Establishing a Framework for Airport Life Cycle Inventory Development: The Case of Schiphol Airport

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Establishing a Framework for Airport Life Cycle Inventory Development: The Case of Schiphol Airport

By

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Nomenclature

Abbreviation	Definition
APU	Auxiliary Power Units
EoL	End of Life
GAV	Ground Access Vehicles
GHG	Greenhouse Gases
GPU	Ground Power Units
GSE	Ground Service Equipment
GSEv	Ground Support Equipment Vehicles
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDE	Leiden Delft Erasmus
LTO	Landing and Take-off Cycle
NLR	Netherlands Aerospace Centre (NLR)
RTHA	Rotterdam The Hague Airport
UHPWB	Ultra-High-Pressure Water Blasting

Abbreviation	Definition
$\mathrm{A_s}$	Pavement surface area
$\mathrm{A_{s,\ RTHA}}$	Pavement surface area at Rotterdam The Hague Airport
$\mathrm{A_{s,\ x}}$	Pavement surface area at airport in question
C_T	Quantity of concrete to construct airport
D_w	Energy demand per aircraft wingspan categories (e.g. B737, B747, A380)
e_{GSE}	Energy demand for GSE equipment (obtained from literature)
E_{GPU}	Total energy demand for GPUs
E_{GSE}	Total energy demand for GSE (calculated)
E_i	Electricity demand for airport section
$\%E_i$	Allocation percentage to estimate electrical demand for airport sections
E_{total}	Total electricity used at airport
G_{ts}	Number of gates at airport facilitating use of either GPUs or APUs
$\mathrm{H_i}$	Pavement sublayer thickness
f_{LM}	Frequency at which top layer of runway is replaced for maintenance
f_{RR}	Accumulated Rubber Removal Frequency
$\mathrm{Fuel_{constuction,\ x}}$	Fuel used to construct airport in question
$\mathrm{MI_{building}}$	Material Intensity for airport buildings
$N_{flights}$	Number of flights at a given airport within temporal scope of study
$N_{flight,\ cat}$	Number of flights at a given airport (e.g. B737, B747, A380)
$\mathrm{\rho_i}$	Material density for pavement sublayers
P_i	Percentage proportion for electrical demand at airports
R_i	Rubber Accumulation Intensity per square meter of runway
$\mathrm{S_m}$	Sublayer Material Quantity
$\mathrm{UFA_{building}}$	Useable Floor Area of airport buildings
$\mathrm{Q_m}$	Material Quantity for airport buildings

Contents

Abstract

The aviation industry is a significant contributor to environmental degradation, responsible for approximately 2% of global CO_2 emissions. While considerable research has examined the environmental impacts of flights, relatively little attention has been paid to airports, which are critical infrastructure for the aviation industry. Existing Life Cycle Assessments (LCAs) of airports are limited due to incomplete inventory data, since the inventory excludes many essential processes required for airport operations. This thesis addresses this gap by developing a framework to support the systematic collection of comprehensive inventory data of airports, enabling more robust LCA studies to be conducted. The framework was developed by compiling data requirements from multiple scientific sources, that all focused on specific intermediate or environmental flows such as energy use, material inputs and emissions from an airport. The thesis also demonstrates how inventory for airports can be collected using the developed framework. Inventory data was collected for Schiphol Airport using secondary data sources such as scientific papers and sustainable reports of the airport. The results highlight that the construction of the airport demanded a lot of concrete, while the use of APUs and aircraft taxiing are the major contributors of the airports GHG emissions. Though the results only focus on the development of the framework and the collection of inventory data from Schiphol Airport, it can be hypothesised that the high demand for concrete and the associated emissions contribute the largest to the environmental impact of the airport. Nevertheless, the findings demonstrate that the framework can be used to collect comprehensive inventory data of airports, which is a stepping stone towards better environmental assessments and better insight into areas that airports need to improve to reduce their environmental impact.

Keywords: Life Cycle Inventory, Framework, Characterisation Factors, Approximation, Estimation, Life Cycle Phases

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1 Introduction

Today's world is facing multiple environmental issues — including biodiversity loss, climate change, and ocean acidification — largely driven by human activities. However, many of these activities also yield economic benefits, such as reducing unemployment and increasing a country's GDP (Serio et al., 2024). One sector that significantly contributes to economic development is aviation, which accounts for 3.5% of global GDP and provides employment to 65 million people worldwide (S. Chen et al., 2024). Airports, in particular, are considered essential to national economies, as they support tourism and facilitate the global movement of people and goods (Jia et al., 2024; Serio et al., 2024). The importance of airports is expected to grow, with air transport closely tied to economic expansion — evidenced by the opening of approximately 42 new airports since 2019 (AIRBUS, 2025).

While airports are essential to global connectivity, they also have significant environmental impacts. Some researchers argue that the environmental burden of aviation begins at airports and is expected to grow due to the continued reliance on air travel (Klöwer et al., 2021). Research shows that aviation contributes approximately 2% of global CO_2 emissions (S. Chen et al., 2024; Greer et al., 2020). This mainly comes from the combustion of jet fuels, which pollutes the environment (Ritchie, 2024). Greer et al. (2020) argues that this estimate excludes the impacts from airport construction and operation, meaning that it remains unclear the extent to which airports contribute to the overall impact of the aviation industry.

There have been several studies that have assessed what the potential emissions originating from airports. According to Saavedra-Rubio et al. (2023), airports contribute 5% to the overall CO_2 emissions from the aviation industry. This means that airports are responsible for approximately 0.1% of CO_2 emissions from the aviation industry. While in another study, the Dutch Aviation industry is found to account for 1.16% of global emissions from the aviation industry (Harrington, 2024). While the Dutch aviation industry accounts for 1.16% of global emissions from the aviation industry, it was also identified that 96% of the CO_2 emissions attributed from Dutch aviation originates from Schiphol Airport. This suggests that large airports do have a huge role in the emissions from the aviation industry.

Some scholars argue that the majority of emissions associated with airports occur during the operational phase. Rupcic et al. (2023) differentiates between emissions produced during the Landing and Take-Off (LTO) cycle of aircraft and those generated by ground-based activities. Their study, supported by Greer et al. (2020), finds that airfield environmental impacts are primarily driven by pollutants such as nitrogen oxides (NO_x), sulphur dioxide (SO_x), carbon dioxide (CO_2), and hydrocarbons—most of which originate from the LTO phase. In contrast, emissions from ground operations—such as those from Ground Support Equipment (GSE), Auxiliary Power Units (APUs), and Ground Access Vehicles (GAVs)— contribute less to the airport pollution of airports, which should also not be neglected in environmental studies of airport (Rupcic et al., 2023). Therefore, a comprehensive evaluation of airport-related impacts requires accounting for all emission sources. Even if ground operations contribute a smaller share of total emissions, they can still have a notable effect on specific environmental impact categories, including climate change and acidification.

The environmental impact of airports is also shaped by the types of GSE in use, such as Ground and Auxiliary Power Units (GPUs and APUs), food and fuel trucks, and refuelling vehicles. Bahman et al. (2024) found that diesel-powered GPUs have significantly higher environmental impacts than biodiesel and electric alternatives. Similarly, Facanha & Horvath (2007), using a hybrid life cycle assessment, revealed that emissions from ground vehicles are often underestimated when only direct fuel combustion is considered. Their study highlights that GSE is a major source of carbon monoxide emissions, while airport infrastructure contributes substantially to particulate matter during operations. These findings emphasize the need to include ground operations and infrastructure in comprehensive airport LCA studies.

Research also shows that airport emissions can vary with seasonal changes. Shen et al. (2016) evaluated emissions from various heated pavement technologies, including traditional systems, geothermal, gas, and electric heat pavements. Their results indicate that the use of heated pavements is both energy efficient and emit less GHG compared to the use of traditional de-icing fluids that require a lot of energy to be manufactured. However, the study focused solely on climate-related emissions, omitting other important impact categories such as acidification, eutrophication, and resource depletion. Shen et al. (2016) therefore recommend adopting a more comprehensive life cycle approach to assess a broader range of environmental impacts.

The environmental implications of transitioning to sustainable aviation have also been explored. Meindl et al. (2023) estimated the potential energy requirements and emissions at Rotterdam The Hague Airport (RTHA) in order to facilitate the operation of hybrid electric flights from the airport. Their study suggests that airports will demand more electrical energy due to the electrification of air traffic and that airport infrastructure will have to be adapted to facilitate electrical flights from RTHA. While there will be higher electrical demand, the study finds that such a transition is attractive due to lower emissions. This highlights that airports play a critical role in mitigating the emissions for the aviation sector.

These insights into airport-related environmental impacts are crucial for conducting comprehensive Life Cycle Assessments (LCAs) in the aviation industry. A notable contribution in this area is the prospective Life Cycle Inventory (LCI) developed by Thonemann et al. (2024), based on the framework by Saavedra-Rubio et al. (2022). Unlike databases such as Ecoinvent, which focus mainly on airport construction, Thonemann et al. (2024) LCI covers all life cycle stages—construction, operation, and demolition—offering a more complete assessment of airport impacts. However, the prospective inventory is intended for scenario-based analysis of future impacts and cannot directly assess current environmental impacts associated with airports. Nonetheless, it provides valuable insights into how emerging technologies may shape the environmental footprint of airports in the future.

Therefore, a research gap has been identified based on the above literature sources. Firstly, it is identified that most studies assessing the environmental impact of the aviation industry focus on the emissions originating from aircraft operations, which in many cases does not include the emissions related to airports, as argued by Greer et al. (2020). Alongside this, all the studies mainly focus on CO_2 emissions, ignoring most of the time other emissions originating from the aviation industry. Though there have been several studies that have focused on airport sustainability, it was identified that there is a lack of comprehensive LCI data that can be used to assess the environmental impact of airports. Within the Ecoinvent database, there is one inventory dataset representing Zurich Airport which is frequently used as a proxy when evaluating the environmental impact of airports. However, this dataset does not contain comprehensive inventory covering all life cycle stages of airports. Moreover, the absence of a standardised methodology for collecting airport LCI data poses a major barrier to measure the sustainability performance of different airports. As a result, this study identifies that there is a knowledge gap into how comprehensive LCI data can be collected for airports, which needs to be gathered in order for better environmental assessments of airports to be conducted. This ultimately leads to a better understanding of the overall environmental impact of airports. As a result, the following research question is formulated:

"How can a comprehensive framework be developed to enable consistent and complete Life Cycle Inventory data collection across all stages of an airport's life cycle?"

With the following sub-research questions:

1. What are the key data requirements for developing airport-specific Life Cycle Inventories across all life cycle stages?
2. How can data for airport Life Cycle Inventories be systematically collected across all life cycle stages of the airport?
3. How can the Life Cycle Inventory data collection process be designed to ensure applicability across different types of airports?
4. How can the developed framework be applied to collect Life Cycle Inventory data from a selected case study airport?

The outline of the study is as follows: Chapter Two below will outline the research methodology utilised in this study. Following on this, Chapter Three will present the results obtained from the utilised methodology, which includes the data found in literature and the developed framework. Chapter Four will apply the developed framework to a case airport to demonstrate how the framework can be applied for the collection of airport inventory, while Chapter Five will discuss the results obtained in this study. This study ends with Chapter Six, which concludes the research.

2 Methodology

This chapter systematically addresses the associated methodologies used to answer each sub-question from the previous chapter. It first details the methodology for identifying data requirements for airport inventory, followed by approaches for data collection. Based on these, a general framework for inventory development is proposed as a key deliverable. Figure 2.1 summarises the steps taken in this thesis.

Figure 2.1. The three steps undertaken to develop the framework for the collection of airport inventory

In order to identify the LCI data requirements of the study, the goal and scope of the study has to be established. This is because a well-defined goal and scope guides the selection of relevant data and ensure the study remains focused (Guinee, 2002). Given this importance, the methodology chapter starts by defining the goal and scope of the study, followed by the methodology used to identify the LCI data requirements of the study.

2.1 Goal and Scope Definition

The identification of LCI data requirements depends on the goal and scope definition described below. The scope determines which unit processes within the airport system need to be included, each of which requires and generates specific inputs and outputs.

Goal

The goal of this study is to develop a LCI framework specifically designed for the collection of airport-related inventory data. As highlighted in the previous chapter, comprehensive airport inventories are currently limited, which hinders the ability to conduct accurate environmental impact assessments. To address this gap, this study focuses on the creation of a LCI framework that can be used as a standardized tool for gathering relevant data from airports. Once implemented, the framework will support future environmental assessments by enabling the collection of comprehensive data from airports, which can be used for impact assessments. It will also facilitate hotspot analysis to pinpoint specific airport operations or components that require improvement to reduce overall environmental impact. Ultimately, the proposed framework will provide a foundation for collecting robust, comprehensive LCI data to support more sustainable airport management and planning.

Scope

Describing the scope and system boundaries of the study ensures that the right unit processes are included within the study. The scope of any study can either focus on a "well to gate analysis" (Shen et al., 2016), which focuses on the environmental impact related to a product system from the extraction of raw materials to the production of a good. Other studies that focused on the construction of airport pavements focused on the environmental impact of the materials used from the extraction of the materials till the construction of the pavement (cradle to gate), excluding the EoL phase of the pavements (Rupcic et al., 2023). Rupcic et al. (2023) argues that there is no harmonisation between different studies because of different goal and scope definitions, making comparison difficult between studies. To ensure flexibility in the developed framework, all the life cycle phases will be included in the framework, which allows for the collection of inventory representative of all life cycles. This research will therefore develop frameworks for each life cycle phase, which can be used in future studies. As a result, this study adopts a cradle-grave approach to the collection of airport inventory.

The geographical and temporal scope of the study is European Airports in the year 2024, meaning that the framework will integrate airport activities related to European Airports in the specified year. This scope will aid with the identification of relevant LCI data requirements required for the development of the framework and airport inventory. Furthermore, it is assumed that the lifetime of the airport is 59 years, based on lifetime data from Andersen & Negendahl (2023).

System Boundaries

This study defines an airport as a complex system requiring various infrastructures to facilitate efficient passenger and cargo departures (Vogel, 2019). Key components include airfields (runways, taxiways, aprons) and passenger terminals (Vogel, 2019). Based on this, the system boundaries of the airport product system can be defined. Guided by the ISO 21931 framework in Figure 2.2, the life cycle phases of an airport are identified to include the following life cycle phases: Product, Construction, Operation and EoL phases of an airport. As a result, this study defines the product system of an airport to include unit processes associated with the identified life cycle phases in Figure 2.2.

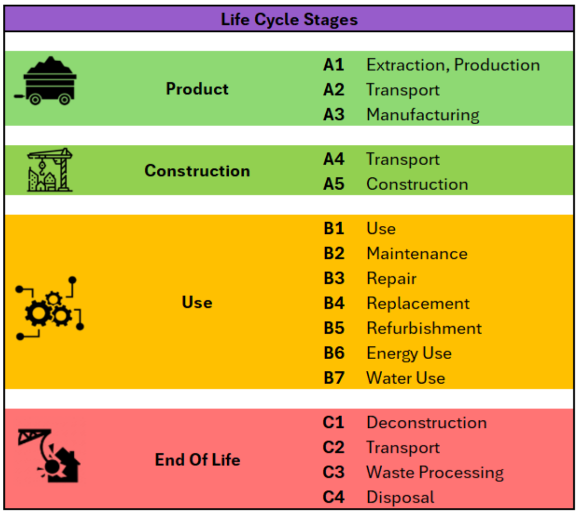

Figure 2.2. Life Cycle of Buildings adapted from (SFTool, n.d.)

However, this study narrows the framework to include unit processes related to the construction, operation and EoL phases of an airport. In this study, unit processes associated with the product phase – such as the mining of natural resources or manufacturing of construction materials – are considered as background processes, which are already accounted for in LCI databases such as Ecoinvent. This means that when the unit processes from the construction, operation and EoL phase of an airport are connected to providers in Ecoinvent (or other LCA databases), the environmental impact of the product stage will also be included in the overall environmental impact result. As a result, the system boundaries of this study include unit processes only related with the construction, operation and EoL phase of airports, which are focuses on in this study.

The life cycle phases considered within the system boundaries of an airport are briefly described below – which are also demonstrated in the system boundary diagram in Figure 2.4.:

- **Construction:** This phase considers the unit processes required to construct all the necessary infrastructure required by an airport, within the temporal scope of the study. This phases also includes the waste treatment of construction waste for example.
- **Operation:** This phase includes unit processes required for sufficient operation of the airport, including unit processes in airport buildings and unit processes on the airfield. This also includes unit processes related to aircraft taxiing on airport premises – while

emissions associated with the LTO cycle are cut-off and not attributed to the airport. Furthermore, this phase also accounts for waste treatment originating from the use of the airport. Lastly, unit processes associated with the maintenance of the airport are considered.

- **EoL:** This phase includes unit processes related to material recovery from the airport, in the event that the airport closes and gets demolished to free up land for other functions.

<u>Multifunctional Processes</u>

Within the airport product system illustrated in Figure 2.3, there are several unit processes that are considered multifunctional, as they either treat waste or generate multiple outputs. For instance, a wastewater treatment plant is multifunctional because it converts wastewater into usable water with economic value. To address this in LCA, allocation methods—such as mass allocation—can be applied to distribute environmental impacts proportionally among outputs, based on principles like mass conservation. Other multifunctional processes commonly found at airports include waste treatment and recycling facilities. It is essential that LCA practitioners account for these processes using appropriate allocation methods to ensure accurate impact assessments. In this study, mass allocation is mainly applied based on the conservation of mass principle, whereby the input into a unit process is equal to the output. This was mainly used for waste treatment plants, with only one identified output, been the treated waste.

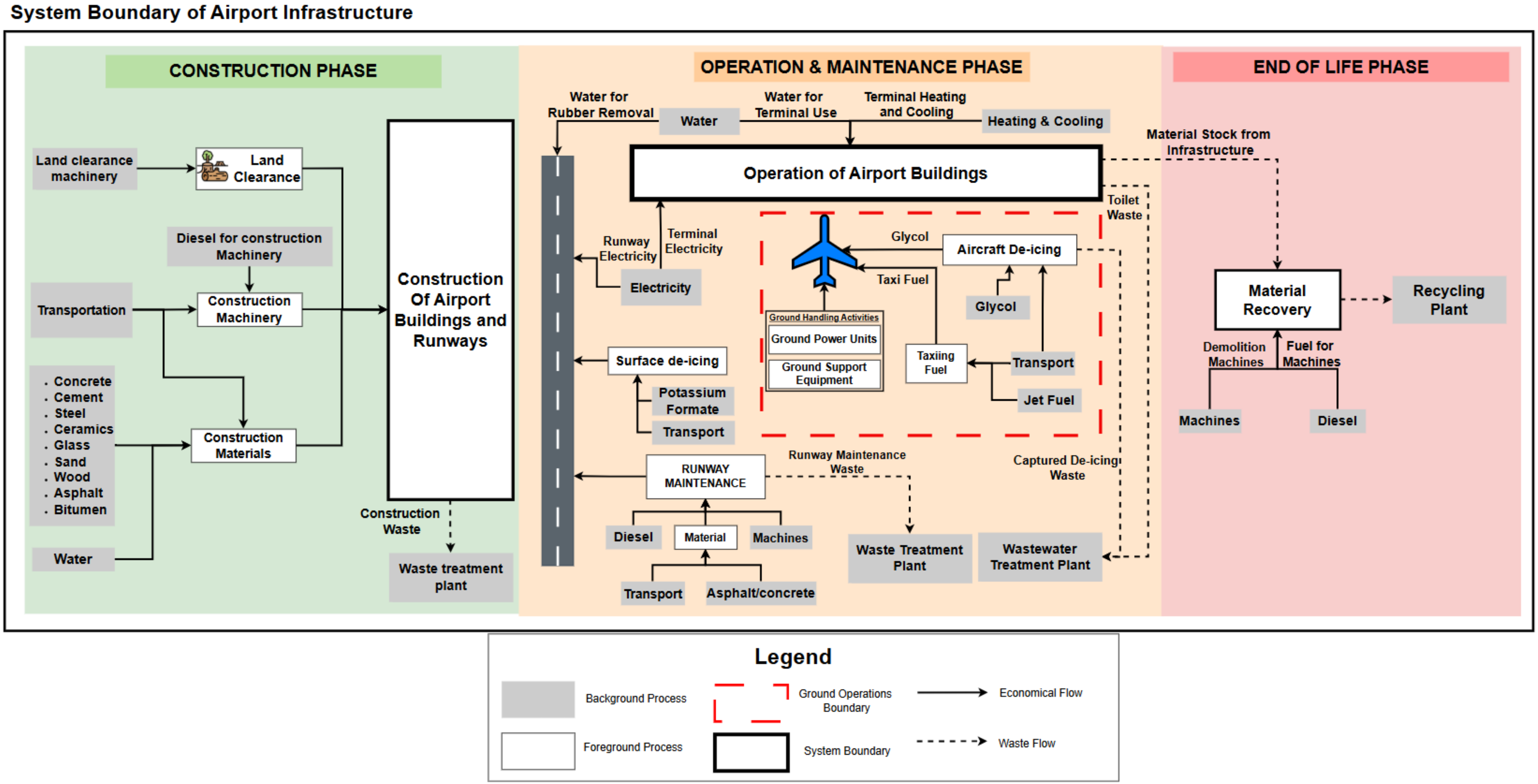

Figure 2.3. System Boundaries of an Airport Including Essential Elements for each Life Cycle Stage

2.2 Identification of Data Requirements

This paper adopts Saavedra-Rubio et al. (2022) definition of LCI data requirements, which are considered as the building blocks of airport inventory, which refer to the inputs and outputs required and generated by an airport during a specific period, within the scope of the product system. Input data requirements into an airport can include the quantity of natural resources, energy or water required by an airport to operate sufficiently, while output data requirements refer to the wastes or by-products generated by the airport. These data points are essential for the development of the framework and the inventory sheets of airports.

The identification of the LCI data requirements was done using scientific papers. First, a search in Google Scholar was done to identify whether there are relevant papers available that can be used to identify LCI data requirements. Using the search term "*LCI data requirements*", led to the identification of a stepwise guide for LCI data collection, which proved useful in defining the data requirements for this study.

The paper by Saavedra-Rubio et al. (2022) was particularly valuable, as it provided insights into various data requirements for several life cycle stages of a general product system. For example, Saavedra-Rubio et al. (2022) paper identifies raw material requirements as a key data requirement for the manufacturing phase of a product system, which was then applied as a relevant data requirement for the construction phase of airports. However, in some instances, Saavedra-Rubio et al. (2022) paper does not provide specific data requirements for the operation of airports. For example, while Saavedra-Rubio et al. (2022) paper suggests that maintenance, emissions and energy demand are important data requirements for the operation of any product system, it does not provide guidance into the unit processes required for the operation of an airport.

To address this limitation, additional scientific papers were searched for on Google Scholar using search terms such as "*Airport Operations*", "*Airport Sustainability*" and "*Environmental Impact of Airports*". These papers were used to identify specific unit processes that are relevant to airport operations and also aided with the identification of LCI data requirements. For instance, Rupcic et al. (2023) highlight the role of Ground Support Equipment (GSE) in airport operations, noting that such equipment consumes both fuel and electricity which contributes to air pollution within airport environments. This example illustrates how, in cases where Saavedra-Rubio et al. (2022) did not provide sufficient detail on LCI data requirements for specific life cycle phases, other scientific sources were employed to bridge the gap. These studies not only identified important unit processes but also outlined their respective inputs (e.g., energy carriers, materials) and outputs (e.g., emissions, waste), which were subsequently treated as relevant LCI data requirements.

Therefore, the identification of LCI data requirements were identified by integrating the general LCI data requirements proposed by Saavedra-Rubio et al. (2022), with additional domain specific data obtained from studies that explicitly focus on airport sustainability and airport environmental impact as shown in Figure 2.4. This approach ensured that the LCI data requirements for each Life Cycle Phase of an airport could be identified and integrated within the framework developed in this thesis.

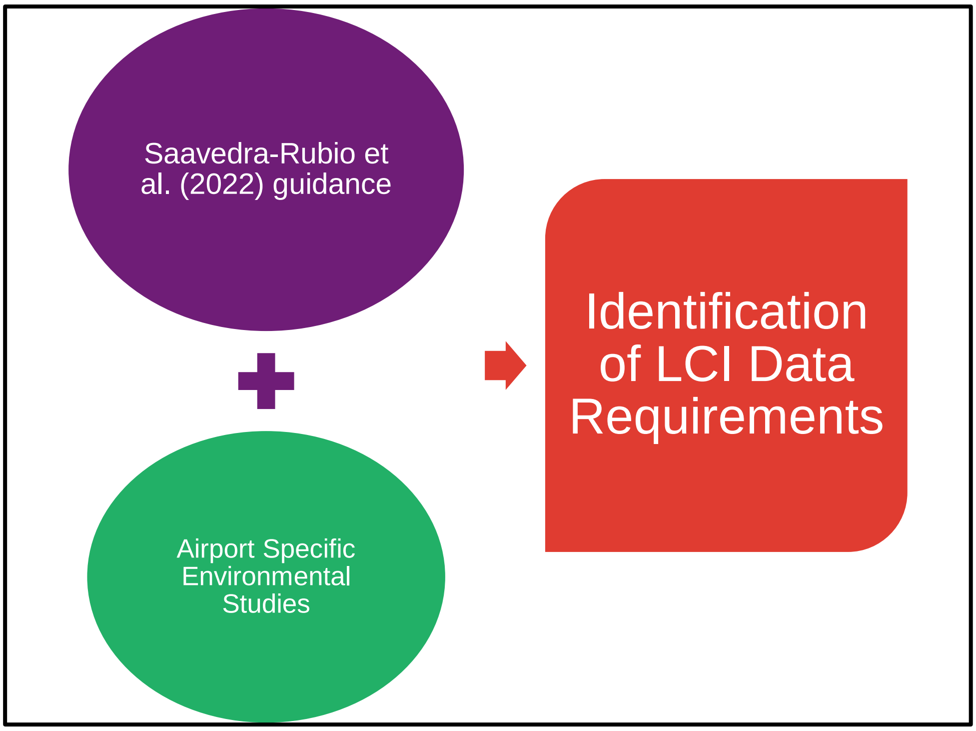

Figure 2.4. Methodology Utilised to Identify LCI Data Requirements for Airports

2.3 LCI Data Collection Methodology

The identification of LCI data requirements was an essential step to the development of a comprehensive framework. In order to address the question on how LCI data can be collected systematically across all life cycle stages of an airport, it is important to first establish which methodologies there are to obtain LCI data that can be used as inventory in future environmental assessments of airports. Therefore, this section aims to describe the procedures taken in this research in identifying potential methodologies that can be taken to collect airport inventory, based on the identified data requirements. To ensure a structured approach, data collection methodologies are categorized according to the three main life cycle stages of airports—construction, operation, and EoL.

Two potential data types have been identified in this research, which are taken into consideration in the development of the framework. According to Saavedra-Rubio et al. (2022), data can be obtained from either primary or secondary sources, whereby primary data can be collected directly from airports. This was done by requesting for data from individuals working in the sustainability office of Royal Schiphol Group. However, due to the lack of primary data, inventory had to be estimated using secondary data sources. As a result, secondary data sources had to be identified to estimate airport LCI data. Identifying the methodologies used for the collection of LCI data influences the development of the framework. The procedure taken to identify data collection methodologies is described below according to the three life cycles defined in the goal and scope of this study.

Construction Inventory Data

Given that there was no primary data available for the construction inventory, secondary data had to be utilised. This research applies methodologies identified in other scientific paper to estimate construction inventory data. Different scientific papers were searched for based on the LCI data requirements identified for airports. For example, the construction of the airport requires data regarding the quantity of materials used for construction. Firstly, scientific papers were searched for that focused on estimating the quantity of materials used for the construction of airports. However, no studies were identified that focused on airport construction. Therefore, scientific papers that focused on estimating material quantities for general infrastructure was utilised in this study to estimate the material quantities required for the construction of airports.

Furthermore, other methodologies were identified in scientific papers to collect construction inventory. For example, it was identified that the energy demand for the construction of an airport can be estimated using the same methodologies utilised in Thonemann et al. (2024) paper. As a result, all the inventory for the construction of an airport is estimated based on methodologies identified in scientific papers. These methodologies were not only used to estimate the construction inventory of Schiphol Airport but also informed how the framework should be developed.

Importantly, the methodologies identified in literature calculates the total construction inventory. This means that the construction inventory had to be scaled down according to the temporal scope of the study. For example, given that the temporal scope of the study is one year of operation, meaning that the total construction inventory had to be scaled to one year of airport operation. This was done by dividing the total construction inventory by the lifetime of the airport.

Operation Inventory Data

The collection of operational inventory data was done utilising various equations identified in scientific papers. The results from the LCI data requirements influenced the identification of potential equations that can be used for the collection of airport inventory. For example, it was identified that electricity needs to be supplied to airports in order to operate efficiently. This is considered as an intermediate inflow, which is the input of electricity into the product system of the airport. Knowing that this is a data requirement (that is the total amount of electricity used by the airport, the electricity demand for each section of the airport), lead to the identification of potential estimation methodologies, which were found in scientific papers.

Google Scholar was utilised to identify potential scientific papers that aided with the collection of airport inventory. The following keywords were utilised: "*Airport Sustainability Assessments*", "*Airport Energy Requirements*" and "*Sustainability of Airport Ground Handling Activities*", which highlighted potential methodologies that can be used to estimate operational inventory. These methodologies were then accounted for in the framework, which can be used in the future for the collection of operational inventories.

The collection of inventory data also meant collecting numerical data that can be used to estimate airport inventory. The numerical data was mainly obtained from secondary data sources, such as airport sustainability reports, which provided the demand for electricity, water and de-icing fluids consumed by the airport, which was utilised for the development of airport operational data. Furthermore, the sustainability reports provided statistical data that had to be combined with other numerical data from the identified literature to estimate the operational inventory of airports. For example, it was found that the energy demand for ground service equipment is given in terms of GWh/flight. The statistics provided the number of flights in one year, which was combined with the data found in literature, which was used to estimate the energy demand for Ground Service Equipment's.

Additionally, airport regulation reports were assessed to obtain an understanding of runway maintenance activities, which ultimately defined the collection procedure of inventory data. For example, (ICAO, 2013) defines the recommended frequency at which airport runways have to be maintained, which influenced the estimation procedure of maintenance inventory.

Lastly, during the time of the study, no study was identified that can be utilised to estimate both the emissions generated from aircraft taxiing at a particular airport. As a result, this research had to rely on different data sources to make an estimation of the total emissions associated with aircraft taxiing. Firstly, FlightRadar24 was utilised to collect data related to the different types of aircrafts present at an airport at a specific period of time, while EUROCONTROL (2024) provided the average taxiing time at the airport in question. Secondly, LRTAP (2019) was used to obtain the emission rates associated with each aircraft type identified from FlightRadar24. Equation (1) below was therefore developed to estimate the emissions associated with taxiing at an airport, using data from the above sources.

$$Total\ Taxi\ Fuel = \sum_{i=1}^{n}(Taxi_{time} \times Rate_i \times Num_i) \qquad (1)$$

Whereby:

- $Taxi_{time}$ is the average taxi time at the airport in question
- $Rate_i$ is the emission rate for each aircraft type (*i*)
- Num_i is the number of aircraft *i*.
- i are the different types of aircraft (for example, B737, B777, A380)

Therefore, the collection of operational data was mainly done using methodologies and data found in both scientific papers and sustainability reports. The methodologies found were both integrated into the framework and utilised to estimate inventory data of Schiphol Airport. However, in some instances, there were no identified methodologies available, such as estimating the emissions from aircraft taxiing. This meant that the study had to develop a methodology to estimate the missing data.

End of Life

In Thonemann et al. (2024) paper, the EoL phase of an airport includes the decommissioning of the airport, which involves the removal of airport infrastructure such as aprons, taxiways and runways. This study considers the removal of all airport infrastructure, which also includes the decommissioning of airport buildings such as terminals. The collection of airport EoL inventory is grounded on several assumptions, which are outlined below. Importantly, the EoL inventory is also scaled to the temporal scope of the study, which is one year of airport operations.

Firstly, it is assumed that there is mass conservation, whereby the input of construction materials to build airport infrastructure is equal to the amount of materials that can be extracted from the airport during the EoL of the airport. It is also assumed that there are no losses of materials from airport infrastructure during the operation of the airport. For example, the quantity of reinforcing steel used to construct the airport is equal to the amount that can be extracted during EoL. It is also assumed that these materials end up in a recycling facility where the materials are recycled for other purposes. Therefore, the airport EoL inventory accounts for all the materials that can be extracted from the airport once the airport operations are terminated, which is assumed to be equal to the quantity of materials used to construct the airport.

Secondly, the EoL inventory considers the energy demand required by the machines used to demolish the airport. Given that this scenario is in the future, it is difficult to estimate what the energy demand will be for machinery in order to deconstruct the airport due to changes in technology. As a result, it is assumed that the energy demand for deconstruction is equal to the energy demand for the construction of the airport. This aided with making an estimation of the potential energy demand that will be required by machines to deconstruct the airport.

2.4 Development of the Framework

To ensure that the identified methodologies can be applied across various airport types, a structured framework has been developed to guide the data collection process for compiling airport inventories. This framework is a key component in addressing the third sub-research question, which focuses on the applicability and transferability of data collection methods across different airport contexts. A framework was chosen because it allows for the systematic organization of methodologies into logical subsections, providing clear guidance for practitioners.

The framework developed in this study is built upon the framework that Saavedra-Rubio et al. (2022) developed for the collection of inventory data. Saavedra-Rubio et al. (2022) developed a decision diagram to guide LCI data collection for any product system. The design of the decision diagram was adopted for the design of the framework in this study, since the design takes into consideration all the stages required to perform a Life Cycle Assessment. Furthermore, an Excel template was designed in which practitioners can store airport inventory in a transparent manner. This will be described below:

Framework development

The development of the framework was strategically done by following the methodologies described in the previous sub-sections. Though the framework was mainly inspired by Saavedra-Rubio et al. (2022) diagram, modifications had to be done. Most modifications had to occur in the first stages of the LCA framework (Goal & Scope and LCI Analysis stages), given that this study mainly focuses on collection of LCI data. No modifications were done to the LCIA and interpretation stages, since this is out of the scope of the study.

The framework was developed in a methodological manner, which can help guide LCA practitioners in the collection of inventory data. Taking this into mind, it was decided that the first step in the framework should focus on defining the goal and scope of the study, which ultimately defines the entire collection of airport inventory. Following this, the inventory framework was developed.

Given the complexity of airports and all the life cycle phases of an airport, multiple frameworks had to be developed. A general framework was developed, which guides the practitioner from the definition of goal and scope to the collection of airport inventory. However, due to all of the life cycle phases of an airport, the inventory framework was divided into three sub-frameworks, which focus on each life cycle phase of the airport (one on construction, operation and EoL). Each sub-framework was developed based on the identified data requirements and identified estimation methods that were all obtained from scientific papers.

Each sub-framework was developed to guide the practitioner, by first recommending the practitioner to identify whether there is primary data available from airports which can be used as inventory. If not, then it is taken into mind that the practitioner can use secondary data to estimate the inventory based on the identified methodologies from literature. At the end, all the data is stored within the developed excel template, whereby the practitioner should describe the data quality of the inventory using the pedigree matrix.

Therefore, the framework is developed by compiling the results of the LCI data requirements with the identified methodologies to estimate inventory from secondary data, which were all obtained from scientific papers.

Excel Template development

In Saavedra-Rubio et al. (2022) study, an excel template was developed for the storage of inventory data. However, this template had to be modified for the storage of airport data. The Excel template was structured into the three different life cycle phases of an airport (construction, operation and EoL), in which data for each unit process can be stored. For each of the different worksheets, different tables were created in which inventory data can be stored. For example, the LCI data regarding the construction of terminals is stored in one table, while the construction of runways is stored in another table, all within the construction worksheet.

Furthermore, the Excel template is developed in such a way that inventory data can be stored transparently. Firstly, the pedigree matrix was integrated into each table, whereby the LCA practitioner needs to evaluate the data quality based on the Reliability, Completeness, Temporal Correlation, Geographical Correlation, and Technological Correlation of the data. Each is rated on a scale from 1 (highest quality) to 5 (lowest quality). The pedigree matrix allows the LCA practitioner to describe the data quality based on the scores, which enables future users of the data to be aware about the different uncertainties associated with the stored data. Secondly, it was taken into consideration that the collected data needs to be referenced. As a result, the development of the template also took into consideration that data has to be referenced.

Therefore, the Excel Template developed in this study (see Supplementary File S.1 or screenshots in Appendix D) was mainly inspired by the template developed by Saavedra-Rubio et al. (2022), but had to be modified for airports. The structure of the template was also changed to suit the storage of inventory according to the life cycle phases of airports.

2.5 Application of the Framework

To demonstrate the application of the framework, inventory data from Schiphol Airport will be collected according to the developed framework and stored transparently within the Excel Template developed in this study. Therefore, this study will deliver a full LCI representing the operation of the airport in 2024, enabling impact assessments to be done for the airport, allowing the airport to identify potential areas that need interventions to reduce their impact on the environment.

As demonstrated in the developed framework in the results section, practitioners should first check whether primary data is available that can be used to quantity the identified data requirements. In the same way, the sustainability office at Royal Schiphol Group was contacted requesting primary data. However, no data was provided within the time period of this research. As a result, inventory data had to be estimated based on secondary sources and using the methodologies identified in literature. The identified methodologies are considered as results in this research, which will be explained in the results chapter.

The secondary data sources that were used to estimate the inventory would be briefly described in this section. Given the identified LCI data requirements (which are summarised in the next chapter), and the identified estimation methodologies, the following data was used to estimate the inventory for Schiphol Airport.

Construction Inventory for Schiphol Airport

Estimating the construction inventory was mainly done using the BAG3D dataset which was inputted into the ArcGIS Pro Software. The buildings within the boundaries of the airport were selected from the BAG3D dataset, in order to determine the useable floor area ($UFA_{building}$) for each building at Schiphol Airport. The $UFA_{building}$ was required order to estimate the material quantities for the construction of the airport based on material intensity coefficients found in Sprecher et al. (2022) paper. However, this data is limited to airport buildings and not to surfaces.

To address this limitation, other methodologies to estimate the material quantity for airport pavements had to be identified in literature. The surface area of the pavements was obtained from ArcGIS Pro, using satellite imagery which is explained in the flow chart in Appendix C. This had to be done since no data was found regarding the surface area of Schiphol's runways and taxiways. Further literature was required to identify what the potential thicknesses of the sublayers are, which was identified to also be an important variable in estimating material quantity for all sublayers of the surfaces.

The same methodology shown in Appendix C was utilised to estimate the quantity of paint used to mark the runways, assuming that the thickness of the markings is 380 µm (ICAO, 2015). Using the Buitenveldertbaan runway as a sample, the total painted area of the Buitenveldertbaan runway was estimated, by analysing satellite imagery using ArcGIS Pro Software. From the satellite images, polygon attributes were created by tracing the markings on the runway, which made it possible for ArcGIS Pro Software to estimate the total area painted on the runway. Figure 2.5 below shows an example of the runway markings on Buitenveldertbaan runway that were analysed. Based on ArcGIS Pro Software, the total marked area of the runway could be estimated. Using the assumed thickness of the paint markings, the volume of paint required to paint the markings on the selected runway was calculated, by multiplying the total area of the markings by the thickness. Lastly, the estimated volume of paint was divided by the total area of the Buitenveldertbaan runway to obtain the paint intensity per square meter of the runway, which can be used to estimate the total amount of paint required for all the runways at the airport.

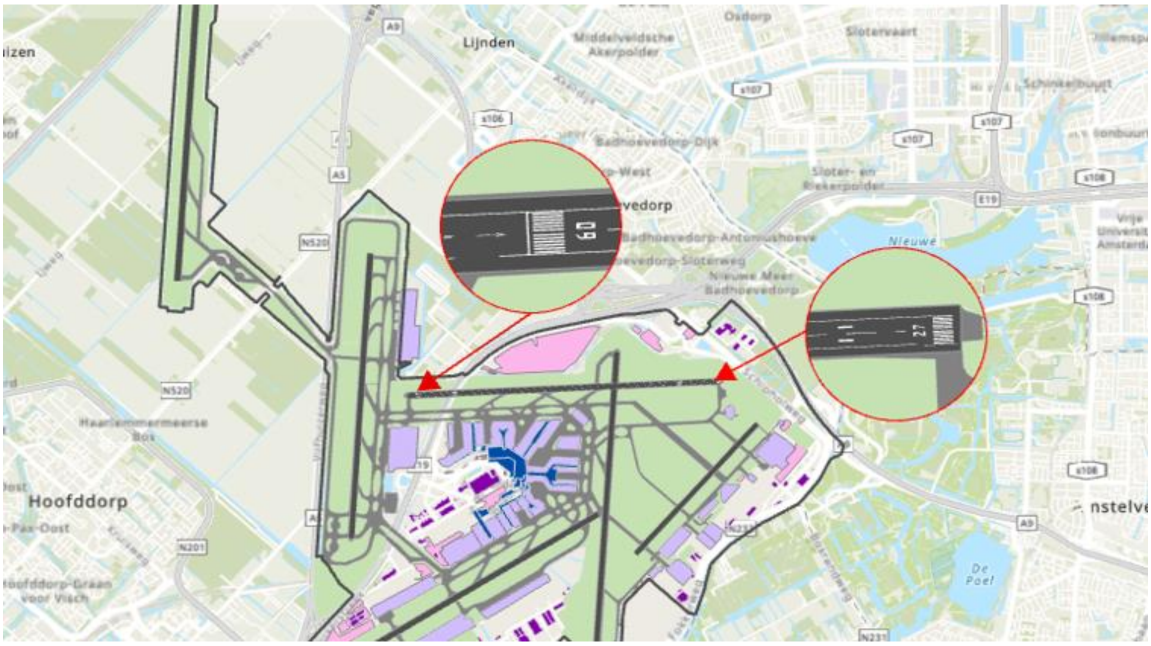

Figure 2.5. Illustration of Some of the Markings Identified in ArcGIS Pro used to Estimate Paint Intensity of Runways at Schiphol Airport

Lastly, data regarding the energy demand for construction machinery was estimated using the methodologies identified in Thonemann et al. (2024) paper, which was scaled to Schiphol Airport according to the area identified from ArcGIS Pro software.

Operational Inventory of Schiphol Airport

The operational inventory of Schiphol Airport was mainly collected from scientific papers and sustainability reports from Schiphol Airport. These two sources mainly provided the necessary data to fulfil the data requirements to estimate operational inventory for Schiphol Airport. However, to estimate the total emissions originating from aircraft taxiing at the airport, data had to be collected from FlightRadar24 and from EUROCONTROL. This data was then inputted into Equation 1, which provided the total emissions associated with the use of the airport.

Therefore, most of the operational inventory for Schiphol Airport was estimated based on scientific papers that focused on some aspects of the airport, which was then compiled into the inventory worksheet to store the data transparently.

3 Framework Results

This chapter aims to present the results that have been obtained from the methodology described above. The chapter starts by summarizing the identified LCI data requirements, followed by the identified methodologies which were all obtained from scientific papers. This was then compiled into the frameworks developed in the study, which will be illustrated at the end of this chapter.

3.1 Data Requirements Results

The LCI data requirements for this study were mainly obtained from Saavedra-Rubio et al. (2022), who also defined data requirements as the building blocks of LCI inventories, considering both the input and output required and generated by a product system. This section will outline the identified data requirements for each life cycle phase of airports identified from literature and summarised in Figure 3.1.

Airport Construction

Saavedra-Rubio et al. (2022) particularly distinguishes between LCI data requirements for raw material extraction and the manufacturing/production stage. As explained in the goal and scope of this study, the raw material extraction stage is considered as a background stage. The product stage considers the manufacturing of the final product, which in this study is the production of an airport that can be used. According to Saavedra-Rubio et al. (2022), the input data requirements for this stage involves material and energy inputs required to produce the product, while outputs are considered as the wastes and emissions generated from producing the product.

The construction phase of an airport is argued to encompass the development of key infrastructure components such as runways, taxiways, and terminal buildings (IATA, 2024), which is typically characterised by substantial material requirements, high energy and water consumption, and intensive use of construction machinery (Li, 2006). Consequently, the construction inventory focuses on key data requirements, including material quantities, energy use by construction equipment, water demand and land demand (Douglas & Lawson, 2003; Šelih & Sousa, 2007). Through the guidance provided by Saavedra-Rubio et al. (2022) and the identified characteristics of airport construction from literature, the data requirements were identified, which are divided into intermediate inputs and outputs and environmental extensions as summarised in Table 3.1.

Table 3.1. Identified LCI data requirements acquired from scientific papers

Intermediate Input	Intermediate Output
Construction Materials	Construction Material Waste
Origin of Materials*	
Material Efficiencies	
Type of Construction Machinery	
Energy Demand for Construction Machinery	
Water demand for Construction	
Environmental Extension Input	**Environmental Extension Output**
	Construction Machinery Emissions
	Land Transformation

** The origin of the materials is crucial as it determines which background processes are required and also influences the transportation distances to the airport, which are crucial to consider in airport inventory.*

Airport Operation

The operation inventory can be divided into three categories: terminal inventory, airfield inventory and maintenance inventory. All these categories have their own requirements, which were identified from literature. In general, airports are known to be major consumers of energy (Yang et al., 2023) and water (Carvalho et al., 2013). In terms of terminal operations, it was identified that terminals require electricity, thermal energy and water. As a result, the intermediate input for airport buildings includes the energy demand and the water required for sanitary purposes. The intermediate output from airport buildings includes the toilet wastewater, which need to be treated at a wastewater treatment plant.

Regarding airfield operations, it was identified that airports rely heavily on GSEs which include the use of airfield vehicles, GPUs/APUs, tractors and belt loaders (Bahman et al., 2024; Facanha & Horvath, 2007; Greer et al., 2020; Rupcic et al., 2023). All this equipment is required to service an aircraft before it departs from the airport. The use of this equipment is also characterized by the demand for fuel and electricity, which are identified as an essential input for the operation of airports. Therefore, fuel and electricity are identified as intermediate input requirements for the use of GSEs. The environmental extensions for the use of GSEs (including the use of GPUs or APUs) include the associated emissions, which have been identified to be carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx), which comes from the combustion of fuels (Padhra, 2018).

Apart from the use of GSEs at airports, aircraft require Jet A1 fuel to be supplied by the airport in order to taxi from the gate to the respective runways. The supply of Jet A1 fuel to the aircraft at airport gates is also considered as an intermediate input. The combustion process of Jet A1 fuel during the taxiing phase of aircrafts leads to various types of emissions such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and particulate matter (PM) (LRTAP, 2019). As a result, the fuel and emissions originating from aircraft taxiing are considered as LCI data requirements which are essential to develop the inventory tables of airports.

Furthermore, in colder climates, winter operations necessitate de-icing procedures to ensure aviation safety (Chen et al., 2020). These de-icing procedures involve spraying de-icing fluids onto aircrafts and airport surfaces, to remove ice. Given its importance, this study identifies the supply of de-icing fluids to the airport as an intermediate input, while the quantity of de-icing fluids captured by the airport as intermediate outputs.

Lastly, the maintenance inventory addresses the wear and tear of airport infrastructure. Repeated aircraft landings and take-offs exert stress on pavements such as runways, necessitating regular maintenance (de Souza & de Almeida Filho, 2020). It was identified that these activities consume natural resources and generate waste materials (Magnoni et al., 2016), meaning that the maintenance of runways requires the intermediate input of natural resources, and generate intermediate outputs such as material wastes. Moreover, it was identified that runway surfaces usually accumulate rubber waste from the landing and take-offs of aircraft (Schiphol, 2018), which has to be removed periodically to ensure runway safety. The removal of the rubber from runways comes with various intermediate inputs such as rubber removal machines (either through mechanical removal, shot blasting, or Ultra High-Pressure Water Blasting (UHPWB)), energy requirements for the use of the machines and the water required to remove rubber. The intermediate output is the removed rubber waste from the runways that needs to be treated at a waste treatment plant.

Therefore, there are a lot of intermediate inputs and outputs that are considered as key data requirements for the development of the airport operational inventory tables. The inventory tables also account for the environmental extensions required or generated by the airport during its operation. Table 3.2 summarises the identified key data requirements, which were obtained from different scientific papers.

Table 3.2. Identified LCI data requirements for airport operations based on scientific papers

Intermediate Input	Intermediate Output
Energy (Electricity & Thermal)	Wastewater from Terminals
Fuel	De-icing Fluids Waste
Water	Rubber Waste
GSE Equipment's	Maintenance Waste
De-icing Fluids	
Maintenance Materials	
Environmental Extension Input	**Environmental Extension Output**
	GSE Emissions
	Taxiing Emissions

Airport EoL

Given the assumption that airports are decommissioned after the assumed lifetime, different data requirements are considered. In Thonemann et al. (2024) paper, the EoL of an airport involves the removal of materials from aprons, taxiways and runways, and then taking concrete material to the landfill. In order to remove these materials, demolition machines are required which require fuel. Therefore, it is identified that the intermediate input for this phase involves the supply of the machines and the supply of the fuel for the machines. The intermediate output considers the quantity of materials removed from the airport, while the environmental extension output considers the emissions originating from the use of machines. These requirements are summarised in Table 3.3.

Table 3.3. LCI data requirements regarding the end-of-life phase of airports

Intermediate Input	Intermediate Output
Supply of demolition machines	Removed material from airport
Fuel for machines	
Environmental Extension Input	**Environmental Extension Output**
	GSE Emissions
	Taxiing Emissions

Transverse Activities

It was identified from Saavedra-Rubio et al. (2022) paper that the life cycle of any product system also includes transverse activities, which come with specific LCI data requirements. Saavedra-Rubio et al. (2022) suggests that the transverse activities include the type of transport used to transport goods (construction materials, fuel, de-icing fluids) to the airport and waste to treatment plants. The type of transports can include the use of trains, tracks or cars for example. Additionally, the type of fuel used for the transportation needs to be accounted for, alongside the distance travelled in delivering the goods to the respective unit process. Other identified requirements are the suppliers for energy, water and fuel, which ultimately influence impact assessments, through the use of data from Ecoinvent. Based on the inspiration from Saavedra-Rubio et al. (2022) paper, the data requirements for transverse activities were identified, which are summarised in Table 3.4. No environmental extensions were identified, since they are already accounted for in Ecoinvent Inventory tables.

Table 3.4. LCI data requirements for transverse activities related to the airport product system

Intermediate Input	**Intermediate Output**
Transportation Mode (Train, Truck, Car)	
Transportation Distance	
Transportation Fuel Type	
Supplier of Fuel, Water and Energy to Airport	
Energy source (Wind, National Grid, Solar Panels)	
Environmental Extension Input	**Environmental Extension Output**

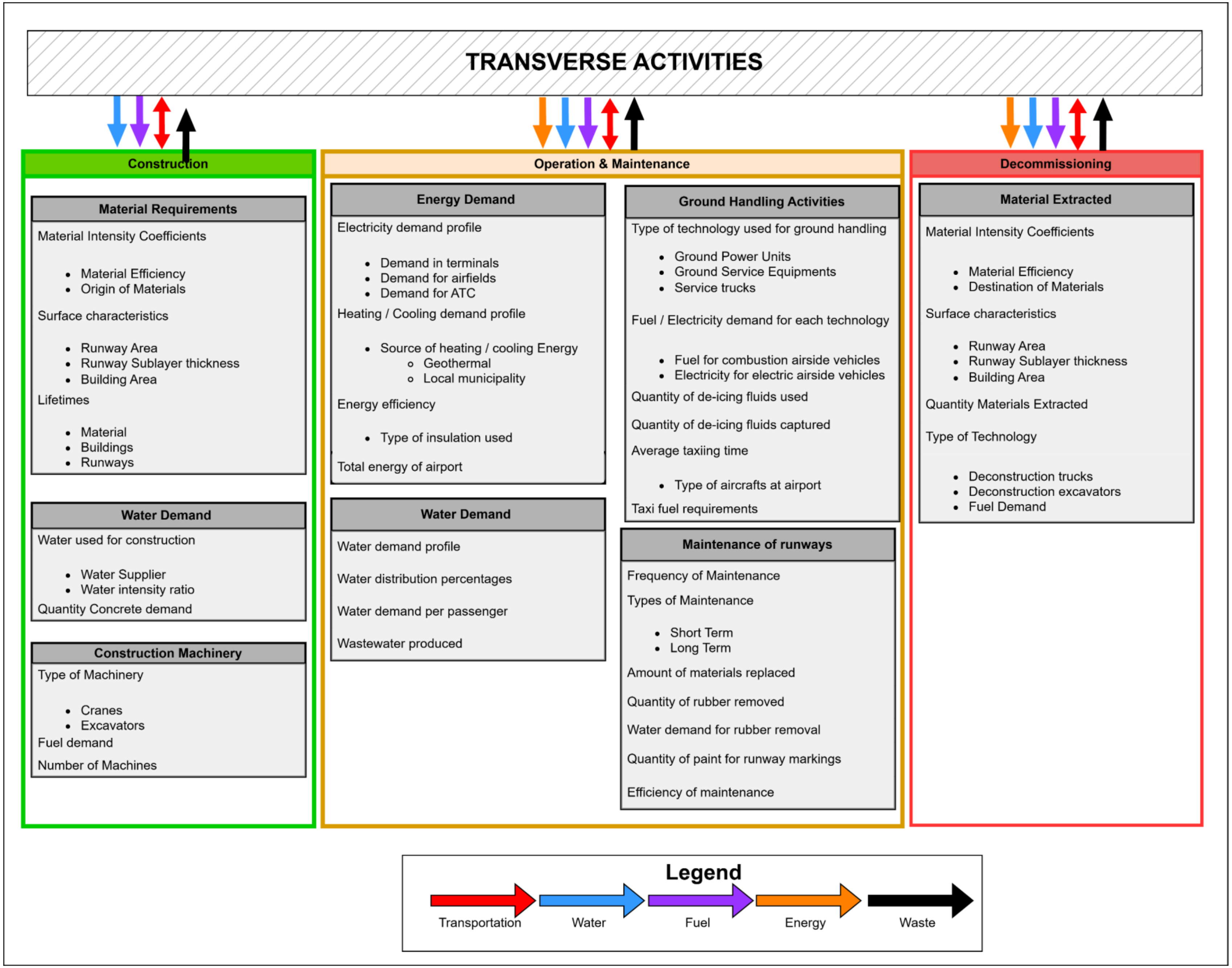

Figure 3.1*. Illustration of the Data Requirements for the Development of Airport Inventory Inclusive with Transverse Activities Across Each Life Cycle Stage*

3.2 Identified Methodologies

Using scientific papers, several methodologies were identified which can be used in estimating inventory data, in the event that primary data is not available. This subsection aims to present the identified methodologies from literature, which are then implemented into the frameworks developed during this research.

Construction Inventory Methodologies

The methodologies identified to estimate construction inventory are dependent on the identified LCI data requirements, which regards the quantity of materials used to construct the airport, energy and water for construction, and construction waste.

Estimating Material Quantities

Literature identifies that there are available methodologies that can be utilised to estimate the quantity of materials used for the construction of airports. It was identified that a bottom-up approach is well-suited for quantifying the potential material requirements for the construction of infrastructure such as airports (Mohammadiziazi & Bilec, 2023). The quantity of materials required to construct airport buildings —such as terminals, offices, and hangars—can be approximated using material intensity coefficients (Fishman et al., 2024; Mohammadiziazi & Bilec, 2023). Fishman et al. (2024) methodology requires two key inputs: material intensity values specific to the different airport buildings denoted as $MI_{building}$ and the useable floor area of the different buildings denoted as $UFA_{building}$. The material intensity values can be obtained from research papers looking at material stocks of buildings, while the $UFA_{building}$ can be obtained from spatial datasets such as BAG3D (specific to the Netherlands). Equation 2 below was identified as a potential way to quantify the material requirements for the construction of the airport, which was obtained from Fishman et al. (2024) paper. Figure A.1 illustrates the mechanisms behind Fishman et al. (2024) methodology.

$$Q_m = MI_{building} \times UFA_{building} \quad (2)$$

However, Fishman et al. (2024) methodology is specific to building infrastructure, which cannot be used to estimate material requirements for airport surfaces such as runways and taxiways. Estimating the material intensity of runways can be done using Grossegger. (2022) methodology, which originally focuses on road infrastructure. This approach calculates the material stock of each pavement sublayer (S_m) based on its thickness (H_i), surface area (A_s)—obtainable from spatial datasets like TOP10NL in the Dutch context—and material density (ρ_i), as formalised in Equation 3. Material specifications for each layer can be derived from literature or airport documentation, depending on data availability. The procedure is illustrated in Figure A.2.

$$S_m = \sum_{i=1}^{n} A_s H_i \rho_i \quad (3)$$

Therefore, this study identifies that both Equation 2 and 3 are potential ways to estimate the total quantity of materials required for the construction of the airport.

Energy Demand for Construction Machinery

One method identified in the literature for estimating the energy demand of construction machinery at airports—expressed as diesel consumption—is presented by Thonemann et al. (2024). In Thonemann et al. (2024) study, the energy demand for the construction of airport surfaces at RTHA was approximated by scaling Ecoinvent data from Zurich Airport based on the surface area of the surfaces (aprons, taxiways and runways). This is illustrated in Figure A.3, which utilises Equation 4. As a result, Equation 4 is adopted into the framework to estimate the potential amount of energy needed by construction machinery.

$$Fuel_{constuction,\ x} = \left(\frac{Fuel_{constuction,\ RTHA}}{A_{s,\ RTHA}}\right) \times A_{s,x} \tag{4}$$

Whereby ($Fuel_{constuction,\ x}$) represents the estimated fuel required to construct a given pavement at a given airport, while ($Fuel_{constuction,\ RTHA}$) is the fuel required to construct a given pavement at RTHA airport as reported by Thonemann et al. (2024), and ($Area_{s,x}$) is the pavement surface area of the airport in question.

Water Demand for Construction

It was identified from Heravi & Abdolvand (2019) that the direct water demand for construction can be estimated using a water intensity factor for concrete production. In their study, a water intensity ratio of 0.41 was used, indicating that 0.41 m³ of water is needed per 1 m³ of concrete. This is equivalent to 0.171 kg of water for 1kg of concrete. This relationship forms the basis of the equation presented below.

$$direct\ water\ demand = 0.171C_T \tag{5}$$

Whereby (C_T) is the amount of concrete needed for the construction of the airport.

Operational Inventory Methodologies

There were a multitude of methodologies and results found from scientific papers that were integrated into the framework developed below. This subsection aims to highlight the results obtained from scientific papers which were then integrated into the framework.

Airport Energy Consumption

Airport energy consumption can be categorised into two categories: Electricity use, and Thermal energy used for terminal heating and cooling.

It was identified from scientific papers that airport electricity use can be categorised into terminal operations, airfield lighting, radio navigation, firefighting facilities, parking, and other support functions (Uysal & Sogut, 2017), with the respective percentages summarised in Table 3.5. Terminal operations can be further disaggregated into energy use by ICT systems, external companies, lighting, and HVAC systems, with their respective shares outlined in Table 3.6. As a result, it was identified that the total electricity consumed by an airport can be partitioned into different sections of the airport based on the results in Table 3.5 and Table 3.6. Based on these values, Equation 6 was formulated in order to distribute the total electricity demand of the airport accordingly. The values in Table 3.5 and Table 3.6 are therefore considered allocation values ($\%E_i$) that can be multiplied by the total electricity demand of the airport (E_{total}), which results in the distributed electricity demand of the airport.

$$E_i = \%E_i \times E_{total} \tag{6}$$

Table 3.5. Breakdown of energy consumption by airport subsystems, as reported by Uysal & Sogut (2017)

Airport Energy Requirements	**Energy Distribution Percentage**
Terminals	77%
Airfield Lighting	7%
Radio Navigation	5%
Firefighting	1%
Parking	2%
Other	10%

Table 3.6. Breakdown of energy consumption in airport terminals as reported by Uysal & Sogut (2017)

Terminal Energy Requirements	**Energy Distribution Percentage**
Terminal ICT	18%
External Companies	12%
Terminal Lighting	20%
Terminal HVAC	25%

Airports also require thermal energy to either cool or heat the buildings to ensure comfort. The heating and cooling demand for airport buildings such as terminals is usually given in terms of number of passengers. For instance, Pabsch (2025) estimated annual heating and cooling demands for six European airports. At Schiphol Airport, the respective demands were 37.1 GWh and 13.6 GWh for 60 million passengers in 2024—equivalent to approximately 0.59 kWh/passenger for heating and 0.22 kWh/passenger for cooling. Given this values from Pabsch (2025), the thermal energy demand for airports can be estimated.

<u>Water Demand</u>

Based on literature, it was identified that airports consume water, which should also be included within airport inventory tables, to account for the water footprint associated with the airport. In order to do so, it was identified that airport water consumption can be divided into the following categories: irrigation, fire control systems, cooling systems, toilet flushing and other unidentified uses (Vurmaz & Boyacioglu, 2018). Vurmaz & Boyacioglu (2018) identified the exact percentage distributions for the above categories, based on a Turkish Airport, which are summarised in Table 3.7 below. Consequently, the percentages summarized in Table 3.7 can be used to allocate the total water demand of the airport across various usage categories, should the practitioner wish to disaggregate the water demand inventory by use.

Table 3.7. Water demand distribution percentages associated with airports found in Vurmaz & Boyacioglu (2018)

Terminal Energy Requirements	**Energy Distribution Percentage**
Irrigation	23%
Fire control systems	7%
Cooling Towers	26%
Toilet flushing	20%
Other uses	24%

Ground Handling of Aircraft

According to Greer et al.(2021), ground handling activities significantly contribute to the environmental impact associated with airports. These activities include the use of various types of technologies, such as the use of GSEs (pushback tractors, fuel and catering trucks, as well as GPUs and APUs). This section will highlight some of the identified methodologies that were implemented into the framework in order to develop operational inventory of airports.

Energy Demand for ground handling vehicles

It is identified from scientific papers that the use of ground handling vehicles, such as baggage loaders, pushback tractors or food trucks (Alruwaili & Cipcigan, 2022), typically demand energy, either in the form of fuel or electricity, dependent on the propulsion system integrated in the vehicle (fuel driven engines or electric engines). Pabsch (2025) study was identified to provide the average energy required to service aircrafts at an airport, denoted as e_{GSE}. For example, Pabsch (2025) found that the use of ground handling vehicles in Schiphol will require 17.1 GWh per year for all flights from Schiphol Airport. This was estimated to be equivalent to 37.2 kWh per flight, given that there were 460,000 flights at Schiphol Airport (Pabsch, 2025). Similarly, the study pointed out Oslo airport required 7.9GWh of energy to service 211,600 flights. As a result, Pabsch (2025) study was identified to provide valuable insight into how to estimate energy demand for GSE at a given period, which can be calculated using Equation 7, which requires the total number of flights in a given year, which is denoted as $N_{flights}$.

$$E_{GSE} = e_{GSE} \times N_{flights} \tag{7}$$

Furthermore, it was identified from literature that the servicing of aircrafts requires the use of APUs and GPUs, which supply electricity to onboard systems such as avionics, lighting, and air conditioning (Greer et al., 2021). According to Greer et al. (2021), the electrical energy demand per aircraft varies by wingspan category. The study distinguishes between two types of ground power sources—APUs and GPUs—which differ significantly in their emissions profiles. The total energy and fuel demand for either GPU or APU use can be approximated using Equation 8. This equation incorporates the energy demand per wingspan category (D_w), the number of aircraft in each category ($N_{flight,\ cat}$), and the number of gates equipped with the respective GPU technology (G_{ts}), as illustrated in Figure B.8. Furthermore, Padhra (2018) provides emission index values for the use of APUs and GPUs. These indices quantify emissions per kilogram of fuel burned. Based on the results obtained from the literature, it is possible to estimate the intermediate inputs using the data from Greer et al. (2021) and the environmental extensions based on the data from Padhra (2018).

$$E_{GPU} = \sum D_w \times N_{flight,\ cat} \times G_{ts} \tag{8}$$

Maintenance

Another aspect that needs to be estimated is the maintenance inventory. Through literature review, there have been different maintenance activities identified related to the maintenance of runways. Periodic surface maintenance includes the renewal of the top layers of pavements, to the remarking of runway markings and the removal of rubber deposits from the top layer (SKYbrary, 2022). All these maintenance activities happen in different frequencies, which influences inventory data that is collected.

The total quantity of material removed from the top layers of airport runways can be estimated based on the quantity of materials used to construct the top layers and the maintenance frequency. For example, at Schiphol airport, it was identified that the top layers are replaced every seven years (Schiphol, 2024). Accordingly, the average annual quantity of material replaced is calculated as one-seventh of the total material replaced over this cycle. This is expressed using Equation 9 which incorporates the material intensity of either asphalt or concrete (M_i), runway area (A_s), and replacement frequency (f_{LM}).

$$Total\ Material\ Replacement = \frac{M_i \times A_s}{f_{LM}} \tag{9}$$

Additionally, the use of runways usually leads to the accumulation of rubber due to the landing and take-off cycles of aircraft (Schiphol, 2018), which reduces runway safety. As a result, the rubber accumulation has to be removed periodically by the airport. It was identified that the quantity of rubber removed annually by airports can be collected directly from airport sustainability reports or other secondary data sources, which can be put into airport inventory tables. It was also identified that knowing the rubber accumulation per square meter of runway (R_i) and the total area of all runways (A_s) of the airport is useful in knowing the total rubber removed from the runway, using Equation 10.

$$Total\ Rubber\ Removed = R_i \times A_s \tag{10}$$

Importantly, from literature, various technologies were identified that an airport can use to remove the accumulated rubber from all runways. According to ICAO (2016), common technologies used for the removal of rubber include mechanical removal, shot blasting, and UHPWB. The use of UHPWB requires water which was also identified as an LCI data requirement. It was identified from ICAO (2016) that requires 2,700L of water to clean 3,700 m² of runway, equivalent to 0.73 L/m². As a result, the total water demand for the removal or rubber could be estimated using the value from ICAO (2016), the frequency of rubber removal (f_{RR}) and the total area all runways (A_s) using Equation 11.

$$Maintenance\ Water = \frac{W_i \times A_s}{f_{RR}} \tag{11}$$

3.3 Developed Framework for the development of airport Inventory

Building on the identified methodologies and data requirements, a structured framework has been developed to support LCA practitioners in compiling airport-specific inventories. The framework is accompanied with an Excel Template (see Supplementary File S.1), which can be used to store inventory data transparently. The framework is organized into a series of diagrams, each representing a specific data collection methodology tailored to various components of airport infrastructure. The major framework developed in this study (known as the general framework) contains references to other smaller frameworks developed in this study, which focus on the different life cycle phases of airports.

The general framework presented in Figure 3.2 is adapted from the work of Saavedra-Rubio et al. (2022), who developed a stepwise approach to guide LCA practitioners in compiling LCI. While the original framework was designed for general application, it has been tailored here to address the specific requirements of airport systems.

The general framework in Figure 3.2 illustrates that the first step required in the development of LCIs is the definition of the goal and scope of the study. The practitioner must clearly establish the temporal and geographical scope of the study. Depending on the study's objective, this may involve selecting a cradle-to-grave approach (covering construction through EoL), cradle-to-gate (up to the start of operations), or gate-to-grave (operations through EoL). Having a well-defined goal and scope enables the practitioner to identify the relevant data requirements for the study and also guides the practitioner on how the Excel Template should be modified. For example, if the practitioner is only conducting a cradle-to-gate study, the data requirements will be limited to the construction phase of the airport. As a result, the Operational and End-of-Life (EoL) worksheets in the Excel Template are not required.

Once the goal and scope of the study is defined and the LCI Excel Template is modified according to the goal and scope of the study, the framework recommends the practitioner to proceed to the collection of LCI data. This first starts by identifying potential methodologies to collect LCI data from airports (either through primary or secondary data), which will guide the collection of LCI data.

For the collection of inventory data, the general framework refers the practitioner to different sub-frameworks, which focus on the different life cycle stages of the airport. It is also here where the goal and scope of the study influences which sub-frameworks are relevant to the practitioner. For example, if the practitioner focuses on the cradle-to-gate of an airport, then the construction framework is the only relevant sub-framework for the practitioner. At the end of the collection phase, the general framework advice the practitioner to describe the data quality using the pedigree matrix and store it within the modified Excel Template, before proceeding to the LCIA and interpretation phase of their study.

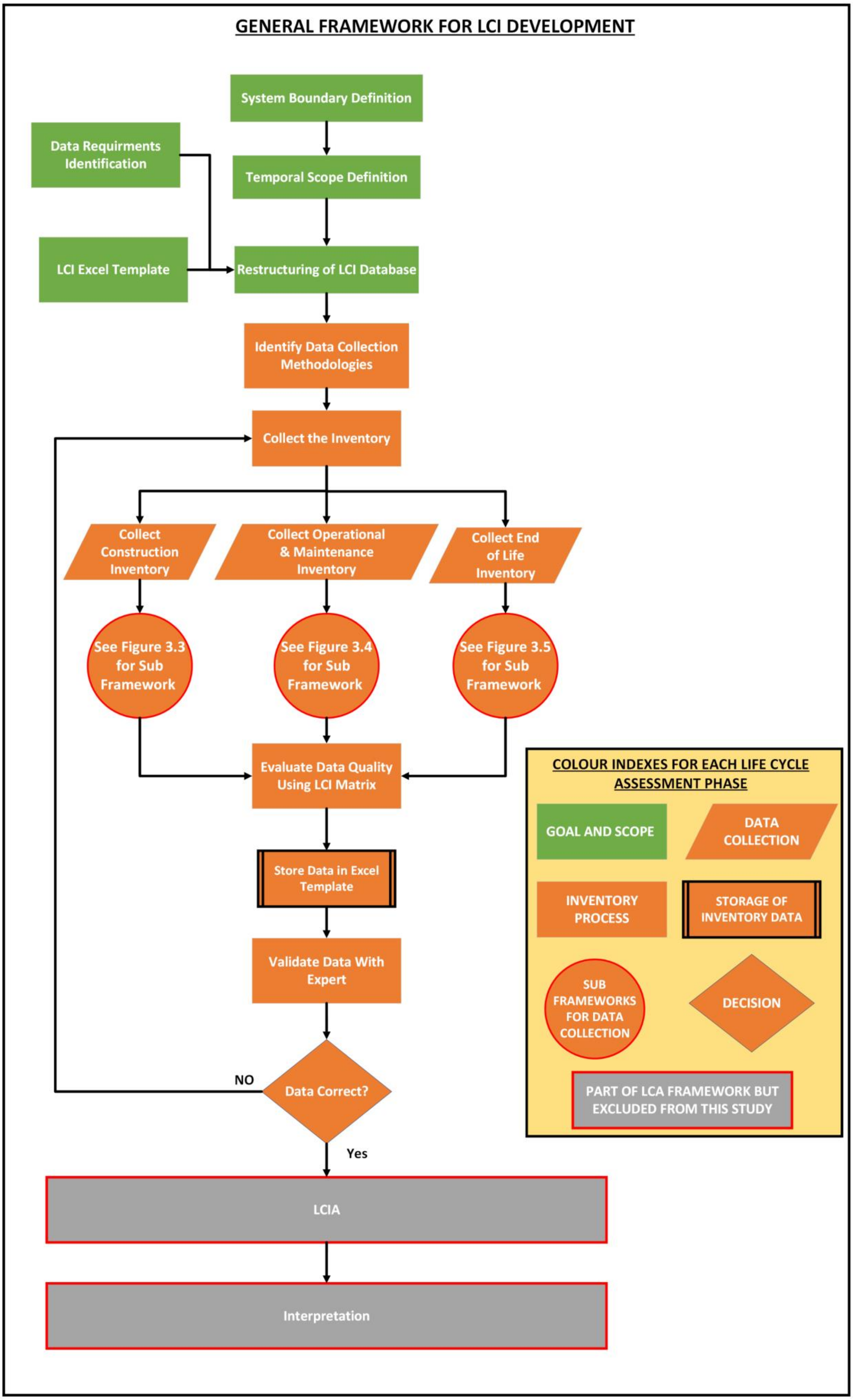

Figure 3.2. General Framework to Conduct an LCA of Airport with Steps on How to Collect Inventory - Adapted from Saavedra-Rubio et al. (2022)

Sub-Frameworks

As described above, the collection of inventories in the general framework is divided into three sub frameworks (construction, operation and EoL of airports). This sub-section will illustrate the sub-frameworks developed and will also briefly describe them. Importantly, the identified LCI data requirements and data collection methodologies are integrated in all of the sub frameworks.

Construction Inventory

The first sub-framework in the general framework focuses on the development of construction inventory related to airports. The construction inventory provides some relevant methodologies that can be used to collect construction inventory of airports. As illustrated in Figure 3.3, the framework is divided into four categories: construction materials, transportation distances, energy use, and water demand. The process begins by determining the availability of primary data for each category which—if accessible from airport sustainable reports—is recorded in the Excel template.

The sub framework also integrates the identified methodologies from literature in the event that primary data is not accessible. For example, if no primary data is available on the quantity of materials used in construction, the framework recommends that the practitioner apply the methodologies proposed by Fishman et al. (2024) and Grossegger. (2022) to estimate the total quantity of materials potentially used in the airport's construction. Detailed references to these methodologies can be found in the specified equations—for example, Equations 2 and 3—which correspond to the estimation approaches for construction material requirements.

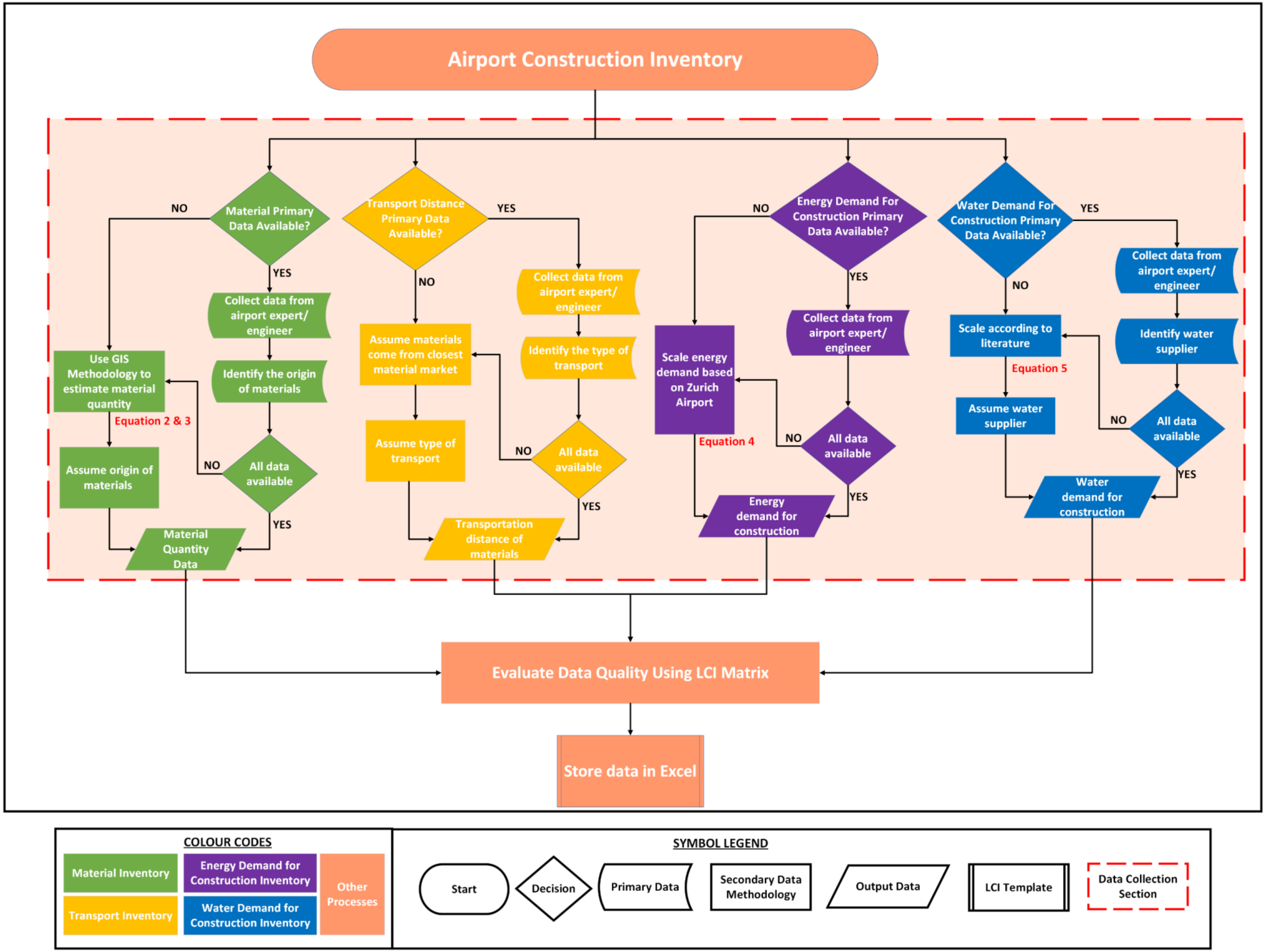

Figure 3.3. Framework Developed for The Collection of Construction Data for The Development of Construction Inventory

Operational Inventory

The second sub framework integrated into the general framework is the operational framework, which focuses on the collection of inventories related to the operation and maintenance of an airport. The structure of the second sub-framework is identical to that of the first sub-framework (Figure 3.3), whereby the practitioner is first asked whether there is primary data available for the collection of inventory data. The sub-framework in Figure 3.4 is organized into four categories: energy demand, water demand, ground handling, and maintenance.

The energy demand section of the sub-framework is divided into two types of energy: electricity and thermal energy. This is done because two different methodologies were identified to estimate the quantity of electricity and thermal energy required by an airport in order to operate efficiently. Importantly, the LCA practitioner should identify who the main supplier of energy is to the airport, which ultimately influences the results obtained from the impact assessment. For example, an airport can either get its electricity from a diesel-powered generator, the national grid or directly from solar panels. Knowing the source ultimately influences the impact associated with the demand for energy.

Additionally, the collection of data related to the water demand of the airport also involves identifying who supplies the water to the airport and also identifying who treats the generated wastewater and with which technology. This is important information which ultimately influences the impact assessment results from an LCA.

On the other hand, inventory related to ground handling activities requires the collection of different types of data—such as the energy consumption of GAVs and GPUs, their associated emissions, and the airport's de-icing requirements. Each of these components has its own associated methodology, all of which are integrated into the framework. For example, the framework recommends using Equation 7 to estimate the GAV inventory and Equation 8 for the GPU inventory.

Lastly, the maintenance inventory integrates a set of methodologies focused on various components related to the upkeep of airport surfaces. These include rubber removal from runway surfaces, replacement of the runway's top layer, and the water requirements for rubber removal when UHPWB technology is used. Each of these components has its own methodology within the framework, which can be used to collect inventory data related to airport surface maintenance.

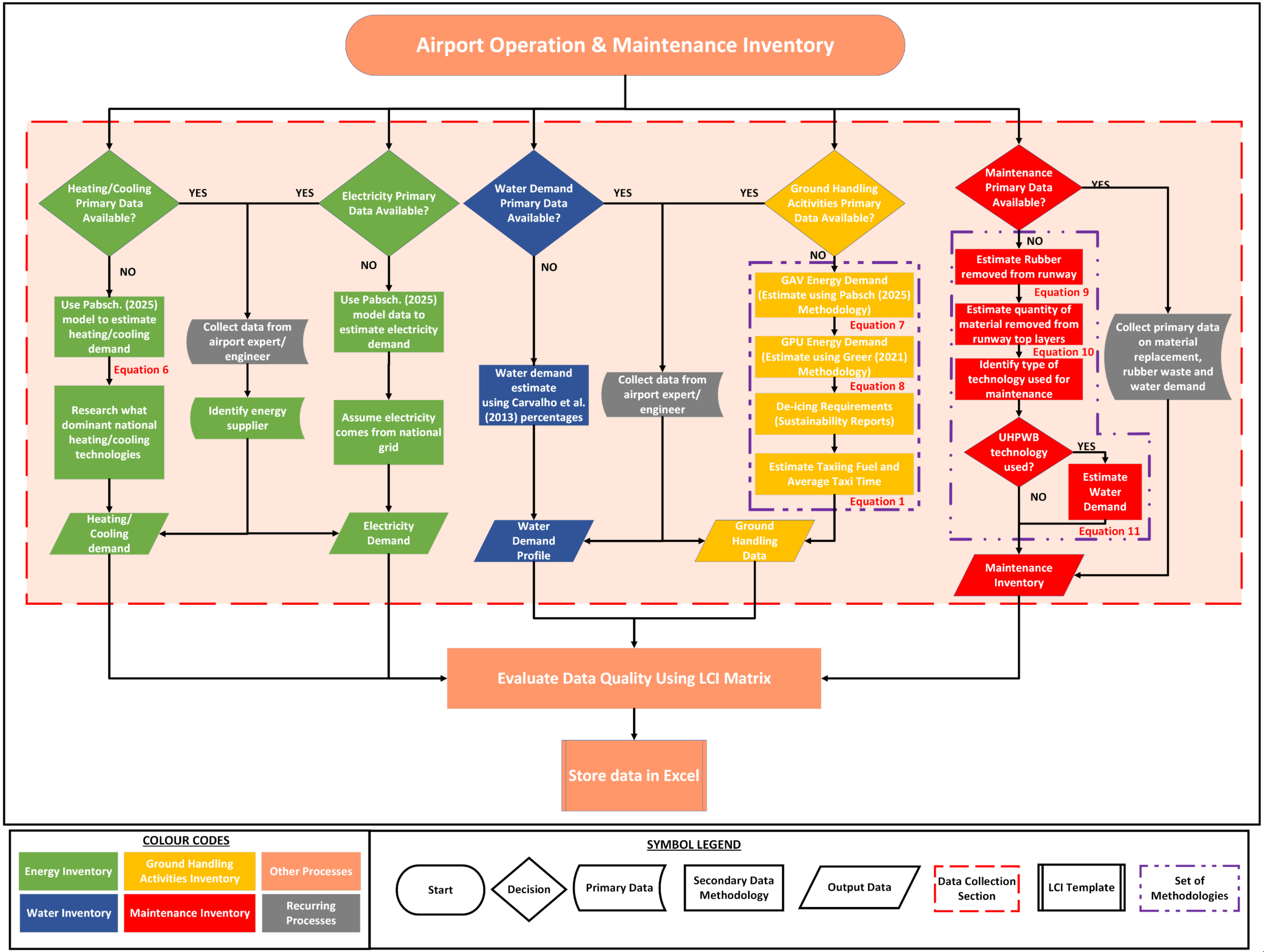

Figure 3.4. Developed Framework Focusing on the Collection of Operational Inventory of Airports

End-of-Life

The third sub-framework presented in the general framework is the EoL framework, which is shown in Figure 3.5. The sub-framework presented below only focuses on two components; the quantity of materials that can be extracted from the airport and the energy required to extract the materials. The methodologies integrated into the framework assume that there is no loss of construction materials during the operation of the airport meaning that the quantity of that the quantity of materials leaving the airport is equal to the quantity used to construct the airport. Additionally, the energy demand for demolition is assumed to be the same as that of construction if there is no data regarding how construction technology has developed throughout the lifetime of the airport.

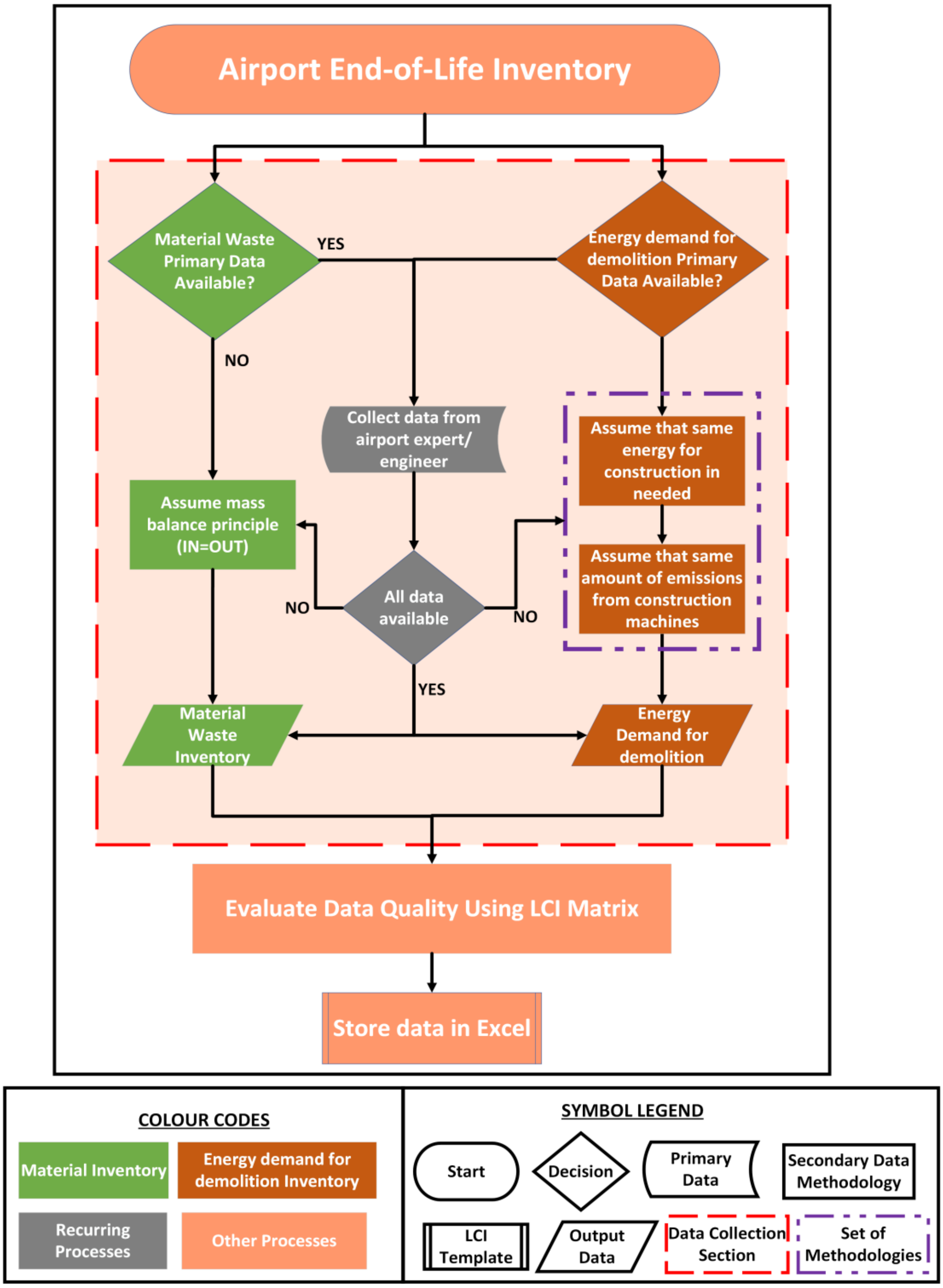

Figure 3.5. Schematic Representation of the End-of-Life Inventory Framework for Airports

4 Case Study: LCI of Schiphol Airport

Schiphol Airport is a world-renowned airport, constructed in 1916 (Schiphol, 2025a) and has been continuously been growing. In 2024, the airport had approximately 66.8 million passengers visiting the airport, with approximately 473,803 flights at the airport (CBS, 2025). However, in recent years, Schiphol Airport has been accused of its environmental impact (NOS, 2025; Ozkurt, 2014) meaning that the airport may have to reduce its growth. As a result, Schiphol Airport has a commitment to making the airport more sustainable to reduce its environmental impact (Schiphol, 2025b).

Given the above facts, this chapter aims to collect inventory data of Schiphol Airport which can later be used to assess the environmental impact of the airport. The collection of the inventory data will be done using the developed framework, in order to demonstrate how the framework can be used to collect inventory data from airports. This chapter starts with defining the goal and scope of this section, before proceeding to the collection of inventory data.

Goal and Scope

The goal of this section is to demonstrate how the developed framework can be utilised to collect inventory data of any airport. The functional unit chosen for the demonstration is one year of operation at Schiphol Airport. This means that the inventory data will be representative of all the intermediate flows and the environmental extension flows required and generated by Schiphol Airport in one year. The temporal scope of this demonstration is 2024, given that this is recent data. From the collected inventory data, impact assessments of Schiphol Airport can be performed.

The inventory that will be collected for Schiphol Airport is influenced by the scope of the demonstration. The demonstration follows a cradle-grave perspective, meaning that the construction, operation and EoL phases of the airport will be considered. Given that the goal of the demonstration is the collection of annual inventories, the construction and EoL inventory will have to be scaled down to represent the inventory for one year. Unfortunately, it is unknown what the lifetime of an airport is, therefore, for demonstration purposes the lifetime of the airport is assumed to be approximately 59 years as identified in Andersen & Negendahl (2023).

The data requirements are the same as those presented in chapter 3.1, which are representative of most European Airports. The data requirements in chapter 3.1 consider all the life cycle phases of an airport, which are considered in this demonstration of the framework. As a result, the same data requirements from chapter 3.1 act as a backbone for the inventory collected for Schiphol Airport. Furthermore, the units used to store the inventory in the Excel Template will be the same units that are used in EcoInvent LCI databases to allow for future comparisons to be done.

4.1 Construction of Schiphol Airport

The construction inventory of Schiphol Airport has been annualised by dividing all the construction inventory by the assumed lifetime of the airport. This is consistent with the defined functional unit. As a result, the inventory results presented are representative of a single year which allows for future studies to compare the environmental impact of the airport between each life cycle phase of the airport.

The construction inventory for Schiphol Airport was primarily developed using the framework presented in Figure 3.3. Due to the absence of primary construction data, the inventory was estimated based on available methodologies. This inventory includes material quantities, energy demand, and water consumption associated with the airport's construction. This section demonstrates how the framework in Figure 3.3 was used to develop the construction inventory, while also presenting some of the associated inventory results.

The first step involved is identifying the various infrastructures at Schiphol Airport, which is essential for estimating the material quantities required for construction and determining the total area occupied by the airport. Figure 4.1 below illustrates these infrastructure components, derived from the BAG3D spatial dataset, which includes detailed building functions, while the area of the runways was derived using the steps outlined in Figure C.2. The total area of the airport was derived to be 22.7 km² of land. Based on these results, material quantities for construction were estimated following the steps outlined in Figure 3.3.

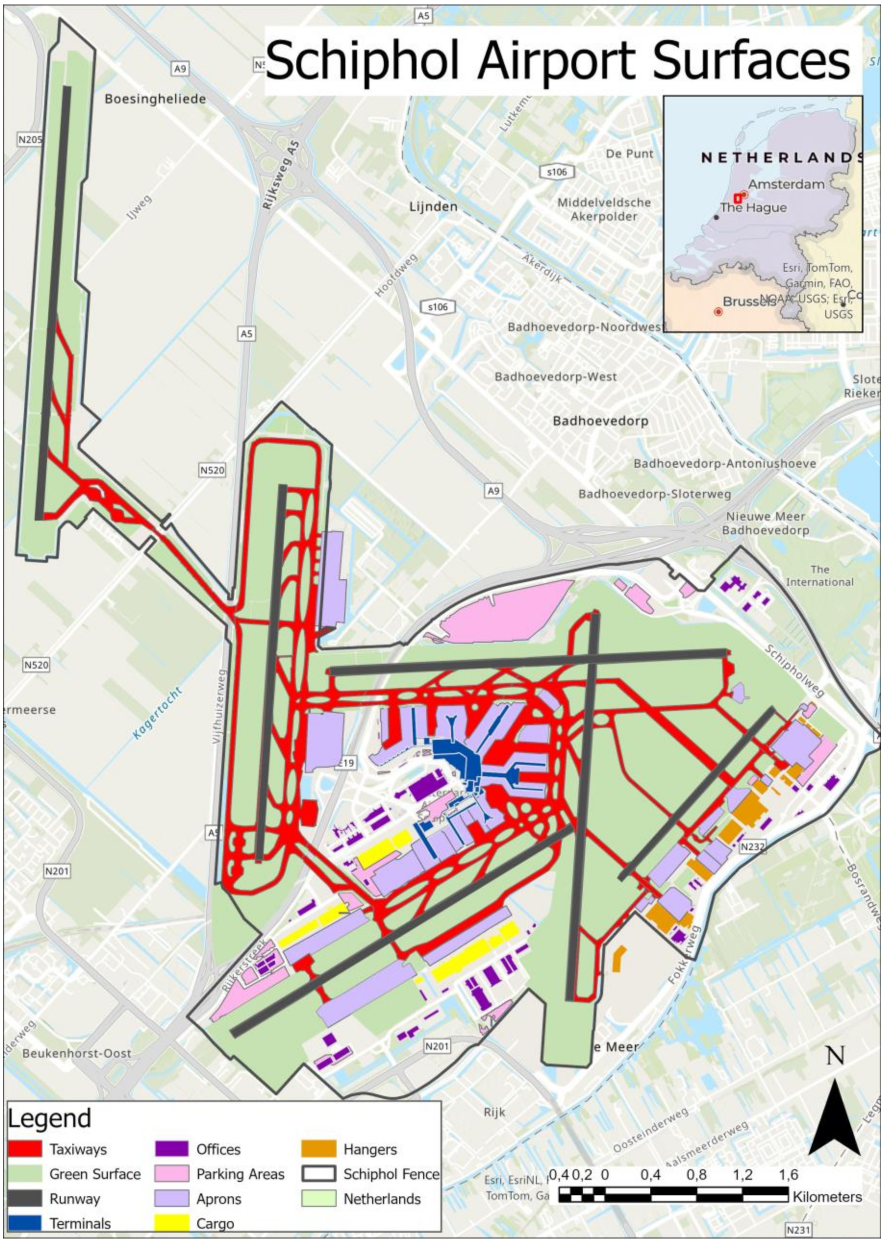

Figure 4.1. Illustration of the Identified Infrastructure at Schiphol Airport

4.1.1 Material Quantity for Building Infrastructure

The material quantities for Schiphol Airport's building infrastructure were estimated using the advised methodology in the construction framework (Figure 3.3), utilising Fishman et al. (2024) methodology, which required the Material Intensities of Buildings and the Useable Floor Area. The Material Intensity values were obtained from Sprecher et al. (2022), while the usable floor area was determined using the BAG spatial dataset processed in ArcGIS Pro software. While the geographic specificity of Sprecher et al. (2022) data enhances its reliability, it is not airport-specific, introducing some uncertainty.

The quantity of material required for the construction of Schiphol Airport was estimated based on the assumption that current building materials reflect the original construction quantities. Figure 4.2 illustrates the material requirements by building type—for example, terminals required approximately 4.81×10^6 kg of reinforced concrete and 2.58×10^6 kg of brickwork. Importantly, these values are based on the material intensity coefficients from Sprecher et al. (2022), which are representative of Dutch buildings. Furthermore, these values are influenced by the $UFA_{buildings}$ of the airport, which demands large amounts of materials for construction. The estimated material quantities are stored in the Excel file containing the inventory data.

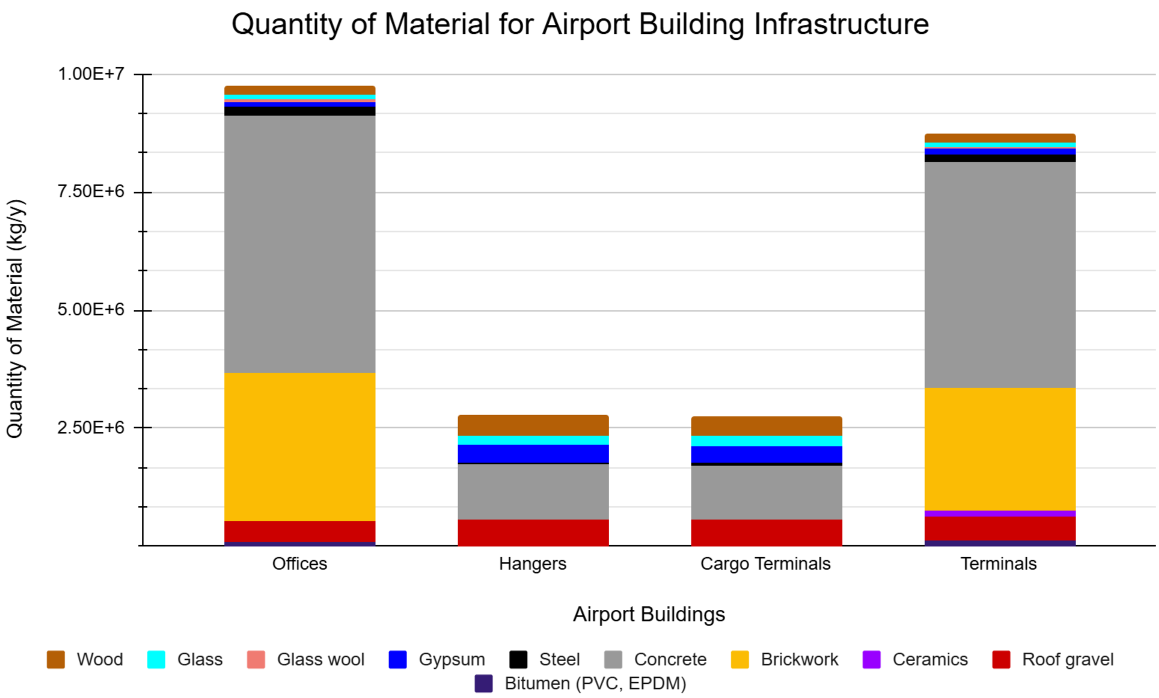

Figure 4.2. Total Material Quantities for Schiphol Buildings Estimated Using Material Intensity Coefficients From Sprecher et al. (2022) scaled to the lifetime of Schiphol Airport

4.1.2 Material Quantity of Schiphol Surfaces

Estimating the material quantities for the construction of Schiphol's pavements (runways and taxiways) utilises Grossegger. (2022) methodology, which requires the thicknesses of each sublayer of the pavements. Figure 4.3 illustrates the various sublayers of Schiphol's runways along with their corresponding thicknesses, which were used alongside Equation 2 to calculate material volumes. Given that no data was available regarding the thickness of taxi sublayers, it is assumed that the thicknesses are relatively the same to that of runways, since the surface needs to sustain the weight of aircrafts. The total surface area of the runways and taxiways, shown in Figure 4.1, was determined using ArcGIS Pro software. These inputs enabled the estimation of material quantities, which were then incorporated into the inventory tables presented in the supplementary Excel spreadsheet. Figure 4.4 highlights selected results derived from Equation 2, demonstrating that a substantial quantity of concrete is stocked in the airport's surface infrastructure and accounted for in the inventory.

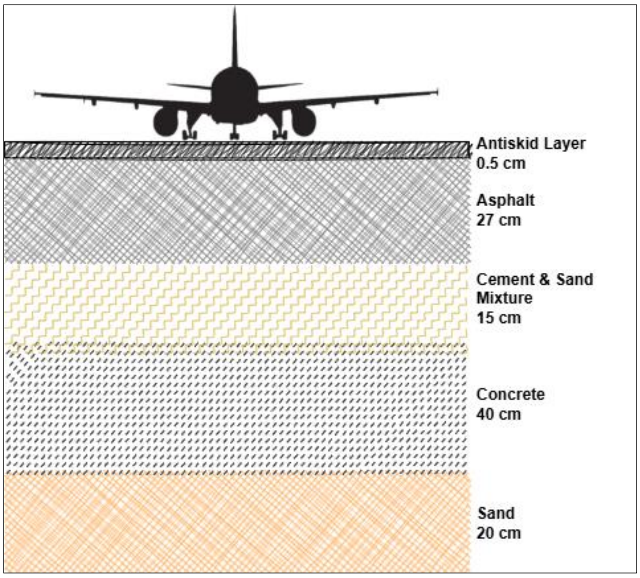

Figure 4.3. Illustration of Schiphol Pavements requirements and thicknesses obtained from Schiphol (2019), Nederend (2023)

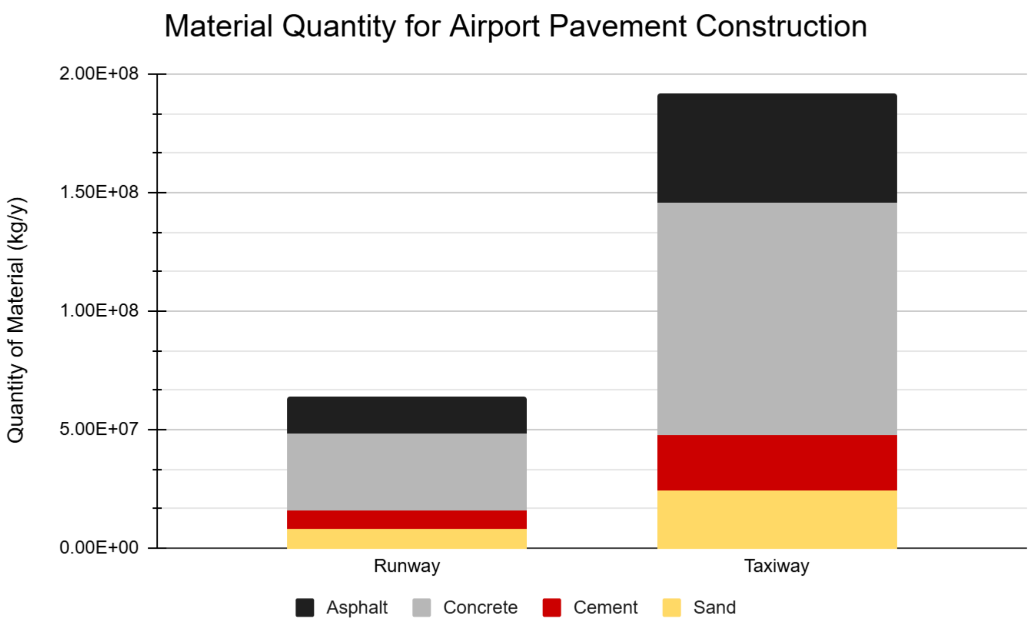

Figure 4.4. Quantity of Materials Required for the Construction of Schiphol's Pavements annually

Another material requirement included in the construction inventory is the quantity of paint used on Schiphol Airport's runways. Using the methodology explained in chapter 2.5, the total area of the Buitenveldertbaan runway was calculated to 255,269 m², while the total painted area was approximated to be 12,875 m². Using the assumed thickness of the markings, the total volume of paint required for the Buitenveldertbaan runway was approximated at 4.89 m³. Finally, by dividing this outcome by the total area of the runway, the paint intensity to mark the runways was estimated to be 1.92×10^{-5} m^3 per square meter (1.92×10^{-2} L/m^2). This intensity factor was subsequently applied to estimate the paint requirements for the other runways at Schiphol Airport. As a result, the application of runway markings at Schiphol's runways requires 459 L of paint.

4.1.3 Energy Demand for Construction

Another aspect addressed in the framework is the amount of diesel used during airport construction. The energy demand for construction at Schiphol Airport was estimated using Equation 4, with the airport's total surface area as the primary input. The calculation is based on energy use data from the construction of Zurich Airport. From Thonemann et al. (2024) paper, it was identified that the construction of Zurich Airport consumed 250MJ of diesel per square meter. This value was utilised as a scaling factor to estimate the diesel demand for the construction of Schiphol Airport. Utilising Equation 4, the energy demand for the construction of Schiphol Airport was estimated to be 2.41×10^7 MJ, which is equivalent to 6.73×10^5 L of diesel.

4.1.4 Water Demand for Construction

The water demand for the construction of Schiphol Airport was estimated using Equation 5. Given that the quantity of concrete used for the construction of the airport has been estimated, Equation 5 was utilised to estimate the potential amount of water used during the construction of the airport. Based on the aforementioned equation, it was estimated that 4.16×10^5 kg of water was required within the functional unit of the study. This is equivalent to 4.16×10^5 L of water.

4.2 Schiphol Operational Inventory

The operational inventory for Schiphol airport was developed using the operational framework presented in Figure 3.4. The corresponding calculations are documented in the Excel inventory worksheet. This section is structured according to the categories defined in Figure 3.4.

4.2.1 Energy Demand for Operation

The energy demand for operation is divided into two categories, the electricity demand for the airport and the thermal energy required by the airport. For both categories, secondary data is utilised to estimate the inventory data.

According to van Dorst (2022), the annual electricity demand for Schiphol Airport is 200 GWh. This is already inventory data that is stored within the Excel Template. However, this result can be distributed amongst end-uses at Schiphol Airport which is beneficial for hotspot analysis during the impact assessment. Using the percentage breakdowns in Table 3.5, the total electricity demand found from literature was distributed to the end-uses at the airport, which lead to the results shown in Figure 4.6. The figure indicates that most electricity is consumed by electrical cooling in the terminals, followed by usage in offices and commercial areas. However, the 'Other' category accounts for a significant portion of electricity consumption, the specifics of which remain unknown.

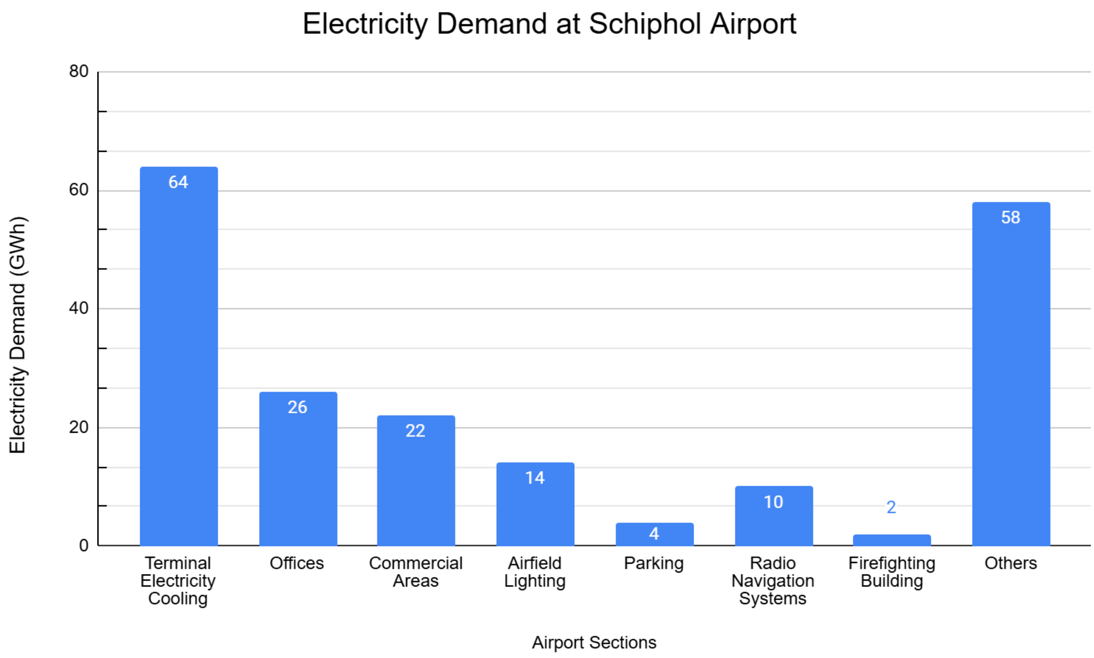

Figure 4.5. Distribution of Electricity Demand at Schiphol Airport

The heating and cooling energy demand for the terminal buildings at Schiphol Airport was estimated using data from Pabsch (2025), which reported that annual heating requires approximately 37.1 GWh and cooling 13.6 GWh for 60 million passengers. This corresponds to 0.599 kWh per passenger for heating and 0.220 kWh per passenger for cooling. Given the total number of passengers at Schiphol Airport in 2024, the total heating and cooling energy demand was approximated to be 40.1 GWh and 14.7 GWh respectively.

4.2.2 Water demand for Operation

The water demand for the operational phase of Schiphol Airport was estimated using secondary data due to the absence of primary sources. According to Pabsch (2025), the water demand at Schiphol Airport is 14.7 L per passenger. Given the total number of passengers that visited the airport in 2024, the total water demand of the airport is approximated to be 9.82×10^8 kg[1] (9.82×10^8 L) of water. Using the values presented in Table 3.7, the water demand for several sections of the airport was estimated as presented in Table 4.1. It is assumed that the airport's water supply is drawn from the Dutch local water market. Additionally, it is assumed that wastewater generation is equal to the water used for toilet flushing, while water losses to the environment correspond to the volume used for irrigation.

[1] The unit for tap water in EcoInvent is kilograms

Table 4.1. Estimate Results of Water Demand at Schiphol Airport

Water Demand Profile	***Amount***	***Unit***
Irrigation	2.26×10^8	kg
Fire control system	6.88×10^7	kg
Cooling towers	2.55×10^8	kg
Toilet Flushing	1.96×10^8	kg
Other	2.36×10^8	kg
Economic flows, out:	***Amount***	***Unit***
Toilet Flushing	1.96×10^8	kg
Environmental flows, out:	***Amount***	***Unit***
Irrigation water	2.26×10^8	kg

4.2.3 Ground Handling Activities

The LCI for ground operations includes a broad range of airport activities. These consist of the use of GAVs—such as pushback trucks, cargo tractors, transporters, and lavatory service trucks—as well as GSE, including APUs and GPUs. Additional components include the application of de-icing agents and the taxiing phase of aircraft, which encompasses both fuel consumption and related emissions. The estimated inventory for these components is outlined in the subsections below.

Energy for Ground Service Vehicles

The inventory related to the use of GSE Vehicles (GSEv) was estimated using two data sources. First, the energy demand associated with GSEv operations at Schiphol Airport was obtained from Pabsch (2025), who reported that in 2023, GSEv consumed approximately 17.1 GWh of energy to service around 460,000 flights, corresponding to an average of 37.2 kWh per flight. Given the total number of flights in 2024, the total energy demand for GSEv is estimated to be 17.6 GWh which is equivalent to 1.77×10^6 L of diesel.

Energy and Fuel Demand for Ground Service Equipment

The energy demand for GSE at Schiphol Airport was estimated using Equation 7, which utilised data from multiple sources. Greer et al. (2021) supplementary data supplies data on both the energy required for GSE use and the diesel consumption per wingspan class of aircraft which are summarised in Table B.1 and Table B.2. Additionally, it was identified that Schiphol Airport has 245 gates in total, with 74 gates equipped with GPU technologies (Benschop, D et al., 2018; Schiphol, 2022). The same equation was utilised to estimate the total fuel demand for either the use of APUs or GPUs at Schiphol Airport. Table 4.2 below represents the estimated results of the electricity and fuel demand for the use of GPUs and APUs based on the current infrastructure at the airport, which are also stored as inventory.

The associated emissions associated with the use of GPUs or APUs was estimated based on emission indexes provided by Padhra (2018), which are available in Table B.3. The values in Table B.3 represent the emissions associated with the combustion of 1kg of diesel in GPUs or Jet A1 fuel for APUs, which can be used to estimate the total amount of emissions, based on the fuel demand for the use of the technologies. The estimated emissions for the use of both technologies at Schiphol Airport are observable in Table 4.3

Table 4.2. Total electricity and fuel demand for GPU and APU use at Schiphol Airport

Electricity & Fuel Demand	Total Electricity & Fuel Demand	Unit
Electricity for preconditioned air for cooling	1.15×10^9	kWh
Electricity for preconditioned air for heating	1.01×10^9	kWh
Electricity for 400Hz GPU	3.47×10^8	kWh
Fuel for preconditioned air for cooling	3.38×10^8	kg
Fuel for preconditioned air for heating	6.77×10^8	kg
Fuel for APU heating/cooling	5.73×10^9	kg
Fuel for APU power	3.56×10^9	kg

Table 4.3. Total emissions associated with the use of APUs and GPUs at Schiphol Airport based on the emission indexes provided by Padhra (2018)

	Carbon Monoxide	Hydrocarbons	Nitrogen Oxides	Unit
GPU	3.37×10^6	6.74×10^6	2.02×10^7	kg
APU	2.21×10^7	1.52×10^6	5.95×10^7	kg

Inventory related to aircraft taxiing

The inventory related to aircraft taxiing at Schiphol Airport includes data on the total fuel consumed and the associated emissions generated by the activity of taxiing. The type of aircrafts at Schiphol Airport during the temporal scope of the study was obtained from FlightRadar24, from which 59 different aircraft types operating at the airport were identified. This distribution was assumed to remain constant throughout the assessment period. A sample of the data is presented in Table B.4, with further details available in the "Flight History" worksheet of the Flight LTO Emissions Excel file (see supplementary file S.3).

The data regarding the fuel demand and emissions for each aircraft was obtained from LRTAP (2019). Equation 1 was utilised to estimate the total fuel demand and emissions emitted from taxiing at Schiphol Airport during the temporal scope of the study. The total demand for Jet A1 fuel for taxiing at the airport was estimated to be 193,759 kg. The emissions that are generated from the combustion of Jet A1 fuel during the taxiing phase at the airport are summarised in Table 4.4.

Table 4.4. Annual Aircraft Taxiing Emissions at Schiphol Airport

Environmental Extension	Amount	Unit
Carbon Monoxide (CO)	1.88×10^6	kg
Hydrocarbons (HC)	1.69×10^5	kg
Nitrogen Oxides (NOx)	3.54×10^5	kg
Particulate Matter (PM)	5.81×10^3	kg

De-icing Activities

As Schiphol Airport is located in the northern hemisphere and experiences winter conditions, de-icing is essential for the safe departure of aircraft. As a result, de-icing activities were included in the inventory, following the steps outlined in the operational framework (Figure 3.4). Relevant data were obtained directly from Schiphol's sustainability reports (Royal Schiphol Group, 2024).

In 2024, approximately 1.12×10^6 L of potassium formate was used for pavement de-icing and 7.84×10^5 L of glycol for aircraft de-icing. Additionally, the report indicated that 9.31×10^6 L of de-icing agents was collected and treated as wastewater. Therefore, this data is used as input for the operational inventory tables.

4.2.4 Maintenance Activities

The maintenance inventory for Schiphol Airport includes rubber removal from runways, water use, and asphalt replacement. Regular rubber removal is critical for maintaining runway traction and is conducted every five weeks (Schiphol, 2018, 2024). For the Kaagbaan runway, 6,500 kg of rubber is removed per cleaning cycle, resulting in an estimated 67,600 kg of rubber waste annually (6,500 kg × 10.4 cycles/year). Dividing this by the runway surface area yields a rubber intensity of 0.269 kg/m² per year. This value was used to estimate the annual rubber removed from all runways at the airport using Equation 10. Given the area of all six runways and the rubber intensity calculated above, the total quantity of rubber removed from all runways is calculated to be 3.80×10^5 kg.

The rubber removal from runways is carried out using high-pressure water, resulting in significant water demand (Schiphol, 2018). By utilising Equation 11, the total water required for rubber removal across all runways at Schiphol was estimated to be 1.07×10^7 L of tap water. It is also assumed that the used water is collected and treated at a wastewater treatment plant that separates the wastewater from the collected rubber.

Lastly, runway asphalt at Schiphol Airport must be periodically replaced. Schiphol maintains one of its six runways each year, resulting in a full replacement cycle of seven years per runway (Schiphol, 2024). The amount of asphalt used for replacement is assumed to be the same as that used during the initial runway construction. Given this seven-year replacement cycle, the annual amount of asphalt replaced was estimated using Equation 9, yielding in 1.29×10^8 kg of asphalt been replaced. It is further assumed that the asphalt application efficiency remains constant throughout the airport's operational lifetime.

4.3 End of Life Inventory

As discussed in chapter 3.1, Thonemann et al. (2024) highlights that the EoL phase of an airport includes the removal of materials from the airport. The EoL Framework also assumes that materials can be removed from the airport at the EoL phase of the airport. It is assumed that no material losses occur during the operational phase, meaning the quantity of materials recovered at EoL equals the materials used for construction.

Table 4.5 below illustrates the quantity of estimated materials that can be recovered from the airport, which is equal to the amount used for constructing the airport (aggregated data). The data presented in Table 4.5 is the data associated with the temporal scope of the study. Similarly, the energy required for decommissioning is assumed to equal that used during construction, under the assumption that technology and fuel efficiency remain constant.

Table 4.5. Estimate of the Potential Materials that can be Recovered from Schiphol Airport in the Event of Decommissioning, within the temporal scope of this study

Potential Materials to recover	**Quantity Estimate**	**Unit**
Bitumen (PVC, EPDM)	2.17×10^5	kg
Roof gravel	9.42×10^5	
Ceramics	1.44×10^5	
Brickwork	5.70×10^6	
Concrete	1.43×10^8	
Steel	4.36×10^5	
Gypsum	9.34×10^5	
Glass wool	1.07×10^5	
Glass	5.88×10^5	
Wood	3.94×10^5	
Asphalt	6.14×10^7	
Cement	3.12×10^7	
Sand	3.24×10^7	
Roof material unspecified	1.13×10^6	
B-wood	8.53×10^5	

5 Discussion

At the beginning of the thesis, a research gap was identified regarding the collection of airport inventory which could be used in LCA studies to measure the sustainability of airports. Several studies have focused on airport sustainability, however, no studies were identified that focused on compiling airport specific LCI data that can be used for environmental impact assessments. As a result, this study focused on how a comprehensive framework can be developed to enable consistent collection of LCI data of airports across the entire life cycle spectrum. To achieve this, a framework was developed integrating several methodologies that can be used to collect airport inventory. This chapter will start by discussing the main results with the applicability of the framework, followed by a discussion of the main strengths of the framework. The chapter ends with discussing the limitations associated with the framework and this study.

5.1 Main Results

This research begun by identifying the key data requirements for developing comprehensive airport inventory, based on the predefined goal and scope that include the construction, operation, maintenance and EoL phases of the airport. The data requirements took consideration of the intermediate flows and environmental extensions associated with the activities associated with each phase of an airport, which then guided the development of the framework that can be used to collect airport inventory.

The identified data requirements emphasise the significance of quantifying the materials used in airport construction, as Schiphol's Inventory reveals that large volumes of materials are required for airport construction, potentially contributing significantly to the environmental impact of airports. Importantly, the construction inventory collected had to be divided by the lifetime of the airport, to obtain inventory data associated with the functional unit of the study (annual operation of the airport). However, the construction inventory stored in Supplementary File S.2 comes with uncertainty, because the lifetime of an airport remains uncertain. This is because airports mainly remain open and rarely close, meaning that there is no known lifetime of airports. As a result, the annual construction inventory data stored in Supplementary File S.2 is uncertain, because the actual lifetime of the airport remains unknown.

The demonstration of the collection of construction inventory from Schiphol Airport highlights that large quantities of materials have to be delivered to the airport. The results highlight that Schiphol demands quite a lot of concrete for the construction of buildings and pavements which ultimately influences the potential results that can be obtained from impact assessments. It can be expected that the large demand for concrete influences the impact scores of the construction of the airport, given that the production of concrete significantly impacts the environment (Mostafaei et al., 2023). Furthermore, the quantity of materials required for construction is heavily influenced by the surface area. Figure 4.4 illustrates that the construction of taxiways requires more materials than runways. This has an implication on future environmental assessments of airports, whereby it can turn out that the construction of runways are more sustainable than the construction of taxiways, because less materials are required to construct runways compared to taxiways.

However, it is important to keep in mind that the results in Figure 4.4 originate from the assumption that the sublayer thickness of taxiways are relatively the same to runways.

Apart from the construction inventory, the developed airport inventory also accounts for other critical activities occurring at airports, such as ground handling operations, energy consumption and maintenance, which are all associated with airport operation. Most of this inventory was estimated based on data obtained from secondary data, representative of Schiphol operations in the year 2024. However, it is important to note that the operational data stored in Supplementary File S.2 is subject to change, given that the parameters used to estimate the operational data for Schiphol Airports operation changes periodically. For example, the water demand at Schiphol airport can change periodically, either because the number of passengers visiting the airport changes, or changes in water use efficiencies. For example, Vurmaz & Boyacioglu. (2018) reported that water demand at Schiphol in 2017 was 13.3 L/pax - lower than the value used in this study – highlighting that there is temporal variability in such parameters. Therefore, it is important to keep in mind that the inventory collected for the operation of Schiphol Airport is representative of the year 2024, and can change each year.

Furthermore, the inventory results for Schiphol's operation highlights that the airport contributes to different types of emissions that originate from different sources. For example, the process of taxiing at Schiphol airport produces four different emissions, with the biggest emission being carbon monoxide followed by Nitrogen Oxides, which have a higher impact on the environment. Additionally, the current use of APUs and GPUs at the airport contribute to airport emissions, with APUs contributing more to airport emissions compared to the use of GPUs at Schiphol airport. It can be argued that this difference comes from the number of gates that facilitate the use of APUs, which is currently at 171, while 74 gates facilitate the use of GPUs. Nevertheless, literature suggests that GPUs have lower emissions than APUS (Greer et al., 2021). Therefore it can be argued that increasing the use of GPUs at Schiphol Airport helps bring down the total emissions associated with the use of power units.

Nevertheless, the results obtained from this study makes airport inventory more comprehensive due to the range of activities that have been included, which are ignored in other developed datasets of airports.

5.2 Applicability of the Framework

The case study of Schiphol Airport was utilised to demonstrate how the proposed framework can be used to collect comprehensive airport LCI data. The lack of primary data from the airport meant that the LCI data had to be estimated using the identified methodologies from different studies. On the one hand, the proposed methodologies identified from literature were effective in estimating airport inventory based on various data sources such as scientific papers and sustainability reports. This meant that the identified methodologies can be applied in the collection inventory from any airport in the world. However, it is important to note that the identified methodologies come with an associated uncertainty since the inventory is calculated based on different data sources.

For example, the methodology used to estimate the quantity of materials used in the construction of airport buildings remains uncertain. In the case of Schiphol's inventory data, the material intensity coefficients utilised to estimate airport inventory represent the average material intensity coefficients of Dutch Buildings. These material intensity coefficient values may not accurately reflect the specific material intensities associated with airport buildings, meaning that the actual quantity of construction materials cannot be precisely estimated using secondary data. The data uncertainty also applies to other methodologies, such as estimating the energy and water consumption during the construction phase, which may vary significantly depending on the airport. As a result, the inventory representing the construction of Schiphol comes with uncertainty. Nevertheless, the inventory collected in this study gives perspective into the potential amount of material required to construct the airport.

Though there is uncertainty behind the data collected, the framework can be applied to any airport to collect inventory data. This is mainly because most of the identified data requirements are common activities that happen at airports during the operation phase. For example, the framework ensures that the LCA practitioner accounts for the intermediate flows and environmental extensions associated with the use of GSEs at a given airport. Therefore, it can be argued that the framework can be used to collect inventory data for any airport around the world. However, this does also mean that some of the data requirements have to be adapted according to the location of the airport.

The developed framework can be adapted in several ways to accommodate the data requirements for a given airport. The framework is flexible to adjustments that can be made by the practitioner, by either removing or adding specific data requirements into the framework. For example, the current framework takes into consideration snow removal activities (de-icing) which are typical of Nordic airports that experience winter seasons. However, the framework can be adjusted for tropical airports that do not experience winter seasons and do not require snow removal activities. In such a case, the framework can be adjusted by the practitioner, which allows for flexibility. Similarly, tropical airports do not require thermal energy for heating, meaning that this requirement can be ignored by the practitioner that is focusing on tropical airports.

Nevertheless, the developed framework can be utilised for the collection of inventory from any airport in the world. This is because the framework accounts for activities that generally happen in most airports. In some instances, the framework can be adjusted accordingly as argued above. Therefore, the framework is flexible to adjustments which is dependent on the data requirements of the airport and the location of the airport.

5.3 Strengths of the Developed Framework

As discussed above, one of the strengths of the framework is its flexibility, which not only allows practitioners to adjust the data requirements according to the location of the airport, but also allows the practitioner to focus on different aspects of the life cycle of an airport. Depending on the goal and scope defined by the practitioner, the framework can still be used to develop specific airport inventory. For example, For instance, if the practitioner focuses solely on the construction and operational phases of a specific airport, the framework can be selectively applied to guide relevant data collection, by just focusing on Figure 3.3 and ignoring the other frameworks. This adaptability enables systematic data gathering across different airport types and boundary definitions, making the framework broadly applicable to various LCA contexts.

Secondly, it can be argued that the framework employs a structured approach that prioritizes the use of primary data. In cases where primary data is unavailable, the framework provides formulas to approximate inventory data, ensuring that essential information can still be obtained. Moreover, the framework emphasizes data transparency through the use of the pedigree matrix, which supports clear communication of data quality and facilitates its reuse by other practitioners. Arguably, this is a strength of the framework, because it guides practitioners to collect inventory data from any source, which needs to be transparently stored in the developed Excel Template in this study. Therefore, the framework not only guides practitioners to collect data, but ensures that the data is stored transparently so that future users of the data can be aware about the data quality.

Another key strength of the framework is its ability to collect inventory data from a wide range of airports, which has significant implications for sustainability studies. This capability not only ensures the development of comprehensive inventory datasets but also supports future research in conducting robust impact assessments of airport product systems. By identifying potential environmental hotspots within the product system of an airport, the framework enables targeted improvements in environmental performance. Additionally, the standardized methodology used for data collection facilitates meaningful comparisons of environmental impacts across different airports. For example, the framework can be effectively applied to compare the environmental footprint of airport operations at London Heathrow and Schiphol Airport over a given year. Such comparisons are made possible by the consistency in data collection processes when the framework is employed.

5.4 Framework Comparison

The developed framework can be compared to other frameworks that have been developed for LCI which brings up discussion points related to the framework developed in this thesis.

The inventory datasets developed using the steps proposed in this framework offer a higher level of granularity compared to the existing airport inventory available in the Ecoinvent database. The current Ecoinvent dataset is based on Zurich Airport and represents the airport as a "black box," focusing solely on the construction phase while omitting a wide range of operational and EoL activities. This limited scope fails to capture the diverse and complex processes that occur over the entire life cycle of an airport. In contrast, the framework developed in this study adopts a more comprehensive approach by considering a broad spectrum of activities—from construction and operation to decommissioning—thereby enhancing the granularity and completeness of the resulting LCI.

A comparable study by Thonemann et al. (2024) focused on the development of prospective life cycle inventories for both conventional and hybrid-electric aircraft technologies and also included an LCI for RTHA. A key similarity between Thonemann et al. (2024) study and the present work is the consideration of the full airport life cycle, including construction materials, water and energy use during operation, ground access transport, ground power units, and the use of de-icing fluids. Both inventories also adopt a similar EoL assumption—that the airport is eventually decommissioned.

However, a notable methodological difference lies in the approach to estimating material quantities for construction. In the RTHA study, construction inventories were primarily based on expert assumptions and subsequently scaled to the airport. In contrast, the inventory developed for Schiphol Airport in this study relies on material intensity coefficients sourced from existing literature. While the method used in the RTHA study may help reduce uncertainties associated with expert judgment, this study demonstrates an alternative literature-based approach that can be applied when primary data is unavailable.

Another key distinction is the intended application of the two LCIs. The RTHA dataset was designed for use in prospective LCA studies, while the Schiphol dataset supports conventional LCA and serves as a proof of concept for the developed framework. Despite these differences, the fundamental elements and data categories considered in both inventories are largely aligned, suggesting consistency with best practices in emerging airport LCI methodologies.

5.5 Limitations

The results obtained in this study (inclusive of the developed framework for the collection of airport life cycle inventory) comes with its own limitations that will be discussed in this section. The limitations will be discussed according to each sub-framework developed in this study.

5.5.1 Construction

One of the limitations associated with the construction inventory is the methodology used to estimate the amount of energy required to construct an airport. In this study, the energy required for the construction of Schiphol Airport is estimated by scaling the results from Thonemann et al. (2024) study using Equation 4. The results from Thonemann et al. (2024) were also scaled from the energy required for the construction of Zurich Airport, obtained from Ecoinvent. However, this approach does not account for technology differences between airports, meaning that it is assumed that the technology used for the construction of Zurich airport is the same as that at Schiphol Airport. Knowing the type of construction technologies is rather difficult if there are no records but is useful in defining the efficiency of the technologies. If different construction machines were used, then the energy demand at Schiphol Airport may be different, due to a difference in efficiency.

Another limitation associated with the construction inventory framework relates to the methodology utilised to estimate the water demand for construction. The methodology assumes that the water ratio in concrete is 0.171 water for 1 kg reinforced concrete. The problem with this is that it assumes that the concrete is mixed at the airport and does not account for other uses of water during the construction of the airport. This remains a challenge to quantify the total water used for the construction of the airport, given that there were no available records. Therefore, the water demand for construction is only estimated based on the quantity of concrete needed for construction, and ignores other uses of water, which also remain unknown.

Furthermore, it is important to keep in mind that the construction inventory for Schiphol Airport is static, meaning that the inventory is only representative of the temporal scope of the study. This means that the inventory for the construction of the airport is only representative for 2024 and cannot be used to evaluate the environmental impact of the airport in 2030. This is because the inventory does not account for potential growth of the airport. Therefore, in the event that new runways or buildings are constructed, then the inventory tables have to be updated to ensure that the accumulation of material use is accounted for.

Lastly, Schiphol's construction inventory does not contain all of the data associated with the construction of the airport. There are several cut-offs that have been made regarding the construction of the airport. For example, the inventory does not account for the number of electrical cables under the pavements of the airport and the number of lights on runways, due to the unavailability of primary data. Knowing the quantity of cables under the pavements of the airport further makes the inventory comprehensive but also helps to account for the environmental impact associated with the production of the cables needed by the airport, which helps pinpoint the true environmental impact of the airport.

5.5.2 Operation

There are multiple limitations associated with the operational inventory developed in this study. One of the limitations identified relates to the methodology to determine the distribution of electrical and water use at airports such as Schiphol Airport. Though the total electrical and water demand of the airport was obtained from literature, the end uses were rather difficult to determine. The data presented in Tables 3.5, 3.6 and 3.7 represent the percentages that were used in this research to determine the amount of electrical energy used in terminals or the quantity of water needed to irrigate the airport. However, the data in the aforementioned tables may not be representative of all airports, which can have implications on hotspot analysis in the future, whereby the hotspot analysis may not be realistic. Thus, the distribution numbers used limit the results and can have an implication on the results from impact assessments.

Secondly, there are some cut-offs present in the operational inventory for Schiphol Airport. The inventory data requirements were mainly based on identified literature, meaning that in some instances, some activities are disregarded. For example, intermediate flows such as the input of food supplies for terminal restaurants, or output of food wastes, or the supply of cleaning agents for the terminals are not accounted for. In other words, the activities occurring within airport buildings are not included within the framework and the developed inventory. As a result, the results from this study are limited to the data requirements identified in literature.

Thirdly, the framework accounts for the quantity of de-icing agents required by an airport within the temporal scope of the study. However, there was an identified challenge associated with the development of de-icing inventory. At the moment, the framework assumes that all of the de-icing agents sprayed on aircrafts or airport pavements is captured and treated in treatment plants. However, some of the de-icing agents can end up in the environment, which impacts surrounding environments. It is argued that the chemicals used for de-icing activities can reduce the oxygen levels in water, which contaminates local groundwater and negatively affects aquatic life (Douglas & Lawson, 2003; Freeman et al., 2015). Despite the potential impact de-icing agents have on the environment, there was no identified methodology to estimate the potential spillages happening into the environment at a particular airport, meaning that the inventory tables created do not consider the environmental extension output of de-icing activities at airports. This has an implication on impact assessments of airports, because when there is no extension available, then the true damage on aquatic environments remains unknown.

Lastly, the framework does not include some environmental extensions which are related to airports, due to the lack of characterisation factors. For example, airports produce significant amounts of noise (Douglas & Lawson, 2003), however there are no characterisation factors available that can be used to assess what the environmental impact of noise pollution is. Therefore, the developed framework and inventory is limited to data requirements that have characterisation factors. Without the characterisation factors of noise, then the true environmental impact of the airport remains unknown.

5.5.3 EoL

One limitation associated with the EoL framework and inventory is that it is impossible to know the type of technologies that will be used in the future to deconstruct the airport during this phase. As a result, the current framework assumes that the same machines used for construction of the airport are the same as that used to deconstruct the airport, meaning that the energy demand for deconstruction is the same as that during the construction of the airport. However, this does not account for potential improvements in technologies, whereby the energy efficiency of the machines in the future would be better than that during the construction of the airport. Therefore, the construction inventory is limited due to the uncertainty on the technology advancements that will occur in the future, since it is impossible to know when the airport will be deconstructed.

Furthermore, it can be argued that the EoL framework is not that realistic, because airports are rarely deconstructed. Although Thonemann et al. (2024) also accounts for the EoL phase of airports, following the LCA convention, airports rarely get closed and deconstructed. Evidence suggests that complete dismantling and material recovery at airports is uncommon. For instance, runways that reach the end of their functional lifespan are often repurposed—either converted into taxiways or holding areas for aircraft (Pullins, 2024), or adapted for entirely new uses. A notable example is the 100-meter runway at Lundtofte Airbase in Denmark, which was transformed into a pedestrian walkway on the campus of the Technical University of Denmark (DTU) (Sørensen, 2014).

Likewise, the case of Berlin's Tempelhof Airport illustrates that decommissioned closed airports are frequently redeveloped into public or cultural spaces, rather than being dismantled. A similar approach is planned for Tegel Airport, which is being redeveloped into a research and university campus, including the Urban Tech Republic and the Schumacher Quartier residential area (dpa, 2024). Therefore, it can be argued that airports usually are not deconstructed like any other building but usually transformed to serve another purpose. This means that the EoL framework for airport inventory is mainly based on the hypothetical scenario that an airport gets deconstructed, following the standard LCA procedure of waste treatment.

Nevertheless, the inventory that is developed is based on the hypothetical idea that airports can become decommissioned just like a normal building. The inventory for Schiphol airport allows researchers to identify the quantity of materials that can be recovered from the airport in the hypothetical case that the airport gets deconstructed, while also been able to conduct a full life cycle assessment using the data in the inventory to evaluate the total environmental impact of the airport.

6 Conclusion, Recommendation and Outlook

At the beginning of this research, it was identified that there is a data gap associated with airport inventory that can be utilised to evaluate the environmental impact of airports from a life cycle perspective. To fill this data gap, the following research question was formulated:

"How can a comprehensive framework be developed to enable consistent and complete Life Cycle Inventory data collection across all stages of an airport's life cycle?"

Based on the literature sources identified in this research, different data requirements were identified which were considered in the development of the framework. The definition of the goal and scope at the beginning of the study was crucial in identifying the data requirements for the development of the framework. Given that the scope was the collection of cradle-grave inventory, key data requirements related to the cradle-grave life cycle of airports had to be collected. Logically, if the scope focused on the collection of gate-grave inventory, then the data requirements will be condensed to this scope. As a result, the key data requirements identified in this research relate to the intermediate flows and environmental flows related to the scope of the study. For example, for the construction of the airport, it is important to know the type of construction materials used during the construction of the airport and the type of material wastes produced during this phase. The identification of the data requirements influenced the development of the framework.

However, the development of consistent and complete LCI data at airports required more than just identifying the data requirements for the airport LCIs. As a result, this research also focused on identifying potential ways to collect inventory from airports. The first method identified is the collection of primary data, which is representative of the airport. However, if this data is not available from the airport, the secondary data was identified as a potential source to fill the data gaps. This research identified several methodologies from literature that can be used to process secondary data into inventory data which can then be stored transparently in the Excel Template. The identification of the methodologies from literature were compiled into the framework in order to develop a comprehensive framework that can be used to collect inventory data of airports.

Both the identified data requirements and methodologies were ultimately compiled into a framework that can be utilised for the collection of inventory data. Importantly, the developed framework accounts for all the identified data requirements, which are mostly representative for all airports in the world. However, in some instances, the framework has to be adjusted, since not all data requirements are representative for all airports in the world. As discussed in the discussion, tropical airports do not require de-icing activities, meaning that this data requirements can be ignored while collecting inventory data for tropical airports. Moreover, the inventory collected for Schiphol Airport demonstrates the applicability of the framework in the collection of airport inventory.

In conclusion, the development of a comprehensive framework that enables the consistent collection of airport inventory is dependent on several factors. First, it is dependent on the goal and scope definition chosen by the LCA practitioner that ultimately influences the collection of inventory from airports. Secondly, the goal and scope definition influenced the identification of the data requirements and the methodologies used to collect inventory data. Based on this outcomes, a comprehensive framework was developed by compiling the above results. Therefore, the development of a comprehensive framework is dependent on the type of data requirements identified and the identified methodologies that can be used to collect inventory data. This research has the implication that better airport inventories can be developed, allowing for better impact assessments of airports to be done. The impact assessments will not only pinpoint how airports contribute to climate change, but also on how it affects other impact categories such as acidification and land use. Therefore, this research acts as a stepping stone towards the improvement of sustainability assessments performed for airports. However, the developed framework can be improved in the future with further research.

Future Research and Recommendations

During the research, it was identified that there is a data gap associated with the collection of inventory data related to the use of de-icing agents at airports. At the moment, the study is assuming that all the de-icing agents are collected by the airport and treated at waste treatment plants. However, there is the possibility of spillage happening, whereby the fluids end-up in the environment, eventually impacting the environment. However, current airport reports do not report on this spillage, and no methodology was identified that can be used to estimate the quantity of de-icing fluids ending up in the environment. Therefore, future research should focus on developing a methodology to estimate the quantity of de-icing agents released into the environment, which has an implication on future environmental assessments of airports.

This research also demonstrated how the developed framework can be used to collect inventory data for Schiphol Airport, with the data been transparently stored in Supplementary Files S2. It is recommended that an impact assessment of Schiphol Airport is performed to identify the potential environmental impact of the airport in 2024. Performing an impact assessment of the airport implies that the environmental impact of the airport becomes clear, which can be used to provide advice to the airport on how they can become more sustainable in the future. Therefore, future research can focus on conducting an LCA of Schiphol Airport which is beneficial for the airport.

However, it is important to keep in mind that the inventory collected in this study is representative for 2024. Though it is logical that the inventory is only representative for 2024, it is important to note that airport data is subjective to changes, due to the dynamic nature of the airport. As discussed in the discussion, airports can grow either through the development of new infrastructure, changes in number of flights and passengers, which influences the intermediate flows and environmental flows associated with the airport. Therefore, it is recommended that future studies should try to develop inventory tables for other temporal scopes to capture the changes in inventory data, ultimately influencing the impact assessment results of an airport.

Lastly, airports are considered as major noise polluters, which should be included within the inventories of airports. However, it was also identified that there are no current characterisation factors available that can be used to assess the environmental impact associated with noise pollution. As a result, this environmental flow had to be disregarded, since it currently cannot be used to assess the environmental impact. Therefore, future studies should firstly develop a characterisation factor for noise pollution, before identifying an appropriate methodology to distinguish the noise pollution emitted from the airport with noise pollution coming from the LTO cycle. This has the implication that the environmental impact of airports becomes more clear, which can influence the creation of policies and regulations for the operation of airports.

Nevertheless, the framework developed in this study represents a significant step towards improving the quality and consistency of airport LCIs. It enables the creation of comprehensive datasets that address current gaps in airport inventory data, such as the overreliance on Zurich Airport inventory as a proxy. By facilitating the collection of comprehensive inventory data, the framework supports more accurate and robust environmental assessments of airport systems. This advancement is particularly useful for the aviation industry that is under pressure to reduce its environmental impact. Furthermore, by incorporating the recommendations above, the framework can be expanded to include additional dimensions – such as noise pollution or quantity of spilled de-icing agents into the environment,-which can be useful in impact assessments of airports.

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Supplementary Files

The supplementary files below contain the links to the supplementary data.

	Name
S.1.	**LCI Airport Excel Template**
S.2.	**Schiphol Airport LCI data**
S.3.	**LTO Emission Calculator**

Appendices

A. Methodological Illustrations

The figures below illustrate the methodologies that can be undertaken to estimate inventory based on secondary data, given that there is no primary data available.

A.1. Construction Inventory

The following diagrams are illustrations of how secondary data can be processed to produce construction inventory of airports.

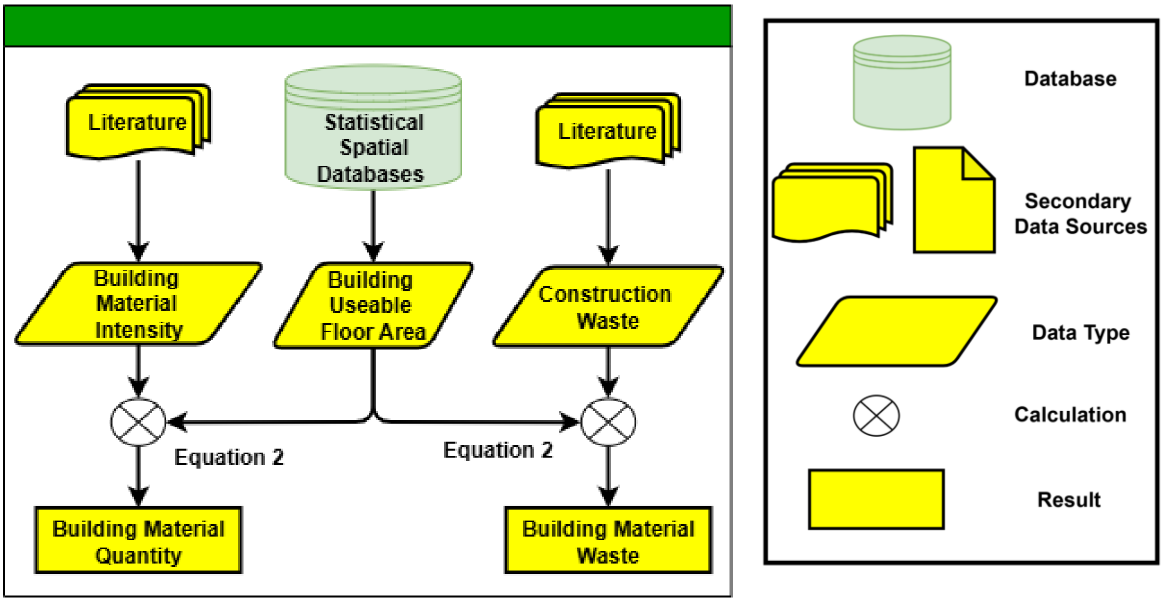

Figure A.1. Illustration of the steps that can be undertaken to estimate quantity of materials required for airport building construction

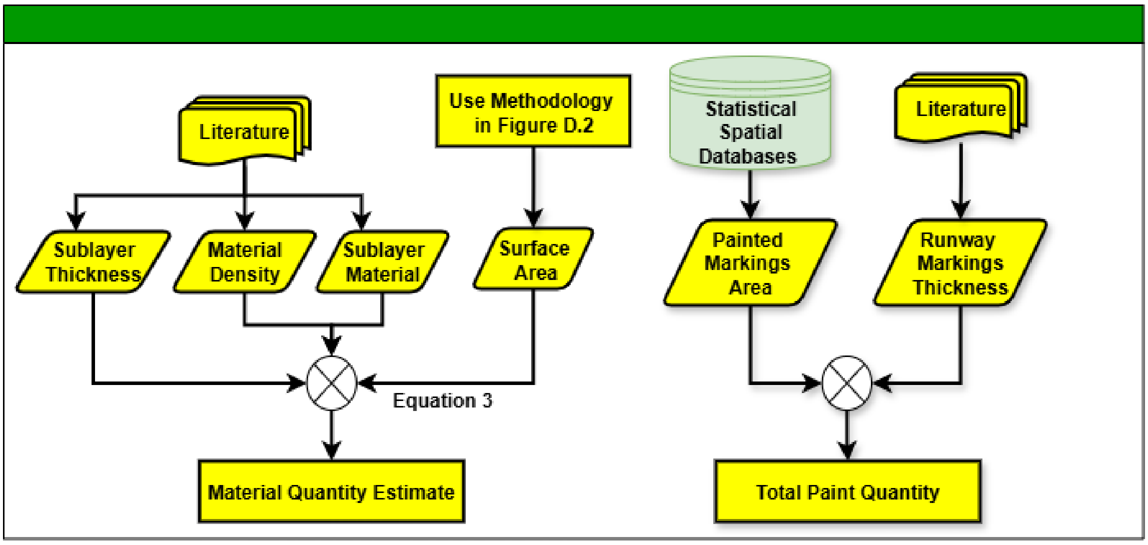

Figure A.2. Methodology used to estimate the quantity of material required for airport pavement construction (for existent airports).

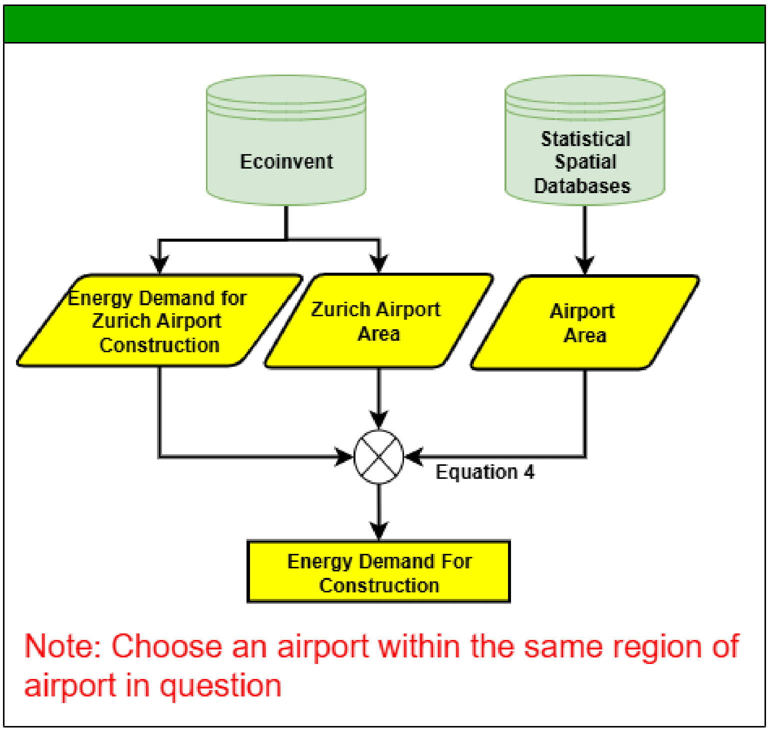

Figure A.3. Illustration of methodology that can be used to estimate amount of energy required for the construction of airports (refers to amount of diesel in MJ)

A.2. Operation & Maintenance Inventory diagrams

The diagrams below illustrate the methodologies undertaken in the estimation of inventory related to the operation and maintenance of an airport using secondary data.

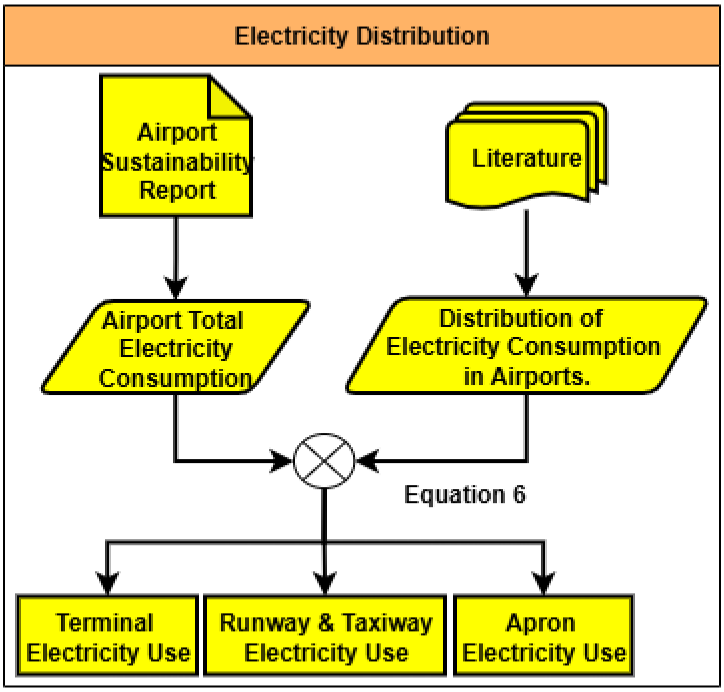

Figure A.4. Illustration of a potential methodology that can be used to estimate amount of electricity used at an airport

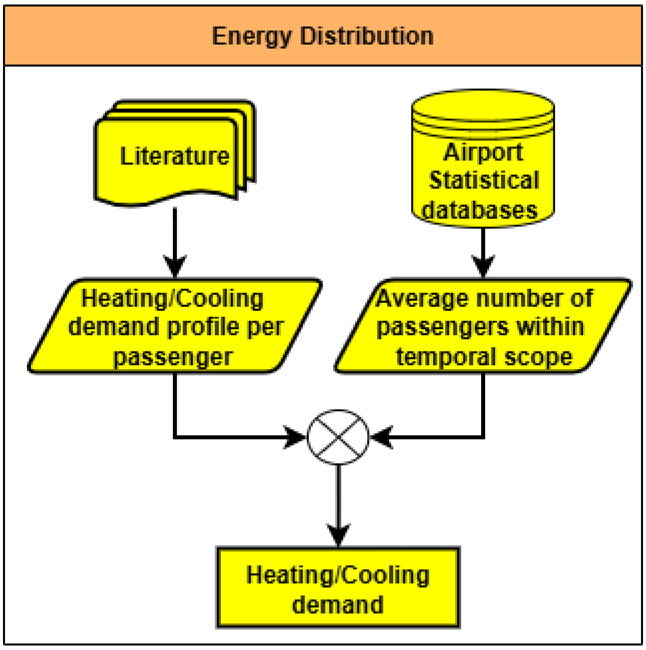

Figure A.5. Illustration of the potential methodology to estimate the heating/cooling energy demand of an airport within temporal scope of study

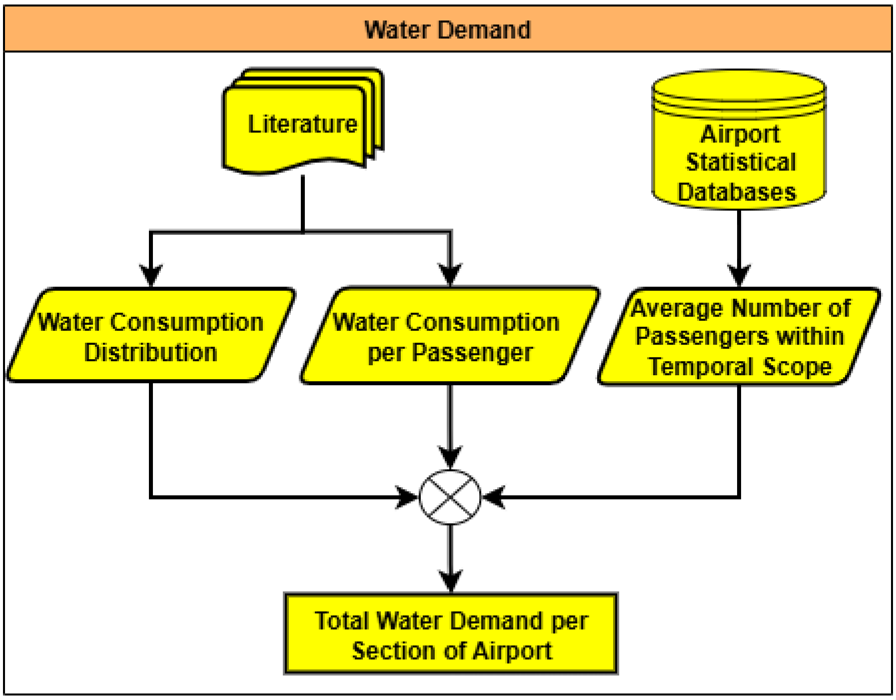

Figure A.6. Illustration of potential methodology used to estimate the amount of water demanded by an operating airport (for several parts of the airport).

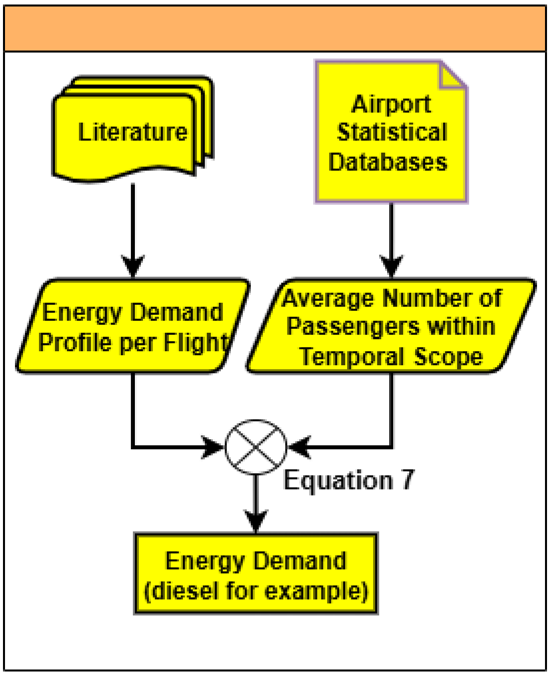

Figure A.7. Illustration of the potential methodology used to estimate the energy demand for the use of Ground Access Vehicles

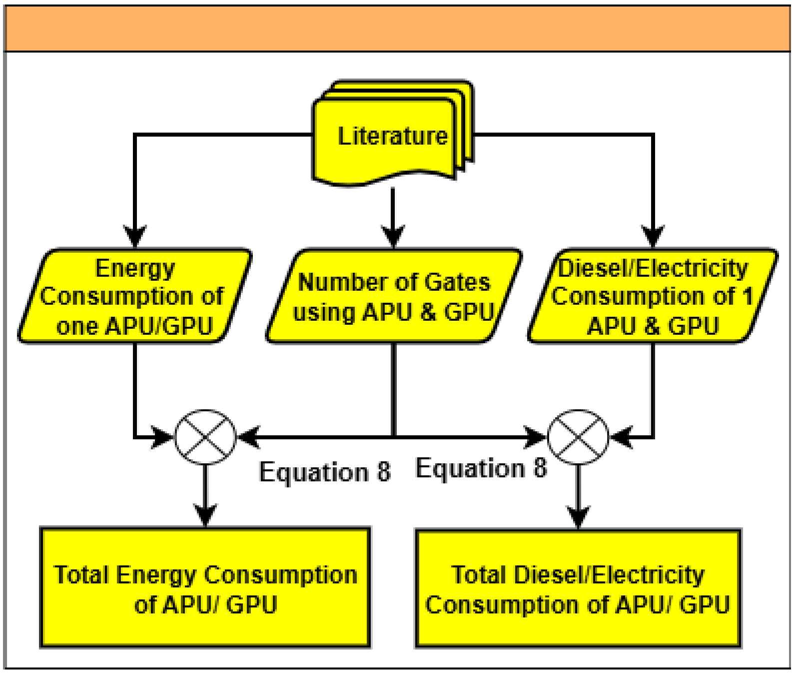

Figure A.8. Illustration of the methodology used to estimate the amount of energy and diesel required to use APU/GPU at an airport

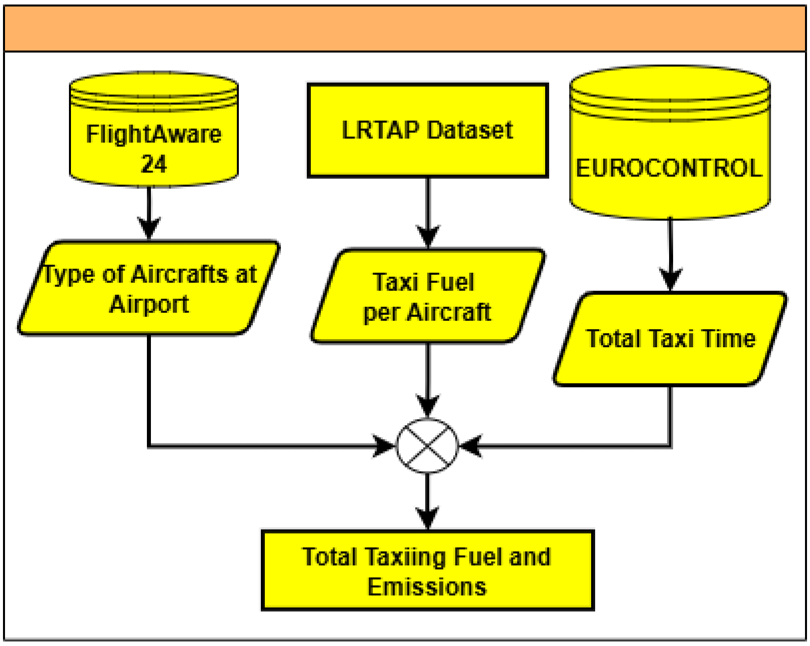

Figure A.9. Illustration of steps taken to estimate amount of fuel needed to taxi at an airport with corresponding emissions

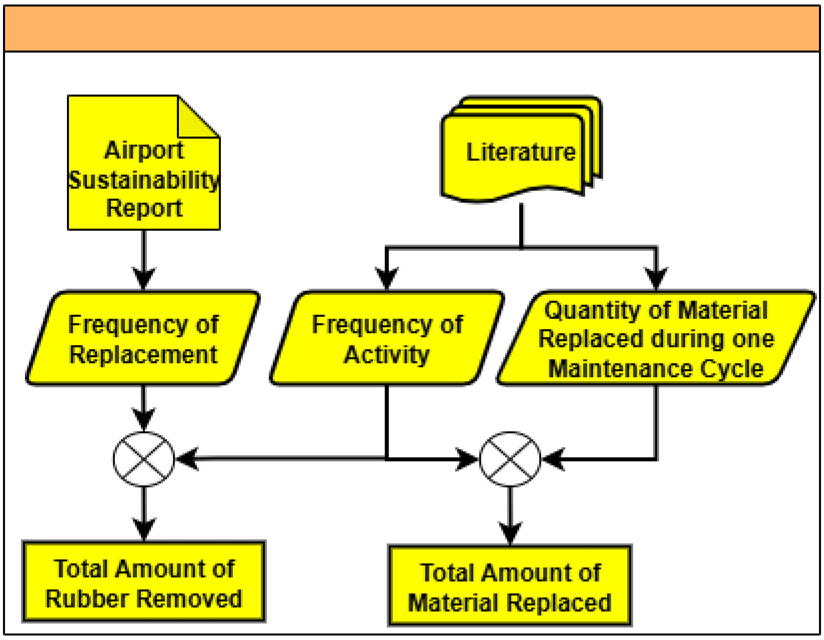

Figure A.10. Illustration of the methodology used to estimate amount of rubber and asphalt/concrete replaced from airport runways in the temporal scope of the study

B. Tables

B.1. Energy and Fuel Demand for GPUs and APUs

The tables below represent the energy and Fuel Demand for GPUs and APUs obtained from Greer et al. (2021) supplementary data, which was used to estimate the total electricity and fuel demand for the use of GPUs and APUs at Schiphol Airport in 59 years.

Table B.1. Energy used by GPUs and PCUs to supply energy to aircraft

Wingspan Class	400 hz Power Rating (kW)	PCA Cooling (kW)	PCA Heating (kW)
C	17	49	47
D	26	130	98
E	34	153	114
F	66	153	114

Table B.2. Fuel used by GSE to supply energy to aircraft

	Diesel Consumption (L/hr)				
Wingspan Class	**PCA Cooling**	**PCA Heating**	**APU Heating/Cooling**	**APU Power Supply**	**Flight Counts**
C	17	16	148	94	199474
D	37	28	233	148	4283
E	54	40	273	157	33490
F	107	80	273	157	808

The emissions associated with the use of both technologies are obtained from Padhra (2018), which are used in this study. The table below represents the data obtained from Padhra (2018).

Table B.3. Emission Indices representing quantity of emissions associated with combusting 1kg of Jet A1 fuel in APUs or 1kg of diesel in GPUSs obtained from Padhra (2018).

	APU (g/kg)	**GPU (g/kg)**
Carbon Monoxide	2.97	4
Hydrocarbons	0.2	8
Nitrogen Oxides	8.01	24

B.2. Sample of types of aircrafts at Schiphol Airport

The table below represents a sample of the data obtained from FlightRadar24 within the three-day period, which is used to estimate the fuel and emissions associated with taxiing at Schiphol Airport, respective of all types of aircraft which have different types of fuel and emissions rates while taxiing.

Table B.4. Sample of the Data Collected from FlightAware Representing the Different Types of Planes at Schiphol Airport on 9th April used to Estimate Total Taxi Fuel and Emissions

Date	Time	From	Airline	Aircraft type	Status
9/4/2025	12:00 am	Shanghai (PVG)	China Cargo Airlines	B77L	Landed 3:45
9/4/2025	12:05 am	Faro (FAO)	Transavia	A21N	Landed 11:41
9/4/2025	12:05 am	Athens (ATH)	Transavia	B738	Landed 12:16

9/4/2025	12:15 am	Barcelona (BCN)	Transavia	B738	Landed 12:0
9/4/2025	12:15 am	Malaga (AGP)	Transavia	A21N	Landed 12:1
9/4/2025	12:20 am	Gran Canaria (LPA)	Transavia	A21N	Landed 12:1
9/4/2025	12:20 am	Alicante (ALC)	Transavia	B738	Landed 12:0
9/4/2025	12:45 am	Marrakesh (RAK)	Transavia	A21N	Landed 12:3
9/4/2025	12:45 am	Milan (LIN)	KLM	B738	Landed 11:5
9/4/2025	1:05 am	Bari (BRI)	Transavia	A21N	Landed 12:5
9/4/2025	1:15 am	Tenerife (TFS)	Transavia	A21N	Landed 1:00
9/4/2025	1:25 am	Gran Canaria (LPA)	Go2Sky	B738	Landed 1:25
9/4/2025	4:40 am	Leipzig (LEJ)	DHL	B763	Landed 4:55
9/4/2025	5:05 am	Anchorage (ANC)	Nippon Cargo Airlines	B748	Landed 4:39
9/4/2025	5:20 am	Seoul (ICN)	KLM	B77W	Landed 5:24
9/4/2025	5:21 am	Paris (CDG)	FedEx	B738	Landed 5:19
9/4/2025	5:40 am	Boston (BOS)	Delta Air Lines	A339	Landed 5:07
9/4/2025	5:55 am	Lagos (LOS)	KLM	A332	Landed 5:51
9/4/2025	6:00 am	Atlanta (ATL)	Delta Air Lines	A339	Landed 5:41
9/4/2025	6:00 am	Detroit (DTW)	Delta Air Lines	A359	Landed 5:22
9/4/2025	6:00 am	Toronto (YYZ)	KLM	B78X	Landed 5:12
9/4/2025	6:10 am	Paramaribo (PBM)	KLM	B77W	Landed 6:03
9/4/2025	6:30 am	Hong Kong (HKG)	KLM	B789	Landed 6:16
9/4/2025	6:30 am	Dubai (DXB)	KLM	B77W	Landed 6:24
9/4/2025	6:35 am	Kuala	KLM	B789	Landed 6:27
9/4/2025	6:35 am	Guangzhou (CAN)	China Southern	A359	Landed 6:00

C. Creation of GIS dataset

To determine the surface area of Schiphol Airports runways and taxiways, a GIS spatial dataset had to be developed. The development of the dataset had to be done since the author was not able to find any spatial datasets regarding the aprons of the airport. This section will highlight the steps taken by the author in the development of the spatial dataset, in order to determine the surface area of the airport.

C.1. Steps taken to calculate the total area of the airport

The area of the airport is calculated using ArcGIS software. This is done by using the BAG (Overheidspublicaties, 2021) dataset that contains the shape files of every building in the Netherlands. This dataset contains the 'oppervlakte' (Area) of all buildings in the Netherlands, inclusive of airport terminals. To calculate the total area of the terminals in ArcGIS, the steps outlined in Figure C.1, were undertaken in ArcGIS. Firstly, the borders of the airport need to be determined within ArcGIS, in order to facilitate the extraction of terminal buildings from the BAG database. The total area is then calculated based on the terminal buildings selected in ArcGIS, which is useful in calculating the material stock. The material stock results are then stored in the LCI database which is useful for the environmental impact assessment.

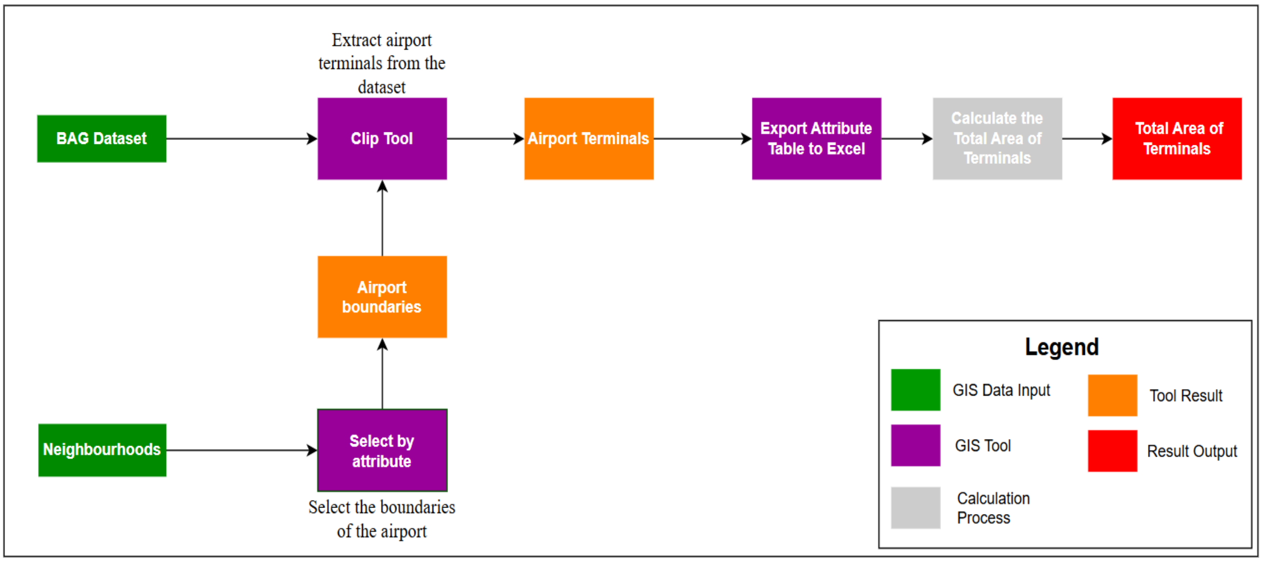

Figure C.1: Steps taken in ArcGIS Pro to calculate the total area of airport terminals

C.2. Calculating the material quantity of runways and taxiways

To calculate the material quantity of runways, two things are required, the material requirements of the runway and the surface area of the runway. The surface area of the runways and taxiways can be obtained from GIS spatial datasets. However, if these datasets are not available, they can be developed by following the steps outlined in Figure C.2.

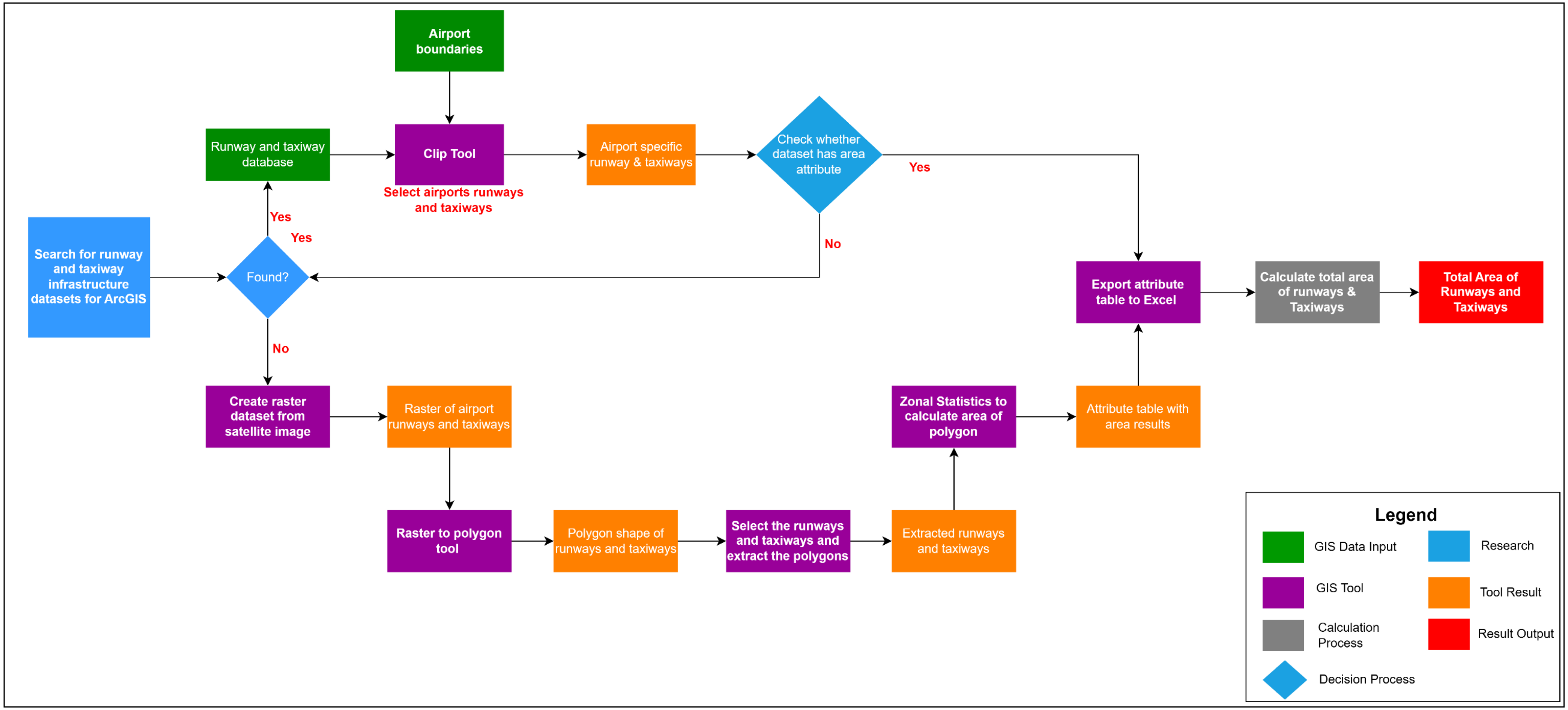

Figure C.2: Steps taken to develop the GIS dataset for airport runways and taxiways

D. Excel Template Screenshots

The first worksheet in the template stores the metadata of the template, with a description of the different worksheets present in the template and also a description of the different columns in each worksheet describing what type of data input is required (whether it is the numerical inventory, supplier name or comments from the practitioner.

This LCI template is inspired by the general LCI template developed by Karen Saavedra Rubio, and modified to meet the purposes of storing airport inventory in a transparent manner. This section describes each worksheet and its purpose, inclusive of what should be done within each worksheet.

Description of the worksheets where data is stored

Work Sheet	Description
Contact List	This worksheet contains the contact of professionals from whom data was collected from. This input makes the data transparent, since the data source of the inventory can be tracked down to the data provider. In this worksheet it is important to include the name of the oranisation, the name of the individual with their job description, email, telephone number and also the type of data provided by the individual. It is also possible to include extra notes if needed
Airport Construction Inventory	This worksheets stores all the data regarding the construction of the airport. Both primary and secondary data can be stored within this worksheet. Importantly, the dropdown boxes should be used to evaluate the accuracy of the inventory inputted into this worksheet. Furthermore, each data input requires a reference (either to the data provider or the secondary source).
Airport Operation& Maintenance Inventory	This worksheet stores all the data regarding the operation of the airport, which includes data related to the energy and water requirements related to the operation of the airport and also inventory associated with the ground handling of aircrafts, the amount of resources required for the taxiing of a plane and the maintenance of the airport. This list is not exhuastive. Any other data related to the operation of the airport should be stored transparently in this worksheet.
Airport EoL Inventory	This worksheet represents the End of Life activities associated with an airport sich as the treament of waste, the disposal of waste and also the quantity of resources that can be recovered in the event that the airport needs to be decommissioned. However, the inventory related to the deconstruction of the airport is purely hypothetical, following the idea that a complete cradle to grave LCA should also include the EoL of the product
References	This worksheet stores all the references for the secondary data used in the three inventory worksheets (Construction, Operation & Maintenance and EoL). In all worksheets, references are made to the data stored in this worksheet

Description of thecolumn names where data is stored

Column Name	Description
Overall Characteristics	This represents the characteristics of the airport (which can include the area of the terminals, area of the runways , material efficiency of construction etc)
Amount	This cell requires a numerical value which either represents a charactistics value such as area, or a calculated value. In essence, characteristical values such as area is inputted in the area highlighted in yellow, while primary or secondary data (calculated) is inputted in the green highlighted area
Unit	This cell requires the appropriate unit of the numerical value
Flow Name	This cell requires a unique name that identifies the numerical value, for example steel for construction
LCI Background Dataset	This cell requires the name of the background provider which is gotten from LCI datasets. This cell connects the flow to a background process. For example, the flow name for steel can be connected to the background process of steel production
Region	This cell represents the region from which the flow is provided from. For example, if the steel is produced in the Netherlands, then the region will be stored as NL
Uncertainty	This cell requires the uncertainty value of the data in percentage
Distribution	This cell requires a description of the type of statistical distribution used for the data
Reliability	This is the first part where the data is evaluated using the pedigree matrix. If the data is quite reliable, then it gets a score of 1 while unreliable data gets a score of 5, with the criteria present in the drop down boxes
Completeness	This represents how complete the data point is for the airport which can be evaluated using the drop down box
Temporal correlation	This evaluates whether the data used is new or old dependent on the temporal scope of the study
Geographical correlation	This evaluates whether the data is representative of the airport. For example, if the data comes from the Netherlands, and the study is about Schiphol then there is a high geographical correlation compared to data from Spain
Further technological correlation	This evaluates whether the data stored is representative of the current technologies used at the airport
Expert Reference	This is where primary data from experts can directly be referenced back to the contact list
References	This is where secondary data can be referenced back to in the References worksheet in order to transparently store the data (shows which sources were used for the data)
Comments	This is where the inventory creator can add notes on the assumptions done or an explanation of the calculations done.

Figure 6.1. First worksheet in the Excel Template, which stores the metadata of the template

The next worksheets store the necessary inventory according to the respective life cycle phases. If inventory data is collected regarding the construction of the airport, then this data should be stored in the construction inventory worksheet.

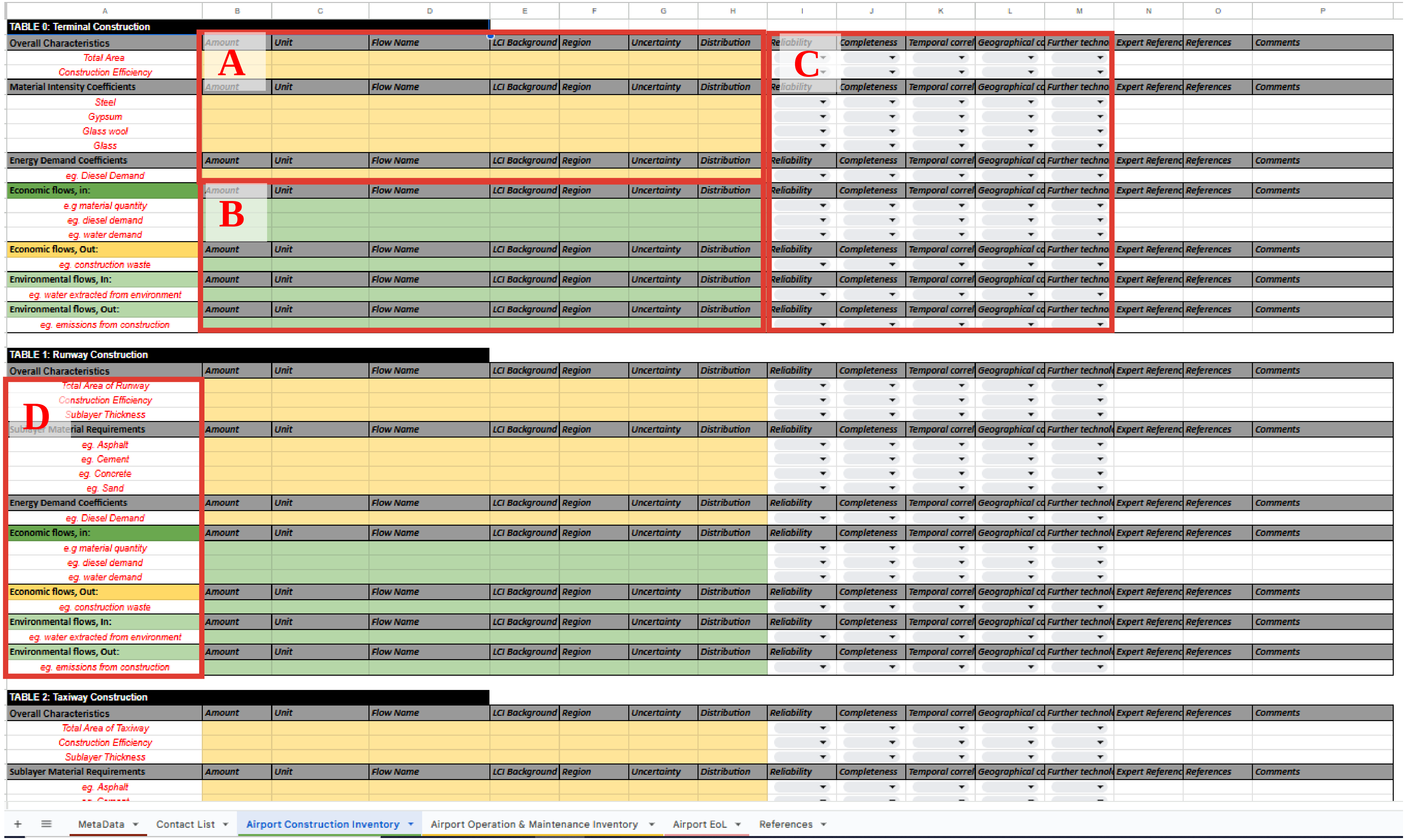

Figure 6.2. Illustration of the tables developed in each of the three worksheets (Construction, Operation& Maintenance and EoL). ***A)*** *This is where raw data can be stored, such as material intensity coefficients, energy demand coefficients, area of airport etc found in literature.* ***B)*** *This is where the calculated inventory is stored. If the data is directly collected from the airport, then it can be included in this section.* ***C)*** *This is the pedigree matrix where the practitioner can describe the data quality based on the five criteria's in each drop down box.* ***D)*** *This are examples of LCI data requirements that can be included in the inventory tables.*