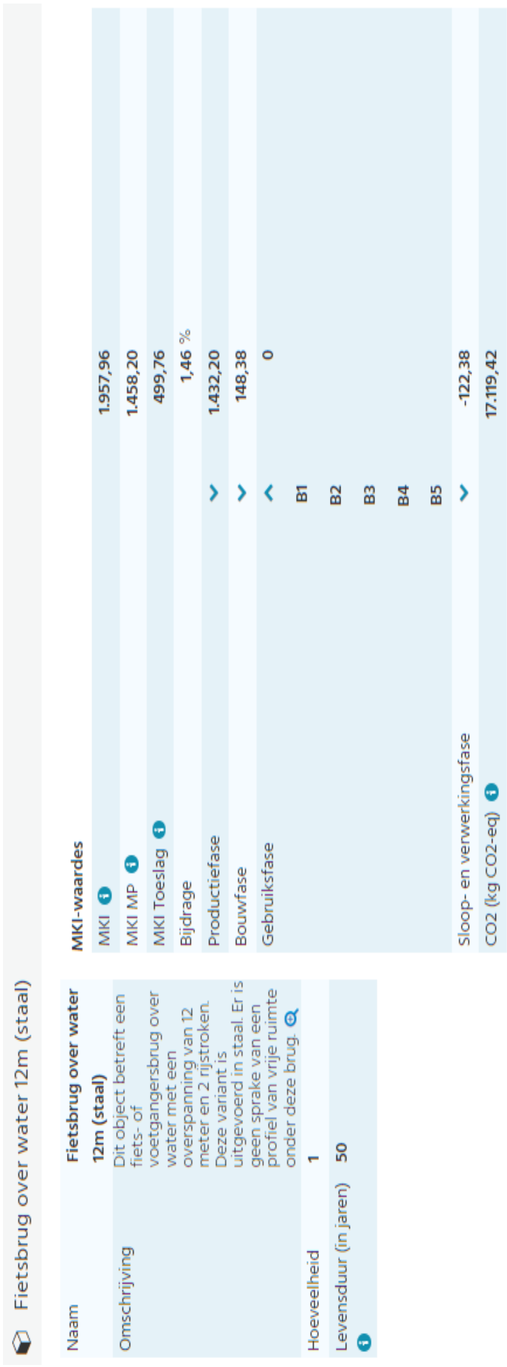
Three bridges have been chosen to be compared with the Dubocalc application. These bridges are made of steel, concrete and wood. Bridges are of similar size and dimensions. The results of this comparison between Dubocalc and MEIM can be found in the below pictures.

(a) Emission from the Dubocalc in usage phase B

				Emission per Maatregel	No of Times maatregel is performed	Emission of the maatregel for lifetime
		CODE	KW_0087			
KW Code	KW_0087	MRL_ID	Instandhoudingsinspectie	10.47	25.33	265.36
Asset	Brug (vast)		Objectvervanging houten brug	223.16	2.13	476.06
Asset Type	Liggerbrug		Reinigen object	23.63	39.00	921.59
Material	Hout		Vervangen beplanking >5 cm	53.31	2.13	113.73
Length	13		Vervangen leuning hout	51.75	4.27	220.82
Breadth	2.93		Vervangen slijtlaag op houten dek	84.74	9.75	826.22
				447.07	82.62	2823.79

(b) Emission from the information model

Figure A.8: Comparison between the emission values from Dubocalc and the Information model

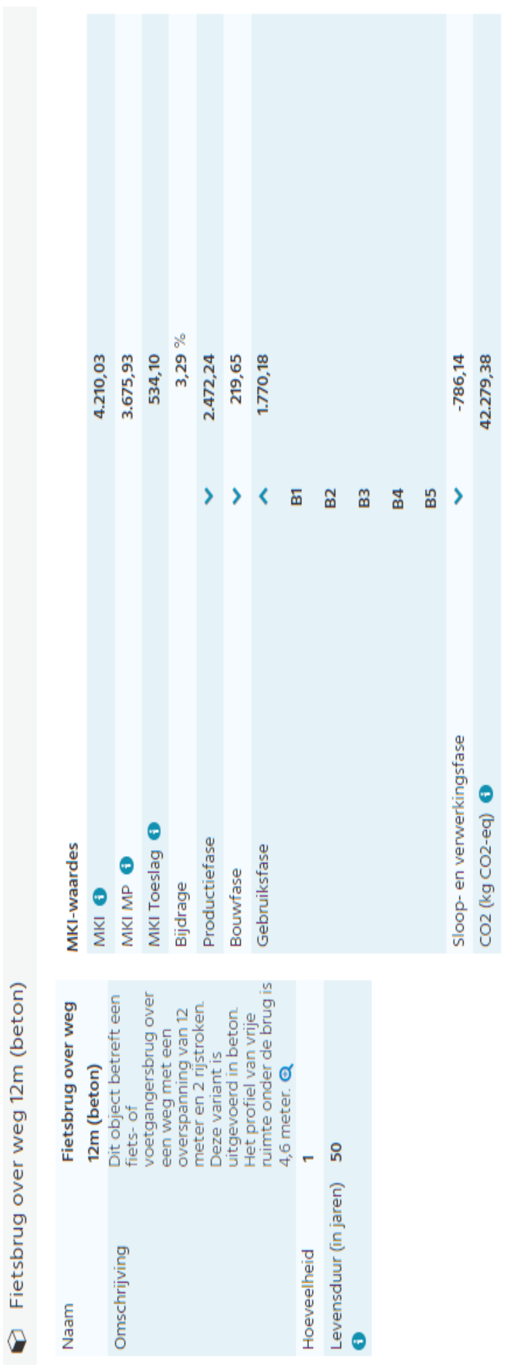


(a) Emission from the Dubocalc in usage phase B

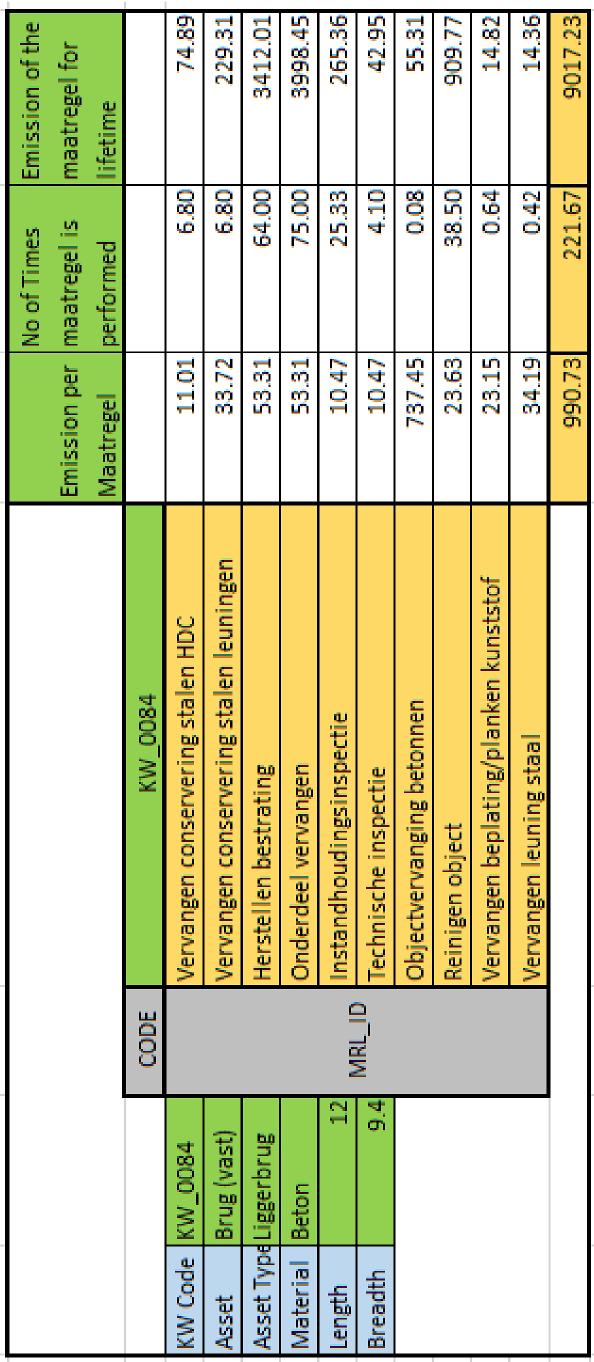
				Emission per Maatregel	No of Times maatregel is performed	Emission of the maatregel for lifetime
		CODE	KW_0082			
KW Code	KW_0082	MRL_ID	Vervangen conservering stalen HDC	11.01	6.60	72.69
Asset	Brug (vast)		Vervangen conservering stalen leuningen	33.72	6.60	222.56
Asset Type	Liggerbrug		Instandhoudingsinspectie	10.47	25.33	265.36
Material	Staal		Technische inspectie	10.47	4.10	42.95
Length	11.1		Objectvervanging betonnen	737.45	0.26	193.58
breadth	3.3		Reinigen object	23.63	38.00	897.96
			Vervangen beplating/planken kunststof	23.15	0.72	16.67
			Vervangen slijtlaag op stalen/kunstof dek	53.31	6.60	351.86
			Vervangen leuning staal	34.19	0.42	14.36
				937.42	88.64	2077.99

(b) Emission from the information model

Figure A.9: Comparison between the emission values from Dubocalc and the Information model



(a) Emission from the Dubocalc in usage phase B



KW Code	KW_0084
Asset	Brug (vast)
Asset Type	Liggerbrug
Material	Beton
Length	12
Breadth	9.4

CODE	KW_0084	Emission per Maatregel	No of Times maatregel is performed	Emission of the maatregel for lifetime
MRL_ID	Vervangen conservering stalen HDC	11.01	6.80	74.89
	Vervangen conservering stalen leuningen	33.72	6.80	229.31
	Herstellen bestrating	53.31	64.00	3412.01
	Onderdeel vervangen	53.31	75.00	3998.45
	Instandhoudingsinspectie	10.47	25.33	265.36
	Technische inspectie	10.47	4.10	42.95
	Objectvervanging betonnen	737.45	0.08	55.31
	Reinigen object	23.63	38.50	909.77
	Vervangen beplating/planken kunststof	23.15	0.64	14.82
	Vervangen leuning staal	34.19	0.42	14.36
		990.73	221.67	9017.23

(b) Emission from the information model

Figure A.10: Comparison between the emission values from Dubocalc and the Information model