Life Cycle Assessment of Scientific Research: Evaluation of Desktop-Research Projects – Formulation of Goal and Scope and Development of Life Cycle Inventory-Data Questionnaires

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Anggie Rahma Pratiwi
Matriculation Number: 453992

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Primary Evaluator: Daniel Freund

Secondary Evaluator: Dr. Christian Pade

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DECLARATION OF AUTHORSHIP

I hereby affirm that I wrote the master thesis titled Life Cycle Assessment of Scientific Research: Evaluation of Desktop-Research Projects – Formulation of Goal and Scope and Development of Life Cycle Inventory-Data Questionnaires on my own without any assistance of third persons and without other resources and sources as denoted in my work. I indicated all parts which I integrated by wording or by meaning. This work was not in part or in all issue of other examination procedures and was not submitted to other examination authorities.

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Place, Date Signature

Abstract

While researchers actively engage and develop a framework to measure the environmental impact of achieving sustainability, paradoxically, the environmental evaluation of research activities that may take significant resources is often overlooked. DLR launched an internal project called *Vorhaben Klimabilanz* to examine the climate impact of scientific research at a project level. This master's thesis is part of the *Vorhaben Klimabilanz*, presenting the preliminary stage of carbon emission estimation for the selected DLR research projects following the life cycle thinking. However, with the absence of a standardized pre-defined life cycle framework to conduct an environmental assessment at a project level, accordingly, this study adopts some aspects of LCA of Product and Organizational LCA and adds some modifications to find a suitable framework to conduct the so-called LCA of a scientific research project. Following the stage of the LCA Framework based on ISO 14044, this study primarily analyses the first two phases: Goal and Scope definition and part of the Life Cycle Inventory.

This research proposes that working hour personnel is the best available functional unit for LCA of a (desktop-)research project in hand. The LCA of (desktop-)research project considers the project-specific process (direct activities including the scientist working hour profile, commuting, traveling, events, and desktop research workstation) and overhead process (indirect activities including supporting staff activities, infrastructure, energy consumption, as well as scientists' building, energy, and ICT usage). Due to the aggregate data in the overhead process, a specific data proportion method is required to determine each respective desktop research project's input share. As a continuation step in the LCI phase, data questionnaire templates are provided as a supporting instrument for data collecting. In the end, the findings of this study provide support for setting the groundwork for the development of LCA at the project level as well as support long-term sustainability monitoring.

Keywords: Life Cycle Assessment (LCA); Organizational Life Cycle Assessment (O-LCA); scientific research project; greenhouse gas emission; LCI data questionnaire template; life cycle inventory (LCI); LCA of scientific research project

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List of Abbreviations

COP	Conference of Parties
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DLR-FF	DLR - Future Fuels
DLR-VE	DLR - Institut für Vernetzte Energiesysteme
DLR-VT	DLR - Institut für Verbrennungstechnik
EC	European Commission
EEIO	Environmentally-extended Input-Output Analysis
e-LCA	Environmental Life Cycle Assessment / LCA of Product
FTE	Full-time Equivalent
FU	Functional Unit
GHG	Greenhouse Gas
HBK-S	*Hochdruck Brennkammerprüfstand* Stuttgart/ High-pressure Combustor Rig Stuttgart
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment (refer to the LCA framework)
LCC	Life Cycle Costing
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
O-LCA	Organizational Life Cycle Assessment
R&D	Research and Development
SDGs	Sustainable Development Goals
S-LCA	Social Life Cycle Assessment
UN	United Nations

1. Introduction

Chapter 1. The introduction explains the background of the research, research problem, research objectives, as well as the current state of the research. The chapter overview will be presented at the end to demonstrate the overall master thesis structure.

1.1 Background

Sustainability is an essential topic throughout the world and achieving sustainability is becoming an ever more important goal. “The word sustainability stems from the Latin *sub-tenere*, assimilated *sustinere* (to hold up). Since the 1980s the concept has been used in the sense of human sustainability on planet Earth, which has resulted in the most widely quoted definition of sustainability and sustainable development, that of the World Commission on Environment and Development (WCED, Brundtland Commission) of the United Nations (UN) in 1987: ‘Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs’” (WCED, 1987 as cited in UNEP/SETAC 2011, p. 2). According to the Triple Bottom Line concept, there are three pillars of sustainability: economic, social, and environmental (Elkington 1997, p. 70). Sustainable development is increasingly being presented as a pathway to all that is good and desirable in society (Holden et al. 2014, p. 130).

Sustainability is acknowledged as a cross-cutting task where the sustainability goals could be reached only by the togetherness that everyone needs to do their part: governments, the private sector, civil society, and every human being across the world (UNESCO 2017, p. 6). Many nations have, for instance, adopted the UN Sustainable Development Goals, and there are several international treaties regulating environmental sustainability issues (e.g., climate protection) or social sustainability (e.g., labor rights and protection). For example, one of the international treaties on climate protection is the Paris Agreement. The Paris Agreement was adopted on 12 December 2015 by 196 Parties at Conference of Parties (COP) 21 in Paris where its goal is to keep the rise of global temperature to well below 2 °C, preferably to 1.5 °C, as compared to pre-industrial levels (UNFCCC 2022b). For Germany itself, the government decided to follow an emissions reduction pathway with a final target of 80 to 95 percent lower greenhouse gas emissions per year compared to 1990 by 2050 (BMUB 2016, p. 7).

For years, sustainability research has been chiefly centered on certain sectors. For instance, the German government emphasizes the energy sector, industry, building, transport, agriculture, waste management and others (BMUV 2022). Within those six main industries, the energy sector is the most significant GHG emissions contributor of 221 million-ton CO_2-eq. in 2020, accounting for approximately 30% of the overall five sectors’ emissions. One initiative on the energy sector, such as shifting toward renewable energy, has resulted in 45.5% of Germany's gross electricity consumption from renewable sources, or 10.4% above the 2020 target (BMU 2021, p. 19). Another sector is waste management and others, which in total represent the remaining 9% of Germany's GHG emissions. One of the sectors included in this category is the research and development sectors. Even though it only represents around 9% of the total German GHG emission, it is worth paying attention to this sector because the volume of R&D activities is arguably huge. By 2020, the German government and industries together invested around 105.9 billion Euro for R&D expenditure, or about 3.14% of German GDP. In 2020, the R&D sector provided job opportunities for a vast amount of scientists and researcher personnel as of 735,239 full-time equivalents (Federal Statistical Office 2022).

A considerable number of areas and fields have initiated policies and measures relating to sustainability. Nevertheless, sustainability practices in the research process have largely been neglected. "Research is a process of steps used to collect and analyze information to increase our understanding of a topic or issue" (Creswell 2012, p. 3). "R&D comprise creative and systematic work undertaken in order to increase the stock of knowledge – including knowledge of humankind, culture and society – and to devise new applications of available knowledge" (OECD 2015, p. 28).

Researchers have already developed cutting-edge technologies and published theories and frameworks to support sustainable development, but it is uncommon for them to assess the sustainability impacts of their own research activities, e.g., in the sense of their greenhouse gas emissions. Since early 2000, there has been an increasing demand for mitigation of environmental impacts and/or carbon emissions of scientific conferences and implementation of sustainable conference management (Neugebauer et al. 2020). This increasing demand for mitigation is due to the rapid expansion of such scientific events and the number of scientists. As of 2015, there were over 8.4 million full-time and full-time-equivalent researchers globally (Sarabipour et al. 2021, p. 296). By 2018, the global number of researchers (full-time equivalent /FTE) is around 13.7% since 2014 (UNESCO 2021, p. 35). In the general practice, there is high possibility of scientists attending several national and international scientific conferences; therefore, this activity inevitably generates a significant amount of GHG emissions. Furthermore, scientific events serve only a partial component of a holistic scientific research project. Other significant components of a holistic scientific research project, such as the equipment, infrastructure, and daily scientist working effort, cannot be reflected by scientific events alone. Accordingly, assessing the sustainability impact of scientific events alone is inadequate to capture the actual sustainability impact of the scientific research process as a whole. Some paradoxical problems arise in public discourse concerning the sustainability of scientific research, for example, the practice of researchers flying by airplane to attend environmental conferences abroad (Grémillet 2008).

1.2 Research Problem

Researchers generally undertake this 6-step research procedure to achieve proper results, which starts by: (1) identifying a research problem, (2) reviewing the literature, (3) specifying a purpose for research, (4) collecting data, (5) analyzing and interpreting the data, and (6) reporting and evaluating the research (Creswell 2012, p. 7). During the scientific research processes, both tangible and intangible resources needed might be significant (Aujoux et al. 2021b; Larsen et al. 2013; Letete et al. 2011). For instance, the prototype phase of the GRAND Project – a multi decade astrophysics experiment – requires 300 radio antennas equipped with solar panels, which will eventually be deployed in an open land area covering more than 200 km^2. This prototype phase (GRANDProto300) will continue to expand over the course of five years. In the final large-scale phase (GRAND200k), it will deploy 200,000 radio antennas in over 200,000 km^2. The GRAND project will also involve international researchers who must travel across the globe to/from the project facility using different kind of transportation means, including air travel. A study by Aujoux et al. (2021b, p. 2) estimates that the GRAND200k project will generate 13,407t CO_2-eq. per year. In that case, the yearly CO_2-eq. emissions of GRAND200k would equal to the yearly CO_2-emissions of approximately 1,577 German citizens[1].

There are several institutions and organizations that specialize in conducting scientific research. One of them is Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR). DLR is the aeronautics and space research center of Federal Republic of Germany. Research institutes of DLR conduct research and development in five fields i.e., aeronautics, space, energy, transport, security, and digitalization (DLR 2020, p. 11). Under the sustainability officer initiatives in the past years, DLR monitors a few energy-related and some employee-related key indicators as a whole organization and assesses each operation location. In 2020, the DLR sustainability officer published the DLR Sustainability Report 2018/2019, which discloses a total of around 25,160-ton CO_2-eq.[2] emitted by the entire DLR organization (DLR 2020, p. 55). Additionally, there are a few more detailed environmental performance data presented such as electricity, gas, heating oil, and water consumption of 8 locations, specifically Berlin-Adlershof, Bonner Bogen, Braunschweig, Göttingen, Cologne, Lampoldshausen,

[1] In 2019, the average German CO_2 emissions is 8.5t CO_2-eq. per capita (BMU 2021, p. 4).

[2] This number refers to the CO_2 emissions of electricity, gas, and oil consumption of the buildings (operational phase) as well as the CO_2 emissions caused by travelling using company vehicles, train and plane. However, CO_2 emissions caused by train-trip is set to zero because Deutsche Bahn would use electricity from renewable resources.

Oberpfaffenhofen, and Stuttgart (DLR 2020, p. 57). The Sustainability Management Unit of DLR would like to investigate to what extent sustainability assessment could be implemented not only at the level of the whole organization or for each individual location, but also at the level of single research projects. They would like to determine whether it is practically and methodologically feasible to incorporate project-level sustainability monitoring into DLR's sustainability management process. Concurrently, there is a strong drive to quantify precisely the significance of the effects of specific research projects.

In 2021, one of the DLR institutes named DLR – Institut für Vernetzte Energiesysteme (DLR-VE) was granted an internal pilot project called *"Vorhaben Klimabilanz".* In general, the project aims to evaluate the climate impacts of selected DLR research projects. One widely used method to carry out climate impact studies is the life cycle assessment (LCA) framework. LCA is a "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle" (ISO 2006a, p. 7). The "classic" LCA is the environmental Life Cycle Assessment (e-LCA) in which the object under study is a physical product, such as coffee, shoes, etc., or a process/service such as mobility service, catering service, etc. In addition to e-LCA, the Organizational Life Cycle Assessment (O-LCA) is also an available potential method. "O-LCA is a life cycle approach that aims to support the identification and quantification of environmental aspects within and beyond the gates of the organization" (UNEP/SETAC 2015, p. 30). In principle, the object under study of O-LCA is a whole organization, such as a whole university, a whole glass company, etc. Therefore, neither e-LCA and O-LCA are quite suitable to assess the climate impact of a scientific research project, given that the object under study and focus are different. Also, a comprehensive explanation of how to determine the appropriate framework to assess environmental impact of scientific research projects is required, as there are various parameters involved in both e-LCA and O-LCA (e.g., functional unit, reference flow, system boundary, etc.) which need to be defined based on certain need and demand. Consequently, there is an urgency to bridge the gap and adapt some aspects of existing LCA frameworks to conduct a so-called LCA of a scientific research project.

1.3 State of Research

"Scientific activity can contribute to the mitigation of climate change but also unavoidably consumes energy and emits greenhouse gases (GHGs)" (Song et al. 2015, p. 1). Often, GHG emissions are more noticeable within manufacturing and service-providing organizations, whereas they may be less apparent within knowledge-based organizations. These knowledge-based organizations include education, science, consulting, finance, insurance, and communications (El Geneidy et al. 2021, p. 2). Hence, on this matter it may be deduced that scientific activities are crucial parts of knowledge-based organizations, but may also pose challenges to be assessed. The absence of a predefined and uniform framework for assessing the environmental impact of scientific research projects represents a potential major challenge. For this reason, in the few studies undertaken on knowledge-based organizations and their activities, insufficient attention has been paid to the project level.

Previously, several GHG emission assessment studies on universities and other higher education organizations have been conducted (El Geneidy et al. 2021; Larsen et al. 2013; Letete et al. 2011; Li et al. 2020; Song et al. 2015). Larsen et al. (2013) estimated the total GHG emission of the Norwegian University of Technology and Science (NTNU) for the year 2009 using Environmental Extended Input-Output (EEIO) modeling. “Environmentally-extended input-output analysis (EEIO) is a long-established technique that continues to grow in popularity as a method for evaluating the relationship between economic activities and downstream environmental impacts” (Kitzes 2013, p. 489). One of numerous justifications for using EEIO modeling in this study is that, given the high complexity level and extensive scope of this study, EEIO provides well-qualified and reliable accuracy data efficiently in regards to time and effort (Larsen et al. 2013, p. 40).

In 2009, NTNU had around 20,000 students and 5,500 employees, resulting in a total of 92kt CO_2-eq equivalent GHG emissions. This number covers some activities of university residents’ energy consumption (electricity and heating), travel, building construction and maintenance, supporting equipment (computers, machinery, etc.), consumable goods, and others (Larsen et al. 2013, p. 41). To understand the significant environmental impacts of university activities, as a comparison, one-year NTNU’s GHG emission represents 8% of Rwanda’s yearly GHG emissions[3].

Not only focusing on the organization as a whole, some studies consider the subject from a different perspective, analyzing the GHG emissions per Ph.D. project or scientific paper. Using LCA framework methodology and SimaPro LCA software, Achten et al. (2013) estimated the GHG emissions of their Ph.D. project case. They concluded that a four-year-case PhD project generates around 21.5 t CO_2-eq. (with a breakdown detail of some various functional units such as 2.7t CO_2-eq per peer-reviewed paper, 0.3 t CO_2-eq. per citation, and 5.4 t CO_2-eq. per h-index unit at graduation). This four-year Ph.D. project’s emissions are equal to the yearly emissions of around 245 citizens of Rwanda[4]. Meanwhile, Song et al. (2015) estimated GHG emissions of scientific publication using a case study conducted at the Dalian University of

[3] In 2018, the average Rwandan CO_2 emissions is 0.1t CO_2-eq. per capita (The World Bank 2018). The population of Rwanda in 2020 is around 12,952,200 people (The World Bank 2021).
[4] See footnote no.3

Technology. They proposed a time-loaded conversion coefficient to transfer indirect emissions to final consumer activities based on various surveys, certification database of Energy Star, reviewed LCA studies and literature, etc. In this instance, Song et al. directly translate the functional unit of e-LCA for their studies as one piece of scientific publication and found that a scientific publication contributes 5.4 kg CO_2-eq. Although this figure seems insignificant, the system boundary considered was limited to four processes, namely literature searches, downloads, reading, and writing. Consequently, this research constitutes only a tiny portion of the complete scientific research.

Fewer studies are focusing on smaller boundaries, rather than the whole organization level and conducting in-depth sustainability analysis of scientific research supporting activities such as conferences, academic mobility, internet usage, and cloud data storage (Boussauw and Decroly 2021; Ong et al. 2014; Posani et al. 2018; Raby and Madden 2021; Spinellis and Louridas 2013). In 2019, there was a study on the environmental impacts of the International Conference Series in Europe (Neugebauer et al. 2020). Using the LCA method, GaBi LCA software, and a few assumptions[5], the authors found that the conference caused 0.57t CO_2-eq. per participant. This is a significant number, as it indicates that one participant's activities of this 3-day conference have already accounted for 6.7% of a German citizen's yearly CO_2 emissions.

Moreover, scientific research could take the shape of a large-scale project utilizing a vast number of materials and equipment. In 2021, a study was conducted on the carbon footprint of the GRAND Project, a multi-decade astrophysics experiment (Aujoux et al. 2021b). The GRAND Project will be developed into three phases, with the first/prototype phase being the smallest one, and the second and third/final phases being considerably larger (concerning personnel, the hardware used, and computational efforts). In the final phase, known as the GRAND200k project, 200,000 radio antennas will be deployed in over 200,000 km2 areas and between 400 to 1,000 members will be involved. Some input data are included in the system boundaries, such as scientist commuting and business travel activities, digital technologies data (e.g. electronic devices and electricity consumption for all digital technology-related activities), and hardware equipment (e.g. raw materials and transportation of radio detection units).

[5] Assuming 800 participants were attending the conference and some activities included were committee conference preparation (such as committee meeting's consumption, computer usage, traveling, and hotel overnight stay), as well as conference execution (such as energy consumption at venue, catering, hotel overnight stays, participant travels to and from conference).

The authors assessed the GHG emissions of all phases by multiplying GHG-generating activity data with emission factors and estimated that the GHG emissions that may be generated in the final phase are approximately 13,407t CO_2-eq. This figure is quite impressive, indicating that a single research project may generate GHG emissions of quite significant dimensions, as the authors note: “As an illustration, the 13 400 tCO2e/year emission estimate of the GRAND200k phase represent about 7900 Paris-Dunhuang return flights. Another comparison can be made with car manufacturing, which emits roughly 15 tCO2e per car: the emissions from GRAND200k per year corresponds to that of the production of less than 1000 cars” (Aujoux et al. 2021b, p. 15). Below is the particular methodology presented by Aujoux et al. (2021a, p. 387) regarding greenhouse gas of large-scale physics experiment assessment. The following table outlines some potential input that could be incorporated into the assessment.

Table 1: Main sources of GHG emissions in a large-scale physics experiment (Aujoux et al. 2021a, p.387), all data in the table is presented without any changes

Sources of emissions	**Quantity of GHG-generating activity**	**Emission factor**
Professional travel	Total distances travelled per year per transportation mode	CO_2e per passenger-kilometer
Digital		
Devices (such as computers, screens)	Manufacturing and usage of each type of device	CO_2e per device
Communication	Emails sent	CO_2e per MB
Simulations	CPU hours	CO_2e per CPU-hour
Data transmission and storage	Electricity consumption of servers	CO_2e per kWh
Hardware		
Metal devices	Metal weight	CO_2e per kg of metal
System batteries	Battery weight	CO_2e per kg of battery
Solar panels	Installed area	CO_2e per m^2
Transportation	Distances travelled and weight hauled per transportation mode	CO_2e per ton-km

All in all, based on an analysis of some existing journals, a number of methodologies (including its parameters like system boundary and functional unit) might be used to assess the environmental impact of knowledge-based organization and their operations. Even if the methodologies of the aforementioned studies vary, they all demonstrate the significant impacts of knowledge-based activities in comparison to other activities. For instance, the GHG emissions generated by one-year of activity of a European university are equivalent to 8% of the yearly GHG emission of an African country[6] (Larsen et al. 2013), the GHG emissions from a participant's activities of a 3-day international conference in Europe already accounted for 6.7% of the total yearly CO2 emission of a German citizen or around 8x greater (Neugebauer et al. 2020), and the yearly emission of a large astrophysics experiment project called GRAND200k represent about 7,900 Paris-Dunhuang return flights[7] (Aujoux et al. 2021b, p. 15), and so on.

However, there is no single methodology that is entirely suitable to assess the environmental impact of scientific research at the project level. The various methodologies may also create confusion for a person with minimal expertise who wishes to conduct and environmental impact assessment of a certain matter. The misunderstanding may result from the different kinds of intended usage and scoping techniques, the various parameters and terms involves, and the potential advantages and disadvantages of each methodology. Due to the aforementioned reasons and the significant environmental impact facts, it can be inferred that there is a need to fill the gap in the existing framework and adjust it accordingly to investigate the holistic environmental impact of scientific research at a project level.

This master thesis presents the comprehensive explanation in order to achieve each specific objective (see section 1.4 Research Objectives) and serves as an integral part of the *Vorhaben Klimabilanz* project (see section 3.1.2). In the future, this master thesis could contribute to the enhancement of sustainability assessment (and management) of research activities by enabling the establishment of a uniform and standardized environmental assessment framework for scientific research at project level. Furthermore, given this study is part of DLR's internal project, it could be helpful to help set the groundwork for the future transformation of DLR sustainability assessment and monitoring.

1.4 Research Objectives

The general objective of this master's thesis is to conduct parts of a life cycle assessment study of a number of scientific desktop-research projects at DLR - Institut für Vernetzte Energiesysteme (DLR-VE). This master's thesis will focus on the first and second phases of LCA which are the Goal and Scope phase and the Life Cycle Inventory phase. Furthermore, the Life Cycle Inventory phase will simply encompass the Data Questionnaire Development. There are five scientific desktop-research projects which could be assessed using LCA within this master's thesis. These projects include:

[6] See footnote no.3

[7] One-way flight distance from Paris-Dunhuang is about 6,925 km (Rome2rio 2022) and emits approximatively 1.7t CO_2-eq. (Aujoux et al. 2021b, p. 6)

1. MTHEO project: development of a prospective multi-criteria assessment method for a comprehensive comparison of energy technologies and their development potential in terms of energy policy (DLR-VE 2017a).
2. MCASE/MCASE+[8] project: further development of a multidimensional evaluation method using the example of electromobility (DLR-VE 2018).
3. HI-CAM: a two-year project that aims to effectively communicate strategies to combat climate change and its effects on various areas of human development (DLR-VE 2022).
4. MuSeKo: a model-based analysis of the integration of intermittent renewable electricity generation by enhanced coupling of power, heat, gas and transport sector (multi sector coupling) (DLR-VE 2016).
5. Zero Brine: a project that aims at demonstrating new solutions to recover and recycle valuable materials present in industrial waste-water streams, in order to implement a circular economy approach in various process industries (DLR-VE 2017b).

Furthermore, the specific objectives are:

1. To bridge the gap between e-LCA, O-LCA, and LCA of research projects by developing a suitable LCA of scientific desktop-research project methodology.
2. To define a functional unit for LCA of scientific desktop-research project.
3. To define the system boundary of LCA study of scientific desktop-research projects.
4. To develop a data questionnaire template/data list requirement of scientific desktop-research projects for the data collection phase.
5. To define the suitable proportion method of aggregate energy as well as material consumption data in the data collection phase.

A more in-depth explanation of each item included in the specific objectives, such as functional unit, system boundary, data questionnaire template, and data proportion method will be explained further in the sections 2.1 Life Cycle Assessment (LCA) to 2.3 Adaptation of e-LCA and O-LCA Methodology to the Life Cycle Assessment of Research Projects.

1.5 Chapter Overview

The chapter overview explains the chapter structure and outline of the whole thesis.

1. Introduction

The introduction chapter lays the foundation of the entire thesis study. The writer provides the context of the study by offering an overview of the selected topic area, the research issue

[8] MCASE+ is a follow-up project of MCASE, from this point on, the term “MCASE(+)” refers to both MCASE and MCASE+ projects.

which needs to be addressed and solved, and the current information and review of prior findings given in the State of Research section. As a result of the findings in the State of Research section, the writer formulates thesis objectives to fill the gap and provide solutions for future benefit. At the end the outline or structure of the thesis is presented.

2. Main Approach and Methodology

The Main Approach and Methodology Chapter follows The Introduction Chapter. The writer provides comprehensive information on the methods used to achieve the research objectives. Following the rough analysis result of the current state of research, this thesis adopts the most widely used method to assess GHG emissions. Some justifications for how the writer adopt this particular method is explained.

3. Results and Discussion

Based on the selected approach and methodology explained in the previous chapter, the writer continues with the research population's identity. Then, the writer designs and develops thesis outcomes in order to answer the research objectives including a thorough rationale and analysis for each finding. There are two main research outcomes in this thesis: the explanation of the goal and scope parameters and data questionnaire templates.

4. Conclusion and Outlook

Conclusion and Outlook is the last chapter of this thesis. This chapter outlines the results and key findings of the study. Furthermore, some limitations of the study are presented in order to give the big picture of study's weaknesses. This aspect needs to be communicated to enhance this study. Finally, some possible future works are suggested to emphasize some opportunities for future scholars. The future works are generally closely related and built due to the current study's limitations.

2. Main Approach and Methodology

This chapter aims to comprehensively describe and justify all the research rationale to conduct the research. Starting with the literature background, which explains the theoretical background and framework, this chapter continues with theoretical framework adjustment based on the research needs, data collection and processing phase. The Appendix 1 illustrates the framework system of conducting this study.

2.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 2006a, p. 7). The life cycle is defined as “consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal” (ISO 2006a, p. 11). The life cycle perspective enables decision makers to have a broad and holistic view of a product and its optimal potential to increase or reduce its environmental, social, or economic impact. Another important benefit of having a life cycle perspective is to avoid shifting the sustainability impact of certain life cycle phases to different life cycle phases or other impact categories, and many more (UNEP/SETAC 2012, p. 18). The LCA standardized framework of assessment is published in ISO 14040 (2006) and ISO 14044 (2006) which intends to carry out environmental LCA (e-LCA) studies and is widely accepted in the international community.

In relation to the Triple Bottom Line concept (Elkington 1997, p. 70) (also commonly called the three Ps: people, planet, and profits), the e-LCA mainly focuses on Planet Pillar, where Social Life Cycle Assessment (S-LCA) concentrates on People Pillar, and Life Cycle Costing (LCC) puts Profit Pillar as the priority. Life Cycle Costing “aimed to provide an assessment of the costs of a product across its entire life cycle consistent to an (environmental) LCA” (UNEP/SETAC 2011, p. 15). Based on ISO 15686-1:2011 terms and definitions, LCC is a “methodology for systematic economic evaluation of life-cycle costs over a period of analysis, as defined in the agreed scope” (ISO 2011, p. 2). Within this context, the life-cycle cost could be defined as the “cost of an asset or its parts throughout its life cycle, while fulfilling its performance requirements” (ISO 2011, p. 2). Moreover, “Social Life Cycle Assessment (S-LCA) is a methodology to assess the social impacts of products and services across their life cycle (e.g., from extraction of raw material to the end-of-life phase, e.g., disposal)” (UNEP/SETAC 2020, p. 20).

The three distinct assessment approaches, Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), and environmental Life Cycle Assessment (e-LCA), make up Life Cycle Sustainability Assessment (LCSA) (UNEP/SETAC 2011, p. 14). “Life cycle sustainability assessment (LCSA) refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle" (UNEP/SETAC 2011, p. 3). "The main drivers for the scientific developments towards Life Cycle Sustainability Assessment (LCSA) are the paradigm shift from environmental protection towards sustainability and the current developments with regard to evaluation methods and tools for environmental and sustainability performance" (Finkbeiner et al. 2010, pp. 3309–3310). To date, it is a common practice that the research being conducted involves one or more LCSA standalone assessment approaches. Figure 1 illustrates how to schematize LSCA (Klöpffer 2008; Finkbeiner et al. 2010, p. 3312).

Figure 1: LCSA Conceptual Formula (Klöpffer 2008, p. 93; Finkbeiner et al. 2010, p. 3312)

Following the (ISO 2006a, p. 17) on Life Cycle Assessment, the LCA consists of four stages: (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation, which can be seen in Figure 2.

2.1.1 LCA: Goal and Scope Definition

The first step in LCA — called Goal and Scope Definition — is intended to formulate the research objective and scope. This step should explain the rationale for the research, the purpose or ultimate use of the research and the target audience. "It includes defining the functional unit, the system boundaries, the assumptions and the (de)limitations of the study, the impact categories, and the methods that will be used to allocate environmental burdens" (UNEP/SETAC 2011, p. 7). Among other things, this master thesis delivers a more comprehensive explanation of some items-related LCA scope such as the object under study, the functional unit and reference flow, as well as the system boundary. The object under study of LCA is an individual product in the form of a (industrial) good or service, for instance, shoes, laptop, washing machine, car, boiler, etc.

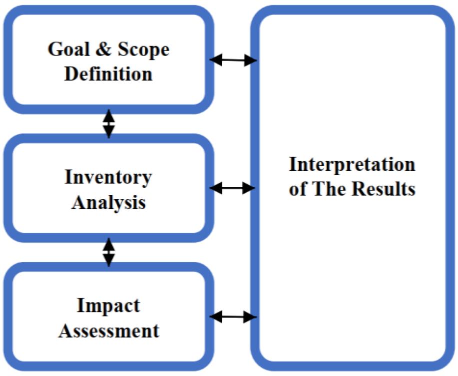

Figure 2: Stages of an LCA (ISO 2006a, p.17)

Another item of LCA scope is functional unit. “The functional unit defines the quantification of the identified functions (performance characteristics) of the product” (ISO 2006a, p. 23). “The purpose of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense)” (ISO 2006b, p. 17). For example, the functional unit of LCA of shoes could be determined as feet protection of one person for 6 months, the functional unit of LCA of a washing machine is laundry washing capacity of 7 kg at 40°C, etc.

Functional unit is closely related to the reference flow, which is a quite common case that people do not fully understand the difference and could mix it up or use it interchangeably. The reference flow is defined as “measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit” (ISO 2006a, p. 11). To make it clearer, continuing the previous examples such as LCA of shoes, one could define the reference flow to be one pair of shoes, while for the LCA of a washing machine, the reference flow might be one washing machine with capacity of 7 kg.

Functional unit and reference flow play an important role in regard to LCA study comparability. It is necessary for the functional unit of an LCA study to be determined and expressed accurately and consistently so that relevant comparisons with other product systems that serve the same purpose of fulfillment can be made adequately. Not only does it consider the functional unit, but also other aspects, characteristics, and further specifications of a system which varies individually for each study depending on the objectives and should be made in detail to have a realistic and comparable LCA study. Still, it is not that easy for someone to compare and judge the product quality based on its LCA study, for instance, the two washing machines produced by different companies even though both have the same washing capacity, the same functional unit and reference flow, because other factors such location of manufacture, machineries used by the manufacturer, etc. affect the LCA result.

Moreover, the system boundary is defined as a “set of criteria specifying which unit processes are part of a product system” (ISO 2006a, p. 11) while product system is a “collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product” (ISO 2006a, p. 11). To define system boundaries in LCA, it is preferable to consider several life cycle stages and unit processes, for instance, acquisition of raw materials, inputs and outputs in the main manufacturing/processing stage, use phase, end of life phase, and so on. To ease understanding, the writer created a fictional simplified System Boundary of the LCA of a laptop, presented in Figure 3 below. In Figure 3, the “classic” system boundary of LCA studies shows different types of life cycle phase of a product and involves input flows, unit processes, and output flows. For example, the system boundary of the LCA of a laptop considers the production phase, use phase, and end of life phase. This type of LCA is called cradle-to-grave, which means that the input added in the system includes the raw material acquisition from suppliers, for example, the production process of LCD panels, motherboard, keyboard, as well as other laptop's components; laptop assembly process, storage, and distribution process in the manufacturer's sites; laptop usage by customer; as well as the end of life treatment such as disposal of the laptop by customer and/or third parties. In this cradle-to-grave system boundary, the manufacturer does not always have the major share of responsibility in regard to the product's environmental impact. The reason is because there are many other parties involved along the life cycle phase, for instance, in the use and end-of-life phase. Even though a manufacturer already developed certain laptop qualities and specifications, the actual habits of usage and disposal treatment will mostly depend on each consumer.

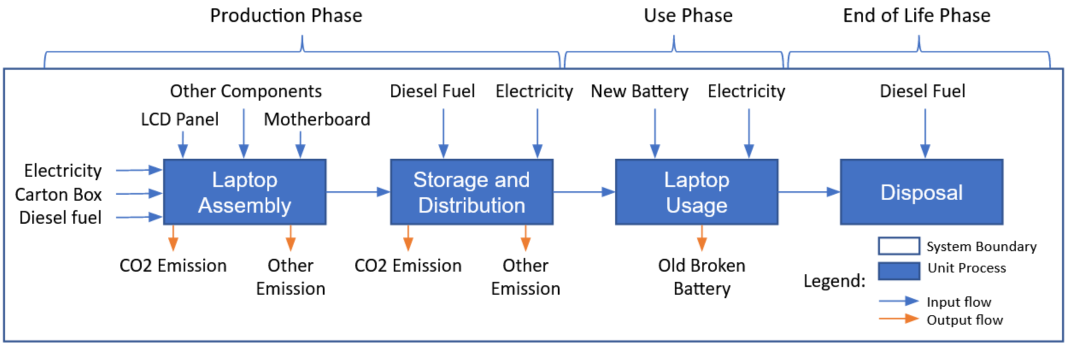

Figure 3: (Fictional) Simplified System Boundary of LCA of Laptop

In some cases, instead of cradle-to-grave LCA assessment, a manufacturer may conduct cradle-to-gate LCA assessment because they have the most responsibility here. The difference is in the life cycle phases included in the system boundary, wherein the cradle-to-gate only includes, for example, the production phase and excludes the customer usage phase as well as disposal treatment. By doing a cradle-to-gate study, a manufacturer may point out better which part could most be improved by their own decisions and not depending on other parties.

2.1.2 LCA: Inventory Analysis

Life cycle inventory analysis (LCI) is the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 2006a, p. 8). Some essential steps involved in carrying out the LCI are data collection and data calculation including data validation and refining the system boundary (ISO 2006a, p. 26).

After the goal and scope — including functional unit, reference flow, and system boundary — are defined, the data collection process is then followed. The data collection phase is intended to gather all data needed for each unit process following the predefined scope which mainly categorize in the form of energy consumption data, raw material data, ancillary data, product, waste, and various emissions (ISO 2006a, p. 26). Take an example of Figure 3, in the Laptop Assembly unit process, there are energy consumption input such as electricity where the actual electricity consumption data (e.g. in kWh) may be collected from the company's utility department based on the monthly electricity meter or bill; raw material input such as LCD panel, motherboard, carton box (for packaging) which could be gather from procurement department or production manager; and emission data like CO_2 emission which could be retrieved from actual emission testing or commercial database. Waste could be seen, for example, in the Usage unit process, where a person needs to replace an old laptop battery, hence an old broken battery is a waste of Usage unit process.

In principle, both qualitative and quantitative data are collected from eligible primary as well as secondary data sources. Primary data is all data which are acquired by the actual measurement or calculation in regard to specific product of specific activities and company, while secondary data is all data which are generic or not organization/company-specific data and usually acquired from publicly shared database or documents. Choosing data sources and data to be used must be done carefully because it will strongly affect the accuracy and credibility of the study. Some common primary data sources that could be used as LCA input data are actual data from company's database system (e.g., human resource data from SAP), company surveys and interviews (e.g., employee commuting survey conducted by one department), any document which contained the company-specific data, etc. Meanwhile, the secondary data sources of an LCA study could be in the form of scientific publications, government documents, standards and patents.

The data collection phase is furthermore continued by the data calculation phase. In this phase, data gathered from data sources are validated, documented, and cross-checked to the predefined scope such as functional unit and system boundary. In principle, the whole data calculation phase is intended to assure the consistency of calculations, procedures and assumptions used throughout the study as well as to verify the data requirements have fulfilled the intended application. Data validation "may involve establishing, for example, mass balances, energy balances and/or comparative analyses of release factors. As each unit process obeys the laws of conservation of mass and energy, mass and energy balances provide a useful check on the validity of a unit process description" (ISO 2006b, p. 27). Data documentation here not only refers to the recording of actual raw data received from data sources but also the comprehensive explanation and recording of the background calculation, estimation, measurement process, as well as additional assumptions and omissions.

Cross-checking the predefined scope is necessary and common due to the iterative nature of LCA study because by this time, researchers might have a better and more detailed picture of what could be included or omitted from the first predefined system boundary. Background calculations might be taken in the first place because all data must be determined to make an appropriate flow in each unit process. For instance, in the Laptop Assembly unit process (Figure 3), the raw data of diesel oil used for a van transporting laptops to an on-site warehouse is 50 liters. One van is able to transport multiple laptops. Therefore, one should know how many laptops are transported by a van which consumed 50 liters of diesel oil and find the share of oil consumption based on the predefined functional unit e.g., to transport one laptop requires 0.5 liters of diesel oil used by a van.

To facilitate the LCI phase to be more efficient and smoother, there are several commercial LCA softwares available which could be utilized to structure, model, calculate, and store LCI data. Also, by using this software, the LCI data could then be connected to the impact assessment categories (this stage so called Life Cycle Impact Assessment/LCIA, further explanation is presented in Section 2.1.3 below). Some available commercial software, for instance, are SimaPro, GaBi, Umberto, etc. Each software is supported by a particular database, which could be from a commercial LCA database such as ecoinvent, as well as companies/organizations' internal database. Ecoinvent is an LCA database containing around 18,000 reliable life cycle inventory datasets of several sectors. For instance, a fictional laptop manufacturer called Dello GmbH may not produce all the components of a laptop under their company: they may source the pre-manufactured components from other manufacturers. Dello GmbH may take ecoinvent life cycle database of some pre-manufactured components such as printed wiring board life cycle data when doing e-LCA assessment of their laptop products because they do not have the actual data from their manufacturing plant.

In general, this LCI whole phase might involve several people from various departments and will be resource intensive. Some factors affect this process are the data storage structure in a company, formal procedure in retrieving data, and the presence of LCA software, etc.

2.1.3 LCA: Life Cycle Impact Assessment (LCIA) and Interpretation

LCIA and Interpretation are the two last stages of an LCA study. LCIA is a "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 2006b, p. 8). There are some mandatory and optional LCIA elements: the mandatory elements are selection of impact categories, category indicators, and characterization models; classification; characterization; the optional elements are normalization, grouping, and weighting (ISO 2006a, p. 30). This section will explain further only the mandatory elements because the optional elements are not necessarily relevant for this thesis. The comprehensive explanation of optional elements could be seen in the ISO 14044 2006, p. 41-43.

The first important step in LCIA is selection of impact categories, category indicators, and characterization models. The impact categories are a "class representing environmental issues of concern to which life cycle inventory analysis results may be assigned" (ISO 2006b, p. 13). where the category indicators are a "quantifiable representation of an impact category" (ISO 2006b, p. 14). This selection process should be taken following the defined goal and scope defined in the first phase. There are several impact categories that could be chosen based on two levels: (1) impact categories on midpoint level such as climate change, ecotoxicity, ozone depletion, land-use, etc. and (2) impact categories on endpoint level such as human health, natural environment, and natural resource. For example, a study chooses to take the midpoint approach by using climate change as impact category, the infrared radiative forcing (W/m2) as category indicator and using the Baseline model of 100 years of the Intergovernmental Panel on Climate Change (IPCC) as characterization model (ISO 2006b, p. 37).

The step is followed by the classification process where the chosen impact category is assigned to the previous LCI data. Next, the characterization process or calculation of indicator results should take place. Characterization "involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category" (ISO 2006b, p. 39). It means all of the data in the LCI is converted using certain conversion factor from some existing LCIA methods, for example, to calculate climate change impact categories, an LCA study may use a conversion factor from IPCC 2021 method such as the emission factor of diesel oil is 74,100 kg CO_2-eq./TJ (IPCC 2022a). Some other available LCIA methods are ReCiPe, CML-IA, TRACI, IMPACTWorld, etc. The outcome of characterization is a numerical result of each of the selected impact categories, including the detailed actual results in the level of each unit process (e.g., 10ton CO_2-eq. generated in the Laptop Assembly Unit Process, where 50% of the CO_2 emission contributed by electricity consumption to produce an LCD panel). It means that the specific unit process which generates the most negative environmental impact or so-called hotspot of each impact categories could be visible. As previously mentioned in section 2.1.2, this whole-lenghty LCIA process could be eased by utilizing a commercial LCA software. For example, the SimaPro LCA software is equipped with an LCA database named ecoinvent, which can be easily used as secondary data source, as well as model and store the LCI data. In addition, there are built-in LCIA methods such as ReCiPe (and many more) which can be directly connected to the LCI model and could largely eliminate the manual calculation and characterization. The LCIA result is presented in several comprehensive visualizations such as Sankey diagram, table, bar chart, so that the reader may choose based on their needs and understand it easily.

After the result from LCIA is achieved, the whole LCA procedure is then continued to the last stage, the life cycle interpretation. The life cycle interpretation is a "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 2006b, p. 8). For instance, decision makers could have a detailed picture of a specific life cycle stage and specific operation/production processes of the most significant negative environmental impact categories generated (hotspot). Hotspot identification using the e-LCA study is very useful to pinpoint the significant and important matter more precisely and quantitatively. In some cases, decision makers might overlook the process and materials of a product and assume that it is just a mere item and does not have a meaningful influence in terms of environmental impact which in the end could also lead to more negative impact economically and socially.

However, though the e-LCA methodology is quite comprehensive, there are several essential aspects of scientific research projects which are not exactly covered by this methodology. Therefore, the LCA of a product is not completely sufficient to assess the LCA of scientific research project. Further explanation of how e-LCA framework is incorporated into a suitable method to conduct this study will be explained in section 2.3.

2.2 Organizational Life Cycle Assessment (O-LCA)

All forms of organizations, be it companies, corporations, firms, or other public institutions, "are paramount to the achievement of the 2030 Agenda for Sustainable Development and all the Sustainable Development Goals (SDGs)" (UN DESA 2021, p. 2). The first step in improving environmental awareness and performance is to implement organizational strategies and regulations that involve environmental considerations in decision-making. Accurate environmental performance information is critical, which later can be used as the foundation for all decision-making actions at various levels, including at the organizational level.

Among other things, to accommodate decision makers' need for reliable environmental performance information of the whole organizational level, a project group within the UNEP/SETAC Life Cycle Initiative has developed life cycle approach at the organizational level called Organizational Life Cycle Assessment (O-LCA). In 2014, the International Organization for Standardization (ISO) published an ISO/TS 14072 which provided a comprehensive guideline on the application of Organizational LCA (O-LCA). O-LCA is "compilation and evaluation of the inputs, outputs, and potential environmental impacts of the activities associated with the organization as a whole or portion thereof adopting a life cycle perspective" (ISO 2014, p. 2). In principle, the procedure to conduct O-LCA study follows the LCA framework based on ISO 14040, as shown in Figure 2 above. Similarly, it starts with (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation.

2.2.1 O-LCA: Goal and Scope

In the Goal and Scope Definition phase, there are several elements involved such as organization to be studied, reference period, reporting flow, system boundary, allocation procedures, and interpretation to be used (UNEP/SETAC 2015, p. 42). Among other things, this section only focuses on reporting organization, reporting flow, and system boundary. A more comprehensive explanation on the other elements which are not included here could be seen in UNEP/SETAC (2015) from section 3.3 Life Cycle Inventory Analysis to 3.5 Life Cycle Interpretation and Uncertainty, as well as 5.2 Reporting and Assurance.

There are three items that should be defined in the reporting organization, i.e., subject under study, consolidation method, and reference period. The subject under study is quite clear to define since it is the name and description of the organization who is assessed. Consolidation methodology is an "approach to be selected by the organization in setting organizational boundaries, for assessing the inputs, outputs, and potential environmental impacts of the activities associated with the organization" (ISO 2014, p. 2). The two consolidation methods that could be selected are (1) control, where the organization assesses impacts of facilities over which it has operational or financial control and (2) equity share, where "the organization includes units according to its share of equity interest" (UNEP/SETAC 2015, p. 45). Reference period indicates the temporal length of the organization assessed. For instance, the subject under study is a laptop manufacturer named Dell (Indonesia branch); the consolidation method is control because the requested O-LCA is intended to only assess activities of Indonesian branch it has control over in its operation; and the reference period is the year 2020.

"The reporting flow is a measure of the outputs of the reporting organization" (UNEP/SETAC 2015, p. 47). It is quite easy to determine the reporting flow of organizations who produce physical products, such as in manufacturing industries, because the output could be quantified based on the amount, mass, volume. Another way to determine the reporting flow could also be to refer to a non-physical term such as economic figure, number of students, etc., which is especially useful for non-manufacturer type of organization. Some examples of reporting flows are number of pairs of boots produced by a shoe manufacturer, pieces of washing machines sold by a company, number of employees of a company in the year 2022, etc.

Another important element of O-LCA scope is system boundary. In O-LCA, "system boundary shall be defined to include direct as well as indirect resource use and emissions. Moreover, supporting activities should be included (e.g., marketing, stock storage, research and development, heating at the offices, etc.)" (UNEP/SETAC 2015, p. 50). Ideally, in the O-LCA system boundary, all activity considered should be categorized into three classifications: (1) indirect upstream activities, (2) direct activities, and (3) indirect downstream activities. In short, direct activities are those which take place in the facility owned or controlled by the reporting organization (to a certain extent), while indirect activities (both upstream and downstream) are all activities which happen outside the reporting organization but have business or operational relations to the reporting organization. To understand it better, a fictional example of a simplified System Boundary of O-LCA of Dello Gmbh (a fictional laptop manufacturer) is provided in Figure 4 below. Dello Gmbh may explain that they take a cradle-to-grave approach which means not only direct activities but also upstream and downstream activities are included, such as activities related to the supplier (upstream), activities in the production sites and management office (direct), and usage of the laptop (downstream). More explanation on which activities' data belong to indirect and direct activities will be explained further in section 2.2.2 OLCA: Inventory Analysis below.

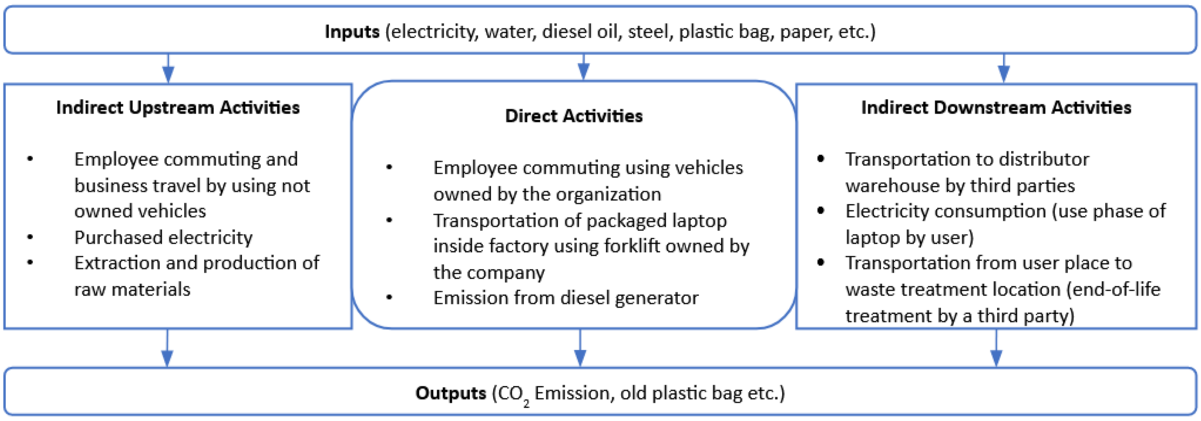

Figure 4: (Fictional) Simplified System Boundary of O-LCA of a laptop manufacturer

2.2.2 O-LCA: Life Cycle Inventory

Because O-LCA was developed and adopted based on LCA, principles from ISO 14040 and ISO 14044 are also applied to O-LCA study including in the LCI stage. Accordingly, in the O-LCA LCI stage the main steps are collection and calculation of data.

Similar to LCA, the data collection phase in O-LCA is intended to collect both primary and secondary data, which later is modeled (refer to each unit process and input-output flow) and analyzed to find out the environmental impact. As previously mentioned above, ideally all input data of activities involved should be categorized into indirect upstream/downstream activities or direct activities. Some activities considered as indirect upstream and downstream activities as well as direct activities are shown in Appendix A2.

For instance, an upstream indirect activity is commuting and business travel using a public/personal vehicle, such as an HR employee of Dello GmbH going to the office by riding his car, or taking the bus/train every day, or the R&D team of Dello GmbH having business travel and going to London by airplane. A direct activity would be a company gathering event which takes place outside the city, but employees go there together by a bus owned by Dello GmbH. A downstream indirect activity would be a reseller van transporting dozens of ready-to-sell laptops to their warehouses as well as transport to the customer.

Continuing to data calculation, there are three inventory calculation approaches that could be used to quantify an organization's data inventory: (1) top-down approach, (2) bottom-up approach, and (3) hybrid or intermediate approach. Top-down approach "considering the organization as a whole, and adding upstream (cradle to gate) models for all inputs of the organization and downstream (gate to grave) models for all outputs", while the bottom-up approach "adding the different LCA of the products of the organization, weighted by the amount of products that are produced during the considered period of time, together with the associated utilities" (ISO 2014, p. 23). The hybrid approach is the combination of both top-down and bottom-up approach. For example, in regard to the water consumption of a laptop manufacturer, one study may implement a bottom-up approach by considering only the water used in production facilities, while in top-down approach, the consideration is not only water used by the production facilities but also water consumption of the management office building, such as kitchen, bathroom etc. After the majority of inventory data is received, data validation is still necessary including properly documenting all the background and assumptions, as well as rechecking the available data to the pre-defined system boundary, whether some items need to be changed, added, or excluded.

2.2.3 O-LCA: Life Cycle Impact Assessment (LCIA) and Interpretation

The LCIA of O-LCA is not largely different in comparison to LCIA of product LCA due to the fact that O-LCA is developed as one application of LCA of product into a different subject. Therefore, in this phase, the main mandatory elements of LCIA are classification and characterization. The same midpoint and endpoint impact categories are applied and may be chosen depending on the needs. Usually, the impact categories selected are based on the consideration and discussion result from related stakeholders. The whole O-LCA LCIA process (and O-LCA LCI process) may be lengthy as well therefore some commercial LCA software could be utilized to develop, structure, and store LCI data as well as connect LCI data to impact assessment method in order to achieve the environmental impact calculation result. In the interpretation stage of O-LCA, a similar process to LCA of product takes place. This last step aims to identify the significant issue and hotspot found based on the LCIA result on each environmental impact category. In the end, it is expected to formulate conclusions, limitation explanations, as well as recommendations which could present some potential solutions.

Even after the whole explanation on O-LCA framework, the quite consideration raised that a standalone O-LCA framework is arguably not covering enough some aspects of scientific research project. A more detailed explanation on why O-LCA is not suitable enough, some gaps and adjustments needed to find suitable methodology will be explained in section 2.3.

2.3 Adaptation of e-LCA and O-LCA Methodology to the Life Cycle Assessment of Scientific Research Projects

Supported by some previous stated research analysis in section 1.3, such as, Achten et al. (2013), Neugebauer et al. (2020), and many more, it appears that the LCA framework (both LCA of product and O-LCA) is well known and widely used by the scientific community to assess environmental impact. The background reason for this adoption is not only because LCA is a widely known and used ISO-standardized framework, but also because a holistic view of life cycle thinking is covered by the LCA framework and is in-line with the long-term motivation of *Vorhaben Klimabilanz* (the parent project of this master thesis), which might later expand the analysis not only about climate change but also other environmental impact categories. Regardless, both LCA and O-LCA have still not fully covered all important elements or activities of scientific research projects: therefore, additional adjustment is needed to develop suitable methodology for the LCA of scientific research projects. Because it is decided that this master thesis' research objectives (see section 1.4) only address the first two phases – the Goal and Scope Definition and Inventory Analysis – the discussion on methodology adaptation will focus mostly on those and less on the last two phases – the Impact Assessment and Interpretation.

First and foremost, the fundamental reason for developing suitable methodology to carry out LCA of scientific research project regardless the LCA of product and O-LCA existence is because the object under study is different. The object under study of so-called standard/classic e-LCA is a product, which is most likely and most suitable for industrial products. In O-LCA, the object under study is an organization. For the LCA of research project, the object under study is a scientific research project, which is neither a pure (industrial) product nor a pure organization. Accordingly, the modified methodology is needed and the rationale as well as process of setting up the modified methodology is explained further here.

In the LCA of product, the guiding or core element is "the product" to be assessed which means that every aspect of e-LCA such as functional unit, reference flow, system boundary, etc. must be derived or determined and oriented on the product. For instance, to develop the system boundary of the LCA of a laptop, one can start by thinking about the laptop (the product) and what aspect, process, or activities happen around the laptop. Firstly, one can directly point out by looking and thinking based on the laptop (the product) life cycle stage whether to just include the production phase, or also the usage phase and end of life phase. Once the life cycle phase has been decided, one can continue to the input and output of each unit process. Again, to determine the input and output, the same approach and center point of view applied, which is the product, or in the other words is by thinking and referring to the laptop itself. In the production phase of a laptop some common items involved in the process are raw materials such as printed circuit board, memory card, processor; the machineries which produce those electronic raw material; the energy consumption used to run the machinery; and transport such as electricity, diesel oil, petrol, etc. Those items involved in the production phase which serves as “the ingredients” could be defined as the input. To determine the output, the same thinking is applied by looking out the outcome or released of activities around the product. For instance, any by-product, any waste produced, air emission from machinery, wastewater, etc. In principle, one can build the whole life cycle of product methodology and conduct e-LCA (from defining the functional unit, system boundary, create and model the LCI, to LCIA and interpretation) by using “the product” as the guiding element and center of orientation.

With O-LCA, the guiding or core element to develop the O-LCA study is not “the product” but “the whole organization” to be assessed. This means that O-LCA was developed to cover elements of “organization”, so to conduct O-LCA one starts by thinking about all the fundamental aspects involved with the organization. The organization could be seen as an entity that needs certain inputs to run its operation and creates or release certain outputs. By thinking about what activities or processes happen around the organization, one can define the scope of study, such system boundary including input and output, which in the end will lead to LCI and LCIA. To define the input and output in the system boundary, it can be started by defining the fundamental aspects which constitute the organization, for instance, the employees, infrastructure, building, and energy and material goods consumed during its operation. Any item needed to run activities related to those fundamental aspects could be defined as the input in the system boundary e.g., the employee activities (commuting, business travel, attending workshops, etc.); building energy consumption (electricity for PC, heating consumption, water usage for employee toilet, etc.); infrastructure (office furniture, IT infrastructure, etc.); and transportation (car, bus, etc.), and so on. The same approach to determine output, one can think about what release produced by the organization. For instance, emissions from transportation, office waste like paper waste, and organic waste from employee canteen, etc. All in all, O-LCA methodology is developed and can be carried out by applying “the organization” as the guidance point.

On the other hand, as previously mentioned, the scientific research project is neither a pure product nor a pure organization. Therefore, neither e-LCA nor O-LCA is directly applicable to assess a scientific research project. However, by taking a closer look, one could view the scientific research project a little bit like a product because there is certain input that goes into a process which creates certain output, for instance, by (vaguely) assuming that the input is the existing knowledge and researcher, the process is the research activities, and the output is the journals or scientific publications. Besides, one could also argue that a scientific research project has some connections with O-LCA because, in most cases, research projects take place in an organization such as a university, other higher education institutions, research institutes, or private companies. Thus, some aspects of O-LCA can be adapted and learned for this study, for instance, the building, office consumption, infrastructure, and so on.

To develop a suitable framework for the LCA of a scientific research project, one can start by defining the guiding or core element. In this case, the guiding element is the subject who carries out the research, I.e., the scientist or researcher. The reason is because the scientist is the “backbone and brain” of any scientific research project. Therefore, to develop the elements of assessment (such as functional unit, system boundary, which in the end lead to LCIA and interpretation), one can start by defining the kinds of activities, processes, and materials that happen around the scientist. This might be done by answering some questions such as what are the main activities the scientist does in carrying out the research process?; what are the work habits of the scientist throughout the project (e.g. the commuting pattern, the working hour profile)?; what are the consumable materials or desktop workstation equipment needed for the scientist to do the project?; what type of major facility, laboratory, and machinery does the scientist utilize to run the project?; and how frequently does the scientist attend internal and external workshops or scientific events?; etc. After roughly answering those question, to develop the proper LCI, one should obtain more detailed information. For instance, regarding commuting, one should know how many scientists are involved, the exact means of transport used, the distance, etc.

All the answers to the questions above could be defined as the input data. Nonetheless, think again about the scientist, the core responsibility and activity of them is by being in-charge in conducting the research project thus it happens that they have the ready-to-use office/sites/lab and does not install and maintain all the infrastructures by themselves. This means that there are indirect supports from other people. For example, the IT infrastructure in the office building, it is unlikely that the scientist who is working on a scientific project installed and maintains the IT infrastructure by themselves. Therefore, other employee activities and consumptions are also relevant and could be included in the assessment as it belongs to the activity or processes that happen around the scientist.

Moreover, another important aspect is the approach to determine the unit of analysis. In LCA, the unit of analysis (or point of comparison) is functional unit and reference flow. As previously explained in section 2.1, the aspect to determine the functional unit is the "function" of the product and the reference flow refers to output (or how many product) needed to fulfil the functional unit. In O-LCA, the unit of analysis is the reporting organization with additional explanation of which facilities/units are included using the consolidation method. The element similar to the reference flow of e-LCA is called reporting flow in O-LCA, which is determined based on the output of its portfolio such as facilities, revenues, employees, etc. However, the LCA of a research project cannot solely use the functional unit as unit of analysis because the primary "function" of research project is to generate knowledge which is practically impossible to be quantified. If directly translating the approach from e-LCA, it means that the FU of the LCA of a research project is the number of physical publications. However, this may create a false impression since not all research projects are publication-oriented. Some might be a classified project which involve several industrial data, or some may focus on developing and improving machines or facilities and therefore very limited publication could be produced. Therefore, the approach to determine FU of LCA of research project is by (again) taking "the scientist" as the guiding element. By looking at the scientist's effort in the form of "person-month or person-year," research activities that has been done can be quantified. One could argue that the more time invested in the research, the more research is done and the more knowledge is created. In conclusion, by following "the scientist" and the research activities, this study could arrive at a suitable methodology for conducting the LCA of a scientific research project, including functional unit and system boundary. Following this approach, a proposed functional unit, system boundary, and other aspects of the LCA of a research project are presented in section 3.3 to 3.5.

Next, regarding the LCI stage, generally it involves several departments and teams, one of which could be the point of contact for a data source. Hence, a data collection form needs to be developed in order to collect consistent data and streamline the process. Since the *Vorhaben Klimabilanz* requires specific data from a specific project and there is almost no common data form widely available, especially for LCA of a research project, a custom data questionnaire is developed (see section 3.6).

The LCIA stages of the e-LCA, O-LCA, and LCA of research project are no different, all sticking to the LCIA procedural from ISO 14040. This is due to the standardization of the existing LCIA steps and until now, there have been almost no additional elements or gaps needing to be addressed in terms of the LCA of a research project. There are several LCIA methods available for LCA and O-LCA which could be used for the LCA of a research project, such as IPCC, ReCiPe, TRACI, CML-IA, etc. For the *Vorhaben Klimabilanz*, because the current need is to calculate the climate change impact, it will most likely be assessed using life cycle impact assessment method IPCC (or IPCC 2021 in SimaPro software). The IPCC impact assessment method might be used to assess greenhouse gas emissions because the method is referred to in the ISO 14067:2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification. Moreover, the method is recognized as the most credible source of information on climate change (UNFCCC 2022a).

The IPCC method is developed by the IPCC's Task Force on National Greenhouse Gas Inventories (TFI). The IPCC TFI "develops and refines an internationally-agreed methodology and software for the calculation and reporting of national GHG emissions and removals and encourages the use of this methodology by countries participating in the IPCC and by signatories of the United Nations Framework Convention on Climate Change (UNFCCC)" (IPCC 2022b). Access additional information on data, metrics, parameters, and methods at https://www.ipcc-nggip.iges.or.jp/public/index.html. In the end, the results of the LCIA stage are delivered in an informative and effective manner during the interpretation stage. Despite being a part of *Vorhaben Klimabilanz*, the LCIA stage and interpretation are excluded from the master thesis study.

3. Results and Discussion

3.1 Data Collection

Data collection will be conducted within the Deutsches Zentrum für Luft- und Raumfahrt (DLR) company involving 3 main institutes: (1) DLR Future Fuels (DLR-FF), (2) Institute of Combustion Technology (Institut für Verbrennungstechnik / DLR-VT), and (3) DLR Institut für Vernetzte Energiesysteme (DLR-VE), with several additional data collected from related central departments to present a thorough investigation. Nevertheless, as previously mentioned in section 1.4, the actual data collection process is excluded from this thesis.

3.1.1 DLR Institute Profiles

DLR-FF is one of the DLR institutes and is based in Jülich and Cologne-Porz. “The vision of the DLR Institute of Future Fuels is to develop technological solutions for harvesting large amounts of solar energy in the sunbelt regions of the earth and use it together with the renewable resources water and air to produce fuels cost efficiently” (DLR-FF 2022b). DLR-FF manages several large-scale facilities, one of them being Synlight, the world’s largest artificial sun. The first operation at the Synlight facility was on 23rd March 2017. The Synlight facility has 149 adjustable Xenon short-arc lamps, which produce a light intensity that is 10,000 times the incident solar radiation on Earth's surface. More information about the Synlight facility is available at: https://www.dlr.de/ff/en/desktopdefault.aspx/tabid-17458/27700_read-71745/.

DLR-VT is a DLR institute located in Stuttgart. DLR-VT attends to technical combustion processes research, focusing on gas turbine combustion chambers which have the primary objective of maximizing efficiency, adaptability, reliability, and minimizing emissions. Similar to other institutions, DLR-VT manages a number of facilities including large-scale facilities, such as High-pressure Combustor Rig Stuttgart (HBK-S). For further detailed information regarding the facility, please visit https://www.dlr.de/vt/de/desktopdefault.aspx/tabid-3085/4664_read-6813/.

The third main institute is DLR-VE. The primary research objective of DLR-VE is to facilitate the development of technology and concepts for managing energy transition. DLR-VE operates at two locations: Oldenburg and Stuttgart (DLR-VE 2021b, p. 6). The Institute is structured into three scientific departments: Urban and Residential Technologies, Energy System Technologies, and Energy Systems Analysis.

3.1.2 Vorhaben Klimabilanz

This master thesis topic is part of a pilot project of DLR-VE called *Vorhaben Klimabilanz*. *Vorhaben Klimabilanz* is a part of the DLR Sustainability Management program, which aims to provide an orientation framework and set the groundwork for a comprehensive sustainability balance sheet to be established by DLR and its research activities over the medium to long term. This will be achieved by calculating greenhouse gas emissions of multiple DLR research projects using the LCA framework. The DLR's short term objective is to focus solely on greenhouse gas emissions. DLR has considered assessing complete environmental impact categories and merging economic and social impacts for a more holistic perspective. *Vorhaben Klimabilanz* also serves as a feasibility study to determine whether it is viable to conduct an LCA analysis on every DLR research project.

As for this pilot project assessment, there is a deliberate limitation to four major types of energy research projects, each of which is considered representative of the DLR-specific energy research practice and diversity. The four selected types of research projects are discussed and differentiated in terms of their respective duration, manpower, energy consumption and material expenditure, and operations (DLR-VE 2021). In general, the four types of selected research projects are projects which involve large-scale facilities called (1) Synlight, (2) High-pressure Combustor Rig (HBK-S), (3) high-performance computing network and (4) desktop-research project. Even though *Vorhaben Klimabilanz* ran under DLR-VE, it does not rule out the possibility of the project involving some other institutes for instance DLR-FF and DLR-VT. The selected research projects are subject to various departments; thus, the data collection phase requires assistance from some related departments. Those selected projects for *Vorhaben Klimabilanz* are:

A. Two Projects from DLR-FF: PEGASUS and INDIREF projects

PEGASUS and INDIREF are the projects involving DLR large-scale facility called Synlight. PEGASUS lasted from November 2016 to June 2021 and INDIREF lasted from December 2016 to September 2019. Both the PEGASUS and INDIREF are the third-party-funded projects, involving several organizational partners. The details of the projects are available to access at https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-9315/16078_read-48367/ (INDIREF) and https://www.pegasus-project.eu/ (PEGASUS).

B. Two Projects from DLR-VT: FLOX® Wobbe and Flüssig FLOX®

Both the FLOX® Wobbe and Flüssig FLOX® projects involved the DLR large-scale facility of High-pressure Combustor Rig (HBK-S) and the SuperMUC-NG, a high-performance computing network owned by Leibniz Supercomputer Centre. FLOX® Wobbe is a project for the development of fuel nozzles for increased fuel which started in January 2013 and finished in December 2015, where Flüssig FLOX® is the project for the development of injector and burner concepts which began in January 2018 and lasted for 4 years. For more details, see https://www.dlr.de/vt/en/desktopdefault.aspx/tabid-9025/15606_read-38673 and https://www.dlr.de/vt/de/desktopdefault.aspx/tabid-3085/4664_read-6813/.

C. Five Desktop-research Projects from DLR-VE: MTHEO, MCASE, HI-CAM, MuSeKo, and ZERO BRINE

To achieve a diverse result as well as heterogeneous variety and comparison, all of the projects chosen from DLR-VE are meant to represent the desktop-research type of project, because the other projects from DLR-FF and DLR-VT already represent large-scale facilities projects. These five desktop-research projects are categorized based on the funding scenario and location, where MTHEO and MCASE are internally funded and owned by DLR-VE Oldenburg, while HI-CAM, MuSeKo, and ZERO BRINE are third-party-funded projects and owned by DLR-VE Stuttgart. The scope of this master thesis, or project to be assessed in this master thesis, is solely limited to these 5 desktop-research projects Therefore, the writer will not take into account other considerations for projects from DLR-FF like PEGASUS and INDIREF, as well as from DLR-VT such as FLOX® Wobbe and Flüssig FLOX®. Appendix A3 Project to be Assessed describes more details about all the desktop-research projects under this master thesis research.

3.2 Objectives and Scope of LCA study of the Scientific Desktop-Research Project

In collaboration with the company representative, the writer has determined the goals of the LCA study of the desktop-research project. Due to the fact that this master's thesis is a part of *Vorhaben Klimabilanz* project, it adheres to the primary objectives of *Vorhaben Klimabilanz*, which are as follows:

1. To comprehensively measure and identify the potential environmental impact, especially regarding the climate change of selected DLR-VE desktop-research projects (i.e., MTHEO, MCASE, HI-CAM, MuSeKo, and ZERO BRINE), while remaining as realistic as possible.
2. To identify the processes, activities, devices, or materials that contribute to a significant proportion of environmental impacts (environmental hotspot) as a basis for decision making in potential resource and energy efficiency and process improvement.
3. To give contribution in providing a baseline LCA model and data for other DLR desktop-research projects, as well as other type of scientific projects. The result of this study will only be made available to the internal stakeholders.

Moreover, the description of the scope of the LCA study of the desktop-research project is based on the LCA methodology which includes "the product system to be studied; the functions of the product system or, in the case of comparative studies, the systems; the functional unit;

the system boundary; allocation procedures; impact categories selected and methodology of impact assessment, and subsequent interpretation to be used; data requirements; assumptions; limitations; initial data quality requirements; type of critical review, if any; type and format of the report required for the study" (ISO 2006a, p. 23). Nonetheless, because the subject/object under study is not purely a tangible product, service, or organization, some of the scope to be discussed will be adjusted based on the needs. The following section will elaborate on the selected scope aspects.

3.3 Functional Unit (FU)

Function is described as "the action for which a person or thing is specially fitted or used or for which a thing exists" (Merriam-Webster 2022b) while unit is described as "a determinate quantity (as of length, time, heat, or value) adopted as a standard of measurement" (Merriam-Webster 2022c). In the e-LCA-related terms and definitions, "the functional unit defines the quantification of the identified functions (performance characteristics) of the product" (ISO 2006a, p. 23). "The purpose of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense)" (ISO 2006b, p. 17). Functional unit also plays an important role in regards to LCA study comparability. It is necessary for the functional unit of an LCA study to be determined and expressed accurately and consistently so that relevant comparisons with other systems that serve the same purpose of fulfillment can be made adequately. Not only the functional unit, but other aspects, characteristics, and further specifications of a system, which varies individually for each study depending on the objectives, should be made in detail to have a realistic and comparable LCA study.

As previously mentioned in the section 2.3, to determine the unit of analysis of the LCA of a research project one can not directly adopt the e-LCA functional unit approach or the O-LCA reporting unit. This is due to the difference of aspect of the object/subject under study. In the LCA of a product (e.g. a car, a monitor, etc.), it is quite clear to determine the functional unit, as it is typically apparent when referring to the intended usage of the physical product. For example, the functional unit of bike is "to transport one person for 5 kilometers throughout 5 years period", or of a jacket is "bodily protection from winter weather of one person for 3 years", etc. Also, there is an e-LCA element which is closely related to functional unit called reference flow, where the value is expressed by the amount/output to fulfil the functional unit. Continuing from previous example, the reference flow could be "one city bike with frame size of 52-55cm", or "one woman's winter jacket of EU size M".

In contrast, it is more difficult to determine a functional unit of the LCA of (desktop-)research projects. Following the definition of research and development from OECD (2015, p. 28), "R&D comprise creative and systematic work undertaken in order to increase the stock of knowledge

– including knowledge of humankind, culture and society – and to devise new applications of available knowledge.", it can be concluded that the "function" of research is to create general new knowledge which eventually will be utilized as a practical application to solve certain issues/problems. However, in terms of "unit", it is quite a challenge to determine the unit of knowledge transferred or produced mainly due to the lack of a method to quantify the output of research activities as well as a standard unit of measurement of research activities. Because research projects are about knowledge and science, this study tries to determine the suitable functional unit of the LCA of a research project by adopting the approach of determining e-LCA reference flow and O-LCA reporting flow. Table 2 presents the proposed functional units in the context of desktop-research projects, with certain considerations and adjustments.

Table 2: (Proposed) Functional Unit of LCA of (Desktop-)Research Project

No.	Functional Unit Consideration	Functional Unit Formulation (could be expressed as)
A.	A research project in a certain location	1 Project X in Location Y
B.	Number of scientific publications which have been published as a result of a research project	1 Piece of International Journal Publication or 1 Piece of Project Report
C.	The amount of personnel working time in a research project	1,650 scientist person-hours, 6 scientist person-months, or 1 scientist person-year

A. A Research Project at a Certain Location

Due to its simplicity, "a research project at a certain location" is the first alternative proposed. "1 Project MTHEO in Oldenburg", for example, expresses one project of MTHEO in Oldenburg. As a functional unit, this expression formula is fairly self-explanatory; thus, the reader can clearly comprehend that the research's output is the project itself. This proposed functional unit may be useful for individuals with a limited understanding of LCA who do not require complex calculations or in-depth information.

However, this functional unit has two major limitations such as the function and comparability. Even though it was explained previously that this functional unit is fairly clear to explain in terms of "unit" (output) of research, this is not the case in terms of "function". Consider the previous example of "1 Project MTHEO in Oldenburg". The public at large is unable to identify the function served by MTHEO Project as how much or how advanced the knowledge generated through MTHEO Project is. Additionally, it will be difficult for the researcher to have adequate one-to-one comparisons between projects because the picture is a whole project that takes into account numerous factors, data, and assumptions in a single calculation.

B. Number of Scientific Publications Which Have Been Published as a Result of a Research Project

As previously mentioned in the table, the functional unit of "number of scientific publications which have been published as a result of a research project" could be expressed as 1 Piece of International Journal Publication or 1 Piece of Project Report. The method of deducing the functional unit as directly referring to the e-LCA approach from the physical product or output of the research project may sound promising. However, this functional unit is not optimal for two fundamental reasons.

The first reason is the variability of research projects conducted in DLR. Some of it is basic research and some is applied research (OECD 2015, p. 52). The basic research (e.g. desktop-research project) has a primary purpose: to generate knowledge. The results are documented in the form of scientific publications, including internal reports, project reports that are accessible to the public, and even submissions to the international journal panel. Applied research, on the other hand, focuses more on practical demonstrations or activities involving facilities and equipment (e.g., laboratory works, development of certain technologies and machines, simulation involving large-scale facilities) and less on publishing reports.

For example,1 piece of HI-CAM project report, 1 piece of MuSeKo project report, and 1 piece of FLOX® Wobbe project report will not be a one-to-one comparison. It might be more or less similar activities that are considered in the reports belong to the same type of project, like a desktop-research project (e.g., HI-CAM and MuSeKo research project). However, the deviation and variation will be significantly higher if the report comes from a different sort of project, for instance, the FLOX® Wobbe project report which involved the use of large-scale facilities.

The second reason is that developing a research report may involve multiple individuals who may not belong to the same research group or institution. Consequently, certain restrictions (such as confidential company data which are meant for internal consumption only) could limit the number of scientific publications created. Suppose the use of the number of scientific publications as a functional unit. It could be concluded that the more reports will eventually result in better environmental performance because the environmental impact burden will be mathematically distributed and normalized into the functional unit (in this case, the number of reports). In this context, it will lead to false information because the quality of research is not solely dependent on the journal writing skills of the researcher and will be unfair to the research project that has some disclosure restrictions.

C. The Amount of Personnel Working Time in a Research Project

The third functional unit proposed – the amount of personnel working time in a research project - might be expressed as person-hours, person-months, or person-years. Based on the definition from the European Commission (EC 2019), “ 'Human effort’ (person-months) is the metric for the time (effort) that the key personnel of an organisation devotes to a specific project”. For example, in DLR, the standard working time of one person-year of work equals 1,650 working hours. Each other standard working time may vary depending on the company policy on vacation days, sick days, location, etc. The following are several reasons to promote this option as a suitable functional unit.

First, the functional unit of personnel working time sufficiently represents in terms of “function” or actual purpose of the research project. The bigger the project, the more likely it may incur additional cost or expenditures. One aspect of the research project cost or expenditures are human resources, or in this case, it could be quantified as working hours. Following this logic, it is possible to argue that the volume of knowledge developed in the research project is almost proportional to the total working time devoted by the researcher. Each research project, in addition, requires a specific number of person-months, which are documented in detailed accounting data. As a result, it is highly achievable (in terms of data availability and sensibility) to normalize each specific project to person-months.

Second, it can be explained that the function of the research project is not only to generate knowledge but also to enable institutions, organizations, or companies to provide employment opportunities. For example, “1,650 person-hours (of MTHEO project)” means that by conducting MTHEO project per year, DLR could provide a 1-year contract of a fulltime employee, or 1-year contract of 2 and more part-time employees. One may argue that the more the projects are conducted, the greater the employment opportunities. Employment opportunities are highly valuable even contained in the SDG, as stated in SDG 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

In conclusion, supported by reasons above, the last functional unit proposed – the amount of personnel working time in a project – is considered the best option for LCA of the (desktop-) research project.

3.4 System Boundary

In this section, the explanation of system boundary is mainly focused on two parts: 1. the life cycle phase/stage of a research project and 2. the data considered in each process category. Even though the term “system boundary” for this study cannot firmly be described as cradle-to-gate, gate-to-gate, or cradle-to-grave as in the LCA of a product, the life cycle phase of a research project is marginally in line with it. Following the common standard practice in DLR, the life cycle phase of a research project could be defined as project initiation → project execution → project closure.

Initiating a project off the ground (also known as project acquisition) involves a number of steps, some of which are planning, preparing a project proposal, setting up the research team, estimating the cost, and acquiring the project itself. During the project execution, the set-up research team, which was already selected to carry out the work, manages and analyzes the project with the primary goal of delivering the outcome based on the agreed-upon milestones. Lastly, the project closure (or project evaluation) tasks include writing and submitting publications, obtaining evaluation sessions from multiple stakeholders (including feedback and lessons learned), disbanding the research team, and handing over all documentation and results to the successor project. After several considerations and discussions, it is decided that the system boundary of the LCA of a research project will not be established until the project execution phase. Even though there was a desire to do the complete LCA – from project acquisition to project evaluation – that appears to be not suitable for the time being.

The reason for this decision is mainly due to the availability of required data. In the project acquisition phase and project evaluation phase of DLR-VE (as well as DLR or other institutions), data are not well recorded or formally documented due to the general research funding and financing practice. As a result, there are no available data that might be used or calculated within the context of the project. In other circumstances, it might use secondary data and assumptions; for example, it might assess the human resources allocated to writing the proposal. This possibility is eliminated, however, because it is inconsistent with the DLR's perspective of the LCA of desktop-research project (and *Vorhaben Klimabilanz* as well), which states that *Vorhaben Klimabilanz* is a pilot project. Even though DLR Management (under the Sustainability Department) previously monitored a few energy-related and employee-related key indicators and published them in the sustainability report in the form of carbon calculations for the organization as a whole in each selected location, the data required for this study is not the same, or nor is it well stored or ready to use. Therefore, it demands a great deal of effort from human resources (in most cases, other departments) and it is very time-consuming to collect data within these two phases. Even the data quality generated by the procedure will be exceedingly questionable and inaccurate.

Furthermore, the proportion of results yielded during the project acquisition and evaluation phases might be insignificant in comparison to the project execution phase. This could be assured with the following rough estimation (by the average practice in DLR), where the project acquisition and evaluation might consume in total around 1.5-2.5 full-time person-months for a project[9] with two full-time person-years in the execution phase. This signifies that the project acquisition labor accounted for approximately 6%-10% of the project implementation phase labor.

Projects shared with a third party are also excluded as the purpose of this study is only to assess DLR environmental impacts; therefore, only DLR's portion/share is counted. This decision is also taken to avoid double-counting on the third-parties part. Against the background of the aforementioned considerations, it is thus proposed to solely include the project execution phase as the system boundary of the LCA of the desktop-research project.

In each of project life cycle phase, there are several processes or activities that occur. In terms of processes, the system boundary of this study encompasses two different process categories: "project-specific processes", which have direct impacts on the project, and "overhead processes", which have indirect impacts on the entire project implementation. In principle, the project-specific processes are defined as activities directly conducted by the scientist personnel who are responsible for running the research to achieve desirable objectives. In most cases, these processes could be identified from project proposals and/or other cost accounting paperwork.

Overhead processes are identified as supporting activities that indirectly contribute to the research project and are typically performed by employees from other departments or institutes. The data generated from overhead processes usually are documented in aggregate data or not separately per project; consequently, various adjustments and assumptions will be needed to perform the data proportion for related projects. The details on required data for project-specific and overhead data will be explained further on the following page.

Figure 5 depicts the system boundaries for this study. Because this study (LCA of desktop-research project) is a part of *Vorhaben Klimabilanz*, the visualization of system boundaries is inextricably linked.

3.4.1 Project-specific Data

There are two process categories considered in project-specific data: the scientist in the project and the desktop-research workstation. A scientist is the foundation of any research, thus the activity and consumption of each individual must be studied and assessed as they have a direct impact on the project. Activities considered within these process categories are the scientists' working-hour profile, scientist commuting, scientist traveling, and events.

[9] The 1.5-2.5 full-time months value does not solely represent the effort of a successful project acquisition but also includes the effort rejected proposal including communication with project partner, calculation of financial aspect, drafting, and revision.

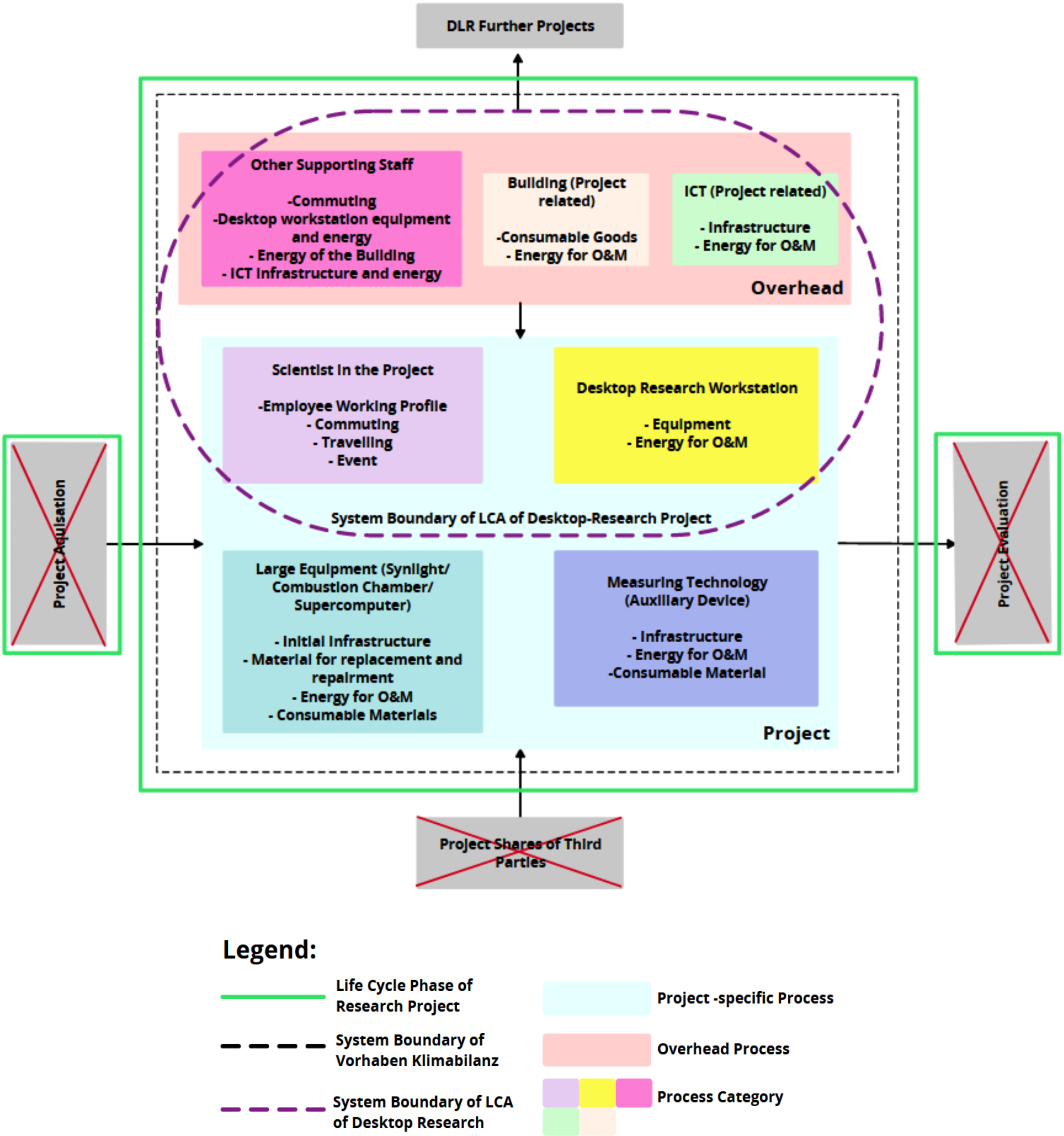

Figure 5: System Boundary of LCA of (Desktop-)Research Project

Every institution or organization, including DLR, has a set standard regulation to properly calculate and record the number of scientists' working hours required for a scientist to work on each project. This suggests that retrieving relevant individual scientist working hour data is highly probable. This information will be used as a foundational calculation for other scientist activities in order to find the optimal proportion method and represent the correct share of each separate project. For example, it is common practice for a scientist with a full-time 8-hour working contract to work on two or more projects simultaneously. Thus, to have a proper estimation of share, it is not effective to have only the number of scientists involved; rather, it is preferable to examine the required working hours to determine how many hours are exactly devoted to each project.

Another point is regarding commuting. “Commute is to travel back and forth regularly (as between a suburb and a city)” (Merriam-Webster 2022a). This aspect is considered in the project-specific processes since this substantial activity is closely related to projects and occurs with a high frequency, resulting in the eventual release of significant negative climate impacts. This study (as well as *Vorhaben Klimabilanz*) selects both projects before COVID-19 and during/after COVID-19 in order to find out the difference, especially regarding commuting habits, whether it is daily commuting or home office work, and its potential environmental impact. There have been numbers of literature studies on the potential environmental impact of remote working or classic in-person working in the office; however, this topic is still in a grey area and could yield large variations of results. Thus, this study could also contribute to giving insight on that matter.

Before COVID-19, all employees were required to commute from their house to the office every day, whether by bicycle, bus, car, or other means of transport. It is fairly usual for employees to commute long-distances every day. Based on the DLR Mobilität survey (DLR 2022, p. 3) on 5,719 employees (representing roughly 60% of the total DLR employee), around 33% of the total employees commute around 20-50 km one-way distance daily, while around 15% of the total employees commute around 50-100 km one-way distance.

COVID-19 made a massive change in daily commutes, including in DLR. From 2020 to 2021, the majority of scientists worked from home, and as of today (July 2022), not 100% employees work in the office every day. In other words, the scientists currently work under hybrid conditions. This circumstance indicates that commuting conditions have not fully returned to pre-COVID-19 times. Put another way, it may be possible for hybrid working conditions to persist indefinitely.

COVID-19 has had the same effect on scientists’ traveling situation. Traveling for work means attending workshops, events, conferences, meetings, and other gatherings held by related department and institutions, as well as third parties. Before COVID-19, scientists frequently traveled by bus, train, and airplane for business purposes. However, during COVID-19 and post COVID-19, the frequency of business travel has fallen significantly due to the shift from physical to online attendance.

Moreover, any internal or external events, workshops, or meetings hosted by the respective department, (in this case, DLR-VE), are considered within the system boundary. DLR-VE conducts a workshop at least once per year, inviting multiple guest experts and professionals from various affiliations and regions. For instance, within the MTHEO project, there were two workshops, each with duration of 2 full days, conducted in Oldenburg. Attendees traveled from wide range of locations, including Stuttgart, Berlin, and Cologne in Germany, as well as from other countries, including the Netherlands, to attend the workshop in person.

Input data for event activities include variables such as the traveling of internal and external participants, food and beverage consumption, and all participants' hotel stays. Importantly, the travel of external participants is included because the only reason for them to travel and participate is to support DLR-VE project. The danger of double-counting would be small, because the external participants' travelling is probably not connected to any of the external participants' projects. Therefore, even if the external participants assessed their research projects as *Vorhaben Klimabilanz*, they would not include the travelling to the DLR-VE workshops, since these have not been part of any of their projects. Accordingly, event activities are taken into account because conducting workshops consumes energy and resources, eventually resulting in environmental impact. Therefore, to perform a realistic and representative study, event activities cannot be completely excluded from the system boundary.

The second process category is the desktop-research workstation. In this category, the calculation takes into account both the desktop workstation equipment (including personal computer (PC), computer monitor, laptop, mouse, and keyboard) and the electricity consumption to power such devices. The desktop-research workstation is considered in the system boundary due to the frequent use of IT devices. Scientists use IT devices to perform the vast majority of their tasks, such as scientific data collection, preparation, and processing; project management and coordination with colleagues and other stakeholders; collaboration via Teamsites and intranet; daily communication; and so on. The intense usage of IT gadgets will affect electricity consumption and significantly contribute to the negative climate impact.

In principle, each scientist and employee are provided with various IT equipment. It is subject to each department to make a decision based on some criteria, which presumably may include the level of employment or job position. The IT coordinators of each department are the ones in charge of handling and requesting the IT equipment from the IT department. For example, an employee and/or scientist may have a PC, two monitors, a mouse, keyboard, headset, and docking equipment in one department, but only a laptop, a monitor, and a mouse in another.

3.4.2 Overhead Data

The overhead data covers three process categories: other supporting staff, building, and ICT. Previously in the project-specific process, the listed activities were only related to each scientist. Meanwhile, the process category of other supporting staff includes activities and consumption of all employees from other departments such as human resources, administration, finance, accounting, IT, and others. This is due to the fact that the activities of these departments indirectly help and contribute to the overall success of scientists in each project. For example, activities such as providing IT infrastructure and support, logging all trip expenses, and many other, will be helpful to ensure the seamless operation of each project. As a matter of fact, in order to achieve assessment results as realistically as possible, it is impossible to overlook the labor, consumption, and environmental impact of employees from other departments completely.

Considered activities of employees from other departments include commuting, desktop-research workstation equipment, energy consumption from the building in which they reside, and ICT infrastructures and energy required to operate them. The commuting habits are equivalent to scientists', who are also affected by COVID-19. The desktop-research workstation equipment consists of similar devices to those utilized by scientists, including PCs, laptops, monitors, mouses, and keyboards. In addition to using their personal desktop-research workstations, all employees are required to use the intranet facility which is managed by the central IT department. This being the case, all related IT equipment, such as internet infrastructure, data storage infrastructure, and so forth. will be assessed. The energy used by the central IT infrastructures and buildings, such as electricity for lighting and gas for heating, will also be examined.

What differentiates scientists from other employees is the way in which they record and process data. In practice, the overhead process is not focused on specific individuals because it is difficult and highly time-consuming to define and distinguish which employees work on which project and for how long. Therefore, the overhead data will be a sum or aggregate of all employee related activities. Eventually, all overhead data must be prorated or proportionally distributed based on certain factors in the assessment and calculation stage to produce realistic shares of each project. The method to conduct data proportion or prorate will be discussed in greater detail in the following section 3.5 Data Proportion Method. The exact type of data required for project-specific and overhead data for this study on each process category will be explained further in section 3.6 Life Cycle Inventory Data Collection.

3.5 Data Proportion Method

The data proportion method will be used to distribute or divide aggregate data according to a calculable factor to determine the fair share in proportion to the whole for each process. In this study, the data proportion is especially important in dealing with overhead data because, as previously mentioned, overhead data are usually recorded and documented as aggregate data, which means, for example, that the data available for electricity consumption per month is calculated for consumption of the entire building rather than per room or per floor. Since a research project does not necessarily utilize all of the rooms in the building, it is vital to collect representative statistics to realistically represent the share of certain projects. Table 3 shows several data proportion method that have been proposed for this study.

Table 3: (Proposed) Data Proportion Method of LCA of (Desktop-)Research Project

No.	Data Proportion Method	(Example of) Data Proportion Formula
A.	The monetary budget/ cost expenditure of a research project	Total budget of project Y per year / Total budget of all project per year
B.	The office room/building area used for a certain project	Total working area of project Y / Total area of the whole building
C.	The amount of personnel in a research project	Total employees of project Y / Total employees of all projects in that period in the building
D.	The amount of personnel working time in a research project	Person-hour of Project Y / Person-hour of all projects

A. The Monetary Budget or Cost Expenditure of a Research Project

This method could possibly be used to calculate the data prorate from aggregate data due to the data availability and credibility. Each project and all department activity require a monetary budget which is be accounted to the board and government. Monetary data is the most reliable and well-documented data because there is standardized procedure to record following certain company and government policy. Each institute has a specialized department and employee who is responsible to record, keep the books, and monitor all the money flow. Also, the data has very low probability of error, variance, or deviation.

This formula will be practical for the data proportion method especially regarding overhead process: other supporting staff such as employees from HR, IT, etc. The primary reason is that the monetary data is the most reliable data and well-recorded, therefore, to get this type of data will be quite easy because the data source is apparent, and the data quality is unquestionable. Also, the formal procedural might not be too lengthy (in comparison to interviews one by one of supporting staff involved or formal procedural for accessing personal data) since it is not related to any personal data.

B. The Office Room / Building Area Used for a Research Project

Another formula that could be used to calculate the data proportion is the office room area used by project scientists as the factor. In the DLR institute building (for example DLR-VE office building), there are various scientists and employees who work on various project and belong to not only one department. Consequently, the plan is to calculate, for example, the energy consumption of a room that will only be utilized by project members by incorporating the total monthly energy expenditure. This formula is to be applied best for the overhead data: building energy consumption such as electricity, natural gas for heating consumption, water etc., because one could argue that the more people are working in the project, the more office space is occupied. To achieve this type of formula is also quite easy because office room / building area is well documented and there is a clear responsible department who could be the potential eligible data source for it. Also, the process of getting this data will potentially not take that long because it does not relate to each personal data (see section 3.7 Data Source Category).

C. The Amount of Personnel in a Research Project

The number of personnel may become a factor for the data proportion method because the scientist is the core of the research project. By that means, the scientists' consumption and activities are integral to the project. Not all scientists in the department or the building are working on the same project; thus, each scientist may bind and factorize the proportion of, for example, energy consumption. By contrast, the drawback of this method is in the fact that a scientist is accountable for working on two or more projects simultaneously. With that being said, this formula might still be subject to high uncertainty and deviation from the actual condition. However, it does not eliminate the possibility of using this formula or as a plan B.

D. The Amount of Personnel Working Time in a Research Project

This formula is a more precise and optimal version of the third formula (the amount of personnel). By factoring in working hours, it is possible to establish how much effort, usage, and consumption were devoted to each project. Each project's working hours must be accurately estimated and recorded in the project's documentation (for example, in the project proposal). It is therefore argued that this formula has the lowest uncertainty and deviation. It could be a suitable representation of the actual effort exerted as it also corresponds with the proposed functional unit. Based on the aforementioned rationale, this formula is selected as the best proportion method especially for project specific processes such as employee commuting, usage of desktop research workstation, etc.

3.6 Life Cycle Inventory Data Collection

In this section, the data questionnaire templates both for the Project-specific Process and the Overhead Process are presented.

3.6.1 Working Hour Profile Data

The best and optimal representative working hour profile of each project member required the completion of a set of inquiry on several important points as listed below.

- Average daily working time in the project (hours per day)
- Average weekly working time in the project (days per week)
- Period of employment in the project (from date to date)
- The total duration of employment in the project (weeks)
- Average daily working time total at DLR (hours per day)
- Average weekly working day total at DLR (days per week)

Data on the average daily and weekly working time on the project is essential to collect due to the fact that scientists in DLR frequently work on multiple projects within the same period. Therefore, it is recommended and proposed to have the exact hours spent and devoted to a particular project. It is necessary to specify the start end dates because there might be scientist turnover over the course of a project. By way of illustration, some scientists may join the project after the first milestone, in the middle, or they may decide to leave the project even though it has not yet been finished. Further, it is important to fill the total employment duration in the project for the scientist who does not work continuously during their employment in the project. In some cases, there might be some unexpected disruptions, such as those related to a health issue and a project put on hold due to data unavailability.

Suppose there is a limitation regarding data availability, data safety, or data security resulting in the incapability of eligible data sources to fill out this questionnaire. In that instance, a simplified data requirement and/or other data assumptions from a secondary source may be needed. The absolute minimum data needed to represent working-hour profile are:

- Scientist working-hours spent for a specific project and,
- Total scientist working-hours in DLR.

For good measure, the data questionnaire template for a collecting working-hour profile is presented in the Appendix A4. The questionnaire template provided below is based on the ideal data requirements.

Anonymization is inarguably needed to prevent data safety and data security and prevent regulation violations. Each project member receives a code designation/nomenclature of **PROJECTCODE_Person_Number** for anonymization purpose. This code designation should be used consistently for a specific scientist in all inquiries (all data questionnaires) so that other information such as commuting to work or the IT equipment used can be accounted for according to the daily/weekly working hours. This data questionnaire will be sent to eligible data sources as a final point (see section 3.7 Data Source Category).

3.6.2 Commuting Data

There are two versions of data questionnaire templates provided for data collection of scientists' commuting profile, i.e., simple and detailed version. Data required for the simple version are:

- Route (from starting location to destination location)
- Distance (km)
- Means of Transport (e.g., train/ÖPNV/Car/E-Bike/bike/by foot)
- Explanation of methods to measure or estimate the distance (e.g., odometer/navigation device in the car/route planner on the Internet)
- The reason of data owner filled the simple commuting data questionnaire

Commuting data queries also follow the same principle as the employee code designation due to the anonymization for data safety and data security (as of from working-hour data query). **PROJECTCODE_Person_Number** is the uniform code designation for the project.

Data owners may fill out the simpler version of the commuting data questionnaire template if certain conditions are met, namely:

a) If the corresponding scientists reach their place of work in only one stage (i.e., without intermediate destinations);
b) If the corresponding scientists reach their place of work exclusively on foot and/or by bicycle (without electric motor);
c) If the corresponding scientists reach their place of work in several stages and/or uses means of transport other than the bicycle (without electric motor) to get to work, but the respective stages and/or means of transport used cannot be determined.

If neither a), b) nor c) apply, the data owner should fill out the detailed version of the commuting data questionnaire template. The significant difference between the simple and detailed versions is that the detailed version includes all information related to intermediate stages, such as distance and means of transport. The simple commuting data questionnaire is included in Appendix A5 while the comprehensive version is included in Appendix A6.

3.6.3 Travelling Data

As previously mentioned, the type of traveling data in this assessment takes into account any business travel that took place within Germany and abroad, with the primary purpose of attending events such as workshops, events, conferences, meetings, etc., hosted by both related departments or institutions and third parties. Similar to the data questionnaire template for commuting, there are two versions of the data questionnaire template for traveling, namely simple and detailed. The simple version of the travelling data questionnaire was designed with the minimum data required to produce eligible results on scientists' travelling climate impact. Several minimum information should be provided, including:

- Route (from the start location to the destination)
- Distance (km)
- Means of Transport (e.g., train/ÖPNV/Car/E-Bike/bike/by foot)
- Explanation on the method to measure or estimate the distance (e.g., odometer/navigation device in the car/route planner on the Internet)
- The reason the data owner filled out the simpler commuting data questionnaire
- Hotel nights with and without breakfast (number of nights)
- Hotel category (number of stars)

Data owner may only fill in the simple version of the travelling data questionnaire (see Appendix A7) if one or more of the following conditions applies:

a) the destination location of the business travel was reached only in one stage (i.e., without intermediate stop or destinations);
b) there were intermediate destinations and/or detours, but these cannot be determined;
c) the means of transport used for one or more stages cannot be determined.

If none of these conditions are met, data owners should fill out the detailed version which can be seen in the Appendix A8.

Again, anonymization is required to ensure the data safety and security of data. For the traveling data questionnaire, the nomenclature/code designation to identify each employee is **PROJECTCODE_Person_LetterNumber.**

"Number" denotes the number of trips that occurred and were associated with a specific project whereas "Letter" refers to each employee who attended a specific workshop or conference on the same specific business trip. There is no need to assign letters if only one person has made the business trip. If several people took the same business trip, an extra line and an "Letter" code (ascending, starting with "a") must be used for each person. Take "**MTHEO_T_1a**" and "**MTHEO_T_1b**" as examples. These examples demonstrate that in the **MTHEO** Project, on the **first** business trip or business trip number **1**, there were **person A** and **person B** on the business trip number 1 to attend the same event. Even though they attended the same event and acted as representatives of the same project, they could travel from separate starting locations and use different means of transport. Hence, the **"Letter"** indication is required.

3.6.4 Event Data

Similar to the data questionnaire template for traveling, there are two versions of the data questionnaire template for event: simple and detailed. Several minimum information should be provided, including:

- Origin institution/location of the participants (affiliation's name or origin city)
- Distance (km)
- Means of Transport (e.g., train/ÖPNV/car/E-Bike/bike/by foot)
- Explanation on the method to measure or estimate the distance (e.g., odometer/navigation device in the car/route planner on the Internet)
- The reason the data owner filled out the simpler commuting data questionnaire
- Duration of attendance (hours or days)
- Hotel nights with and without breakfast (number of nights)

The data owner may only fill out the simple version of the event data questionnaire (see Appendix A9) if one or more of the following conditions applies:

a) the destination location of the business travel was reached only in one stage (i.e., without intermediate stop or destinations);
b) there were intermediate destinations and/or detours, but these cannot be determined;
c) the means of transport used for one or more stages cannot be determined.

If none of these conditions are met, data owners should fill out the detailed version which can be seen in Appendix A10. Again, anonymization is required to ensure the data safety and security of the data. For the event data questionnaire, the nomenclature/code designation to identify each employee is **PROJECTCODE**_**EventTrip**_**NumberLetter.**

3.6.5 Desktop-research Workstation Data

A desktop-research workstation data questionnaire will be used to collect information on hardware or IT equipment that DLR provides to each scientist to help their research activities. The type of IT equipment and the duration of usage of each IT device will also be documented. The desktop-research workstation data questionnaire is designed based on the detail and ideal data requirement to provide the best input to the life cycle assessment. The ideal data requirement is as follows:

- The number of PCs used by scientists in specific projects, their average daily usage time (hours), and the specifications of the respective PC (brand/manufacturer/model, serial number, processor model type, RAM model and capacities, hard disk type and capacity, energy efficiency class, etc.)

- The number of laptops used by scientists in specific projects, their average daily usage time (hours), and the specifications of the respective laptop (brand/manufacturer/model, screen diagonal size, battery type, processor designations, main memory designation and capacities, hard disk type and capacity, energy efficiency class, etc.)
- The number of external monitors used by scientists in specific projects, their average daily usage time (hours), and the specifications of the respective monitor (brand/manufacturer/model, serial number, screen diagonal size, type (LCD/LED), resolution (pixels), energy efficiency class etc.)
- The number of keyboards used by scientists in specific projects and the specifications of the respective keyboards (brand/manufacturer/model, serial number, wired/radio/Bluetooth, etc.)
- The number of mouse used by scientists in specific projects and the specifications of the respective mouse (brand/manufacturer/model, serial number, wired/radio/Bluetooth, etc.)

To ensure anonymity, each project employee receives a code designation of **PROJECTCODE_Person_Number** which is uniformly used for a specific individual as in previous queries. Assume that under certain circumstances, the data owner is unable to fill in the ideal information needed (see Appendix A11), the bare minimum information required is the number and type of each device owned by each scientist involved in a specific project.

3.6.6 Other Supporting Staff/Management

Ideally, the data input consideration for overhead data would be equivalent to the project-specific data; notably, that only input data that accounted for each of the selected research projects would be used. It is, however, hardly possible to separate management consumption or management-employee activities from specific projects and claim that they are merely for the usage and support of that exact project. Therefore, another approach proposed is to not focus on individual employees, but rather on the sum of all employees. Regarding the working time profile, for instance, the sum of the full-time equivalents of the personnel groups, such as from the administration department, the HR department, etc., should be used instead of individual employee working time. The summation number will be prorated using a certain factor calculated by the data proportion method. The proration step is needed to determine the shares of overhead expenses allotted to each individual research project. Among the necessary data are:

- Data on full-time equivalents of each related department such as Administration, Human Resources, Finance, Accounting, etc.,

- Data on the number of employees who live in the same location, categorized based on postal code area.,
- Compilation of the IT/ICT equipment of the non-scientific areas (e.g., PCs/laptops, external monitors, printers, telephones, etc.), and,

Compilation of energy expenses for buildings to accommodate related departments (e.g., power consumption, heating consumption, water consumption, etc.)

3.6.7 Building (Project-related Consumption)

Previously in the “other supporting staff/management” process category, the energy expenses of the building under consideration will be prorated based on factors from the sum of several non-scientific related departments’ full-time equivalent. In the Building (project consumption related) process category, it is regarded as the energy expenses of a building, consumed by scientific employees to support and facilitate research projects. However, the same limitation is presented, as it is difficult to separate each energy expense into a specific research project. Therefore, the data proportion approach should be applied to determine the most representative share of each specific projects’ energy expenses. The best data proportion method would be to factor the sum of the total energy expenses into the working area of specific projects (see section 3.5 Data Proportion Method). Data questionnaire on Building (project-related consumption) can be seen in Appendix A12.

3.6.8 Information and Communications Technology (ICT) (Project-related Consumption)

ICT equipment and infrastructures are crucial facilities to support and ensure a smooth operation of all research-related and other management activities. Because of the day-to-day operation of some vital ICT infrastructure over an extended length of time, ICT infrastructure operation and maintenance arguably consume a significant quantity of electricity. As a result, it will be included as one of the inputs to this study, and certain data proportion methods will be employed to determine the appropriate, balanced input share for each specific research project (see section 3.5 Data Proportion Method). Data questionnaire on ICT (project-related consumption) can be seen in Appendix A13.

3.7 Data Source Category

Ideally, to obtain the required data, both the data questionnaire template of project-specific processes and overhead processes that have been developed before should be delivered to eligible data sources or data owners. Several data sources potentially could give contributions to specific data categories. In Appendix A14, a comprehensive list of potential primary data sources is provided.

Before the member of *Vorhaben Klimabilanz* may submit the data questionnaire templates and collect data from other departments and institutions, a critical step must be completed. This crucial step is regarding data security and data safety. It is necessary to follow certain procedures because *Vorhaben Klimabilanz* will involve not only the institute who owns the project (DLR-VE) but also other institutes and departments (i.e., DLR-FF, DLR-VT, Central Travel Management, etc.). Moreover, it will handle some sensitive data which may yield results that could be extracted from the analysis; may conclude or reveal personal data about employees, including their personal habits, personal working patterns; and so forth. Therefore, there is a certain procedure that should be taken, called application for Processing of Personal Data. This application should be filed to both the data security officer and all relevant works councils, in this case Oldenburg, Stuttgart, and Köln Works Councils. The entire application process for personnel could take up to three or four months.

It was decided in the beginning that *Vorhaben Klimabilanz* will utilize SimaPro software for the LCI stage. Accordingly, after all data required is received, checked, and structured, the next step is to couple those raw data to the ecoinvent database in the SimaPro. This coupling procedure translates an individual raw material or input data into each potential environmental impact.

There are database of various means of transport in ecoinvent SimaPro, for instance, the commuting raw data (how far the distance traveled, how often, how many scientists use this) can be coupled with ecoinvent database named "Transport, passenger train {GLO}| market for |Cut-off, U" where it specified each input and output to commute by SBahn train such as energy, emission, and raw material, etc. and the potential emission per "personkilometer" (pkm) train traveled. Another example is overhead data: once the data on energy demand of office heating is provided, it could be coupled with ecoinvent database following the type of source, which could be natural gas (Natural gas, high pressure {DE}| market for | Cut-off, U), or electricity (Electricity, low voltage {DE}| market for | Cut-off, U) etc.

After the coupling process to ecoinvent database, the LCI inventory is established and ready to be continued to LCIA step and Interpretation. In SimaPro, there are several impact assessment methods that could be used such as IPCC, ReCiPe, TRACI, CML-IA, etc. Once the LCIA method is chosen, the LCA model could be run and, in the end, there will be some numbers and figures which specified the value of each environmental impact. The value could be achieved for instance, 1-year activity of a scientist works on MTHEO project generates 10-ton CO_2-eq., and the process which contribute the most emission is the commuting activities.

4. Conclusion and Outlook

This master's thesis, in conjunction with the *Vorhaben Klimabilanz*, serves as a pilot study for DLR-VE, pioneering an initiative to establish the base work for future DLR comprehensive sustainability monitoring and assessment. In this study, the modified LCA framework to conduct sustainability assessment at the project level is developed. The base work is developed in accordance with the life cycle thinking, especially with an emphasis on the estimation of greenhouse gas emissions. This master's thesis inclusively focuses on stage 1: the Goal and Scope Definition, and part of stage 2: the Life Cycle Inventory (LCI), under the four stages of the LCA framework (Figure 2).

In the goal and scope phase, several scope parameters have been tailored and defined based on the need to conduct the LCA of a (desktop-)research project. The first concern relates to the functional unit (see section 3.3 Functional Unit). As the subject under study, in this case, is a research project and not a physical product, service, or organization, a researcher cannot solely translate the method to determine the e-LCA and O-LCA functional unit for the functional unit of a research project. There are three possible options for a functional unit: (1) a research project in a certain location; (2) the number of scientific publications that have been published as a result of a research project; and (3) the amount of personnel working time in a research project. It is decided that the third option – the amount of personnel working time in a research project – is the best-available functional unit for the LCA of a (desktop-)research project. The rationale behind this decision is that personnel working time well quantifies the "function" of a research project which is the knowledge generates. The more working hour devoted to carrying out research projects, the more knowledge may be generated.

The second scope parameter is the system boundary (see section 3.4 System Boundaries). It has been agreed that the phase of the research project covered by this study should be only the project execution phase. The project execution phase of a (desktop-)research project is primarily divided into two processes: project-specific processes and overhead processes. There are a number of process categories within each process. The project-specific processes consider all data which directly contribute to the research project, including the working profile of scientists, scientists' travel activities and commuting habits, as well as events held by related project members. In addition to that, the system boundary of this study also includes both the equipment and the energy consumption of a scientist's desktop research workstation. On the other hand, the overhead process consists of all input data that contributes indirectly to the research project but plays an essential function in ensuring the seamless operation of the research project.

The allocation procedure, which in this case is closely related to the data proportion method, is another key part of the goal and scope phase. The data proportion method is helpful for discovering the optimal and equitable share of overhead data to be inputted into the system. Four data proportion methods were proposed, namely: (1) The monetary budget/cost expenditure of a research project; (2) The office room/building area used for a certain project; (3) The number of personnel in a research project; and (4) The amount of personnel working time in a research project. Each option is suitable to prorate certain data for instance, (1) the monetary budget option is best suitable for overhead-supporting staff activities, (2) the office area option is the most practical for defining the overhead-building energy consumption, while the option (3) or (4) are best to prorate data related to project specific process-scientist activities.

To continue, data collection will take place in the second phase of the life cycle inventory. The writer does not collect the actual data during this phase, but instead provides a data questionnaire template and data list requirement of scientific (desktop-)research projects as guidance and a tool for *Vorhaben Klimabilanz* project members to collect the data required. There are eight data questionnaire templates in total for each data input in each process category. Those data questionnaire templates pertain to the working hour profile (see Appendix A4), scientist commuting both simple and detailed version (see Appendix A5 and A6), scientist business travel both simple and detailed version (see Appendix A7 and A8), event both simple and detailed version (see Appendix A9 and A10), desktop research workstation (see Appendix A11), building (project-related) (see Appendix A12), and ICT (project-related) (see Appendix A13).

Regardless, there are several limitations applicable to this study. Firstly, the research project phase considered in the system boundary only focuses on the project execution phase; therefore, the calculation will not fully represent the environmental impact of the entire research project. This decision is taken because, according to a rough preliminary calculation and assumption, the environmental burden generated from the preceded and succeeded phases of the project execution phase are less significant or lead to much less emission in comparison to the main project phase which is the execution phase. Time restrictions and limited human resources are further compelling reasons. The second limitation is regarding the scope of this study, which includes the development of data questionnaire templates but excludes the data collection activity itself. This limitation is a result of the internal DLR's lengthy procedure and bureaucracy in handling sensitive data. Thirdly, related to the functional unit "personnel working time", there must be a difference in each scientists' working efficiency and one scientists' yield will never be exactly the same as another. Regardless of that drawback, it is still valid to use this option because to measure each scientists' working efficiency is challenging, and if it is a group project, in the end the result will be claimed as group work where the efficiency is the average of, for example, senior and junior scientists. Lastly, since this is the first LCA pilot project of the scientific research project at DLR-VE, a critical review by a third party to verify the reliability of this study will not be performed. This is mostly due to confidentiality and the fact that this study is intended for internal purposes exclusively.

There is a significant amount of room for advancement and additional scientific findings that will need to be conducted in light of this study's limitations. In principle, future researchers are required to comprehensively conduct the LCA of the (desktop-)research project in order to estimate greenhouse gas emissions by completing the second stage of the LCA framework, which entails collecting the primary data required from eligible sources. Again, since this study (as well as *Vorhaben Klimabilanz*) is a pilot project, the data availability might be limited, hence alternative approaches, such as modeling, calculation, commercial databases, published material, and assumptions may be used. There is a suggestion to use commercial LCA software such as SimaPro, along with a commercial environmental database called ecoinvent database, to make the LCA calculation more reliable and applicable. Furthermore, the work is continued to the third stage of the LCA framework which is life cycle impact assessment (LCIA). LCIA allows future researchers to select different assessment methods to measure certain environmental impact categories. In this case, because the focus is greenhouse gas emissions, IPCC GWP 2021 is a feasible method. In the last stage of the LCA framework, the future researchers get the result of greenhouse gas emissions of certain research projects, as well as hotspot processes or materials that generate the greatest environmental burden.

The DLR Sustainability Department plans to take several actions in response to the findings of the comprehensive analysis. The DLR Sustainability Department will have a clearer understanding of the possibility of conducting LCA at the level of scientific research projects. This could affect DLR policies where it might be the case that DLR Sustainability Department will establish and/or amend some DLR policies or research procedures in order to reduce the negative environmental impact collectively. Another scenario might be that the results will be released as an internal publication that may be openly assessed by all DLR employees by the means of raising employee environmental consciousness and communicating ways to reduce the negative environmental impact of conducting a research project. With an even broader outlook, DLR researchers might undertake LCA to evaluate not only greenhouse gas emissions but also other environmental impact categories associated with each specific scientific research project. In the future, it is also possible to expand this study into a comprehensive LCSA by conducting LCC and S-LCA.

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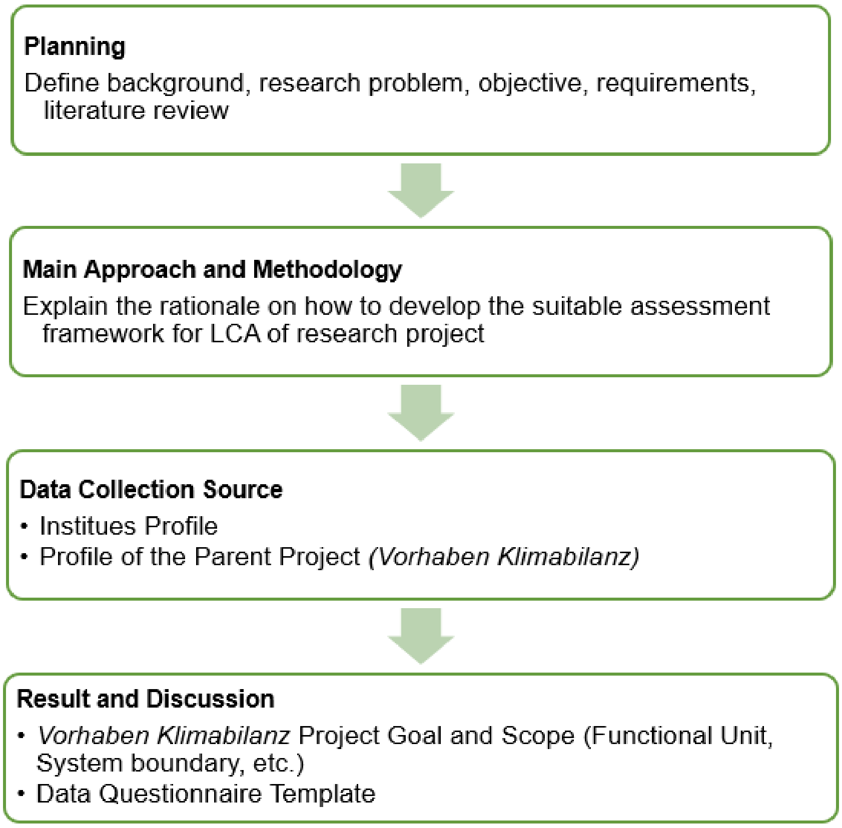
Appendix

A1. Master Thesis Methodology



A2. O-LCA: Direct and Indirect Activities (UNEP/SETAC 2015, pp. 54-57)

No.	Indirect Upstream Activities	Direct Activities	Indirect Downstream Activities
1	Extraction and/or production of purchased: - Raw materials (e.g., sand, wood and water), - Fuels (e.g., crude oil and natural gas), - Goods (e.g., packaging and intermediate products), - Outsourced services (e.g., marketing, legal, information technology (IT) and logistic services), - Capital equipment (e.g., machinery used in production processes, buildings, office equipment, transport vehicles and transportation infrastructure).	Emissions to air and discharges to water and soil from intentional or unintentional releases (e.g., cooling water released to a river, emissions after application of fertilizers to soil, and gaseous or liquid emissions leaked through cracks in collection pipes).	Transportation and distribution of products to the client or travel of the client to the place of consumption, where the means of transport are not owned or controlled by the reporting organization.
2	Extraction, production and distribution of purchased electricity, steam and heating/cooling energy.	Generation of energy resulting from combustion of fuels in stationary sources (e.g., boilers, furnaces and turbines).	End-of-life (EoL) treatment of products sold.
3	Disposal and treatment of solid/liquid waste generated by operations of the reporting organization when processed in facilities it neither owns nor controls.	Physical or chemical processing (e.g., from manufacturing, processing and cleaning).	Use or consumption of the provided goods (e.g., electricity and water consumed while using and cleaning a certain house appliance) and services (e.g., electricity and water consumed during the accommodation of a guest in a hotel).
4	Transportation of raw materials, fuels, goods and capital equipment (between suppliers and from suppliers), and waste, in vehicles not owned or controlled by the reporting organization.	Transportation of materials, intermediate products, products and waste in vehicles owned or controlled by the reporting organization.	Operation of franchises, investments and assets, owned by the reporting organization (lessor) and leased to other entities.
5	Employee commuting and organization personnel travel using vehicles not owned or controlled by the reporting organization.	Employee commuting, organization personnel travel, and client and visitor transportation using vehicles owned or controlled by the reporting organization.	Processing and storage of products provided to the client (e.g., when the good is an intermediate product that needs small additional transformation before being offered to the final consumer) in facilities not owned or controlled by the reporting organization.
6	Operations of assets leased by the reporting organization.	Disposal and treatment of solid and liquid waste when processed in facilities owned or controlled by the reporting organization.	
7	Extraction, production and transportation of electricity consumed during raw materials extraction and fuels, goods and services consumed for the disposal and treatment of solid/liquid waste generated.	Consumption of natural resources extracted with equipment owned or controlled by the reporting organization (e.g., consumption of river water, extraction of minerals and trees).	

A3. Project to be Assessed in this Master Thesis

No.	Project Name	Objective	Duration	Funding Source	Project Owner in DLR	Data Source
1	MTHEO - *Methodenentwicklung zur multikriteriellen Bewertung*	The overall objective of the project is to establish a multi-criteria assessment method for a comprehensive comparison of energy technologies and their development potential in terms of energy policy	01.2018 - 12.2019	DLR core-funded	DLR VE Oldenburg (internal project)	Confidential internal data
2	MCASE – *Multikriterielle Technologiebewertung «Elektromobilität»*	To conduct a comparative evaluation of the environmental implications and the economic efficiency, security of supply, and acceptance of the technology "electromobility" in comparison to alternative and conventional propulsion systems and infrastructures currently in use, as well as an analysis of the medium-term development potentials until the year 2030	01.2018 - 12.2019	DLR core-funded	DLR VE Oldenburg (internal project)	Confidential internal data
3	HI-CAM – Helmholtz-Initiative Climate Adaptation and Mitigation: two Sides of the same Coin	Research on Climate Change Adaptation and Mitigation	07.2019 - 06.2021	Helmholtz Association	DLR-VE Stuttgart (external project)	https://www.helmholtz-klima.de/en/projects
4	MuSeKo – *Multi-Sektor-Kopplung*	Model-based analysis of the integration of renewable electricity surpluses by coupling the electricity supply with the heat, gas and transport sectors (multi-sector coupling)	07.2016 - 12.2019	Bundesministerium für Wirtschaft und Energie (BMWi)	DLR-VE Stuttgart (external project)	https://elib.dlr.de/135971/1/MuSeKo-Endbericht-2020-08-31.pdf
5	ZERO BRINE	demonstrate how valuable materials in industrial waste streams can be recycled and recovered, and to implement circular economy principles across a variety of process industries.	06.2017 - 11.2021	European Commission under Horizon	DLR-VE Stuttgart (external project)	https://zerobrine.eu/

A4. Data Questionnaire Template - Working Hour Profile

Employee [#]	Average daily working time IN the PROJECT [hours per day]	Average weekly working time IN the PROJECT [days per week]	Period of employment IN PROJECT [from DATE to DATE]		Total duration of employment in the PROJECT [weeks]	Average daily working time TOTAL at DLR [hours per day]	Average weekly working day TOTAL at DLR [days per week]
			Starting Date	End Date			
MTHEO_P_0	6	3	8/1/2018	12/31/2019	45	8	5
MTHEO_P_1							
MTHEO_P_2							
MTHEO_P_3							
MTHEO_P_4							
MTHEO_P_5							

A5. Data Questionnaire Template – Simple Commuting

Employee [#]	Route [from starting location to destination location]		Distance [km]	Means of Transport	How was the distance measured/ estimated?	Which variant applies: a), b), or c)
	Starting Location	Destination Location				
MTHEO_P_0	Hude, Zentrum	Oldenburg, Geb. A	29 km	car	Google maps - Auto-Route	a)
MTHEO_P_1						
MTHEO_P_2						
MTHEO_P_3						
MTHEO_P_4						
MTHEO_P_5						

A6. Data Questionnaire Template – Detailed Commuting

Employee [#]	Route [from start location to 1st stopover location]		Distance (from start location to 1st stopover location, one way) [km]	Means of transport (from start location to 1st stopover location, one way)	How was the distance measured/ estimated?	Route [from 1st,2nd or 3rd stopover location to destination location]		Distance (from 1st,2nd or 3rd stopover location to destination location, one way) [km]	Means of transport (from 1st,2nd or 3rd intermediate destination place to destination place, one way)	How was the distance measured/estimated?
	Starting Location	1st Stopover Location				1st,2nd or 3rd stopover location	Destination Location			
MTHEO_P_0	Bremen, Haltestelle Brunnenstr.	Bremen Hbf	1.5	ÖPNV (Straßenbahn)	rome2rio.com	Oldenburg Hbf	Oldenburg, Haltestelle Uni Campus Wechloy	4.4	ÖPNV (Bus)	rome2rio.com
MTHEO_P_1										
MTHEO_P_2										
MTHEO_P_3										

A7. Data Questionnaire Template – Simple Travelling (both Outward and Return Journey)

Trip [#]	Route [from start location to destination location]		Distance [km]	Means of Transport	How was the distance measured / estimated?	Which variant applies: a), b), or c)	Hotel nights WITH breakfast [number of nights]	Hotel nights WITHOUT breakfast [number of nights]	Hotel category [number of stars]
	Starting Location	Destination Location							
MTHEO_T_0a	Hude, Bahnhof	Berlin, Haltestelle Friedrichstraße	403.9	Bahn/ÖPNV	rome2rio.com - Bahn über Bremen-	c)	1	1	***
MTHEO_T_0b	Oldenburg Hauptbahnhof	Berlin, Haltestelle Friedrichstraße	420.5	Bahn/ÖPNV	rome2rio.com - Bahn über Bremen-	c)	2	0	****
MTHEO_T_1a									
MTHEO_T_1b									
MTHEO_T_2									
MTHEO_T_3									

A8. Data Questionnaire Template – Detailed Travelling (both Outward and Return Journey

Trip [#]	Route [from start location to 1st stopover location]		Distance (from start location to 1st stopover location, one way) [km]	Means of transport (from start location to 1st stopover location, one way)	How was the distance measured/ estimated?	Route [from 1st,2nd or 3rd stopover location to destination location]		Distance (from 1st,2nd or 3rd stopover location to destination location, one way) [km]	Means of transport (from 1st,2nd or 3rd intermediate destination place to destination place, one way)	How was the distance measur-ed/ estimated?	Hotel nights WITH breakfast [no. of nights]	Hotel nights WITH-OUT breakfast [no. of nights]	Hotel cate-gory [no. of stars]
	Starting Location	1st Stop-over Location				1st,2nd or 3rd stopover location	Destination Location						
MTHEO_T_X 1	Bremen, Haltestelle Brunnenstr.	Bremen Hbf	1.5	ÖPNV (Straßenbahn)	rome2rio.com	Berlin Hbf	Berlin, Haltstelle Friedrichstraße	1.3	ÖPNV (S-Bahn)	rome2rio.com	1	1	***
MTHEO_T_X 2	Hude, Bahnhof	Hannover Hbf	148.6	Bahn (InterCity)	rome2rio.com	Berlin Hbf	Berlin, Haltstelle Friedrichstraße	1.3	ÖPNV (S-Bahn)	rome2rio.com	2	0	****
MTHEO_T_A 1													
MTHEO_T_A 2													
MTHEO_T_B													

A9. Data Questionnaire Template – Simple Event

Event Trip [#]	Origin institution/ location of the participants	Distance [km]	How was the distance measured / estimated?	Which variant applies: a), b), or c)	Duration of attendance (hours/days)	Hotel nights [number of nights]
MTHEO_ET_0a	TU Berlin, Berlin	419.1	Google maps	c)	2 fulldays	1
MTHEO_ET_0b	Hannover	165.1	Rome2rio.com	c)	1 half day	2
MTHEO_ET_1a						
MTHEO_ET_1b						
MTHEO_ET_2						
MTHEO_ET_3						

A10. Data Questionnaire Template – Detailed Event

Event Trip [#]	Route [from start location to 1st stopover location]		Distance (from start location to 1st stopover location, one way) [km]	Means of transport (from start location to 1st stopover location, one way)	How was the distance measured/ estimated?	Route [from 1st,2nd or 3rd stopover location to destination location]		Distance (from 1st,2nd or 3rd stopover location to destination location, one way) [km]	Means of transport (from 1st,2nd or 3rd intermediate destination place to destination place, one way)	How was the distance measur-ed/ estimated?	Duration of attendance (hours or days)	Hotel nights [no. of nights]	Catering (times per day)
	Starting Location	1st Stop-over Location				1st,2nd or 3rd stopover location	Destination Location						
MTHEO_ET_1X	TU Berlin	Berlin Hbf	1.5	ÖPNV (Straßenbahn)	rome2rio.com	Berlin Hbf	Oldenburg Hbf	433	Train Intercity (ICE)	rome2rio.com	1 full days	1	2
MTHEO_ET_1Y	Leibniz Uni	Hannover Hbf	2.3	ÖPNV (Straßenbahn)	Google Maps	Hannover Hbf	Oldenburg Hbf	169	Train Intercity (ICE)	rome2rio.com	3 half days	0	1
MTHEO_ET_1A													
MTHEO_ET_1B													
MTHEO_ET_2A													

A11. Data Questionnaire Template – Desktop Workstation

Employee [#]	PC [Piece]	PC type and further specifi-cations	Average daily usage time PC [hours]	Laptop [Piece]	Laptop type and further specifi-cations	Average daily usage time laptop [hours]	External Monitor [piece]	Screen type and further specifi-cations	Average daily usage time external screens [hours]	Key-board [piece]	Key-board model and further specifi-cations	Mouse [piece]	Mouse model and further specifi-cations
MTHEO_P_0	1	Dell OptiPlex7090 Small Form Factor,Intel® Core™ i5-10505 der 10. Generation, Windows 10 Pro, 1 x 8 GB DDR4-Arbeitsspeicher	5	1	Dell Latitude 3420, Intel® Core™ i3-1115G4 der 11. Generation (2 Cores, 6 MB Cache, 3,0 GHz bis 4,10 GHz), Windows 10 Pro, 8 GB	2	2	1. Dell 22 Monitor – E2221HN, LED-hintergrundbeleuchteter LCD-Monitor - 54.68 cm (21.5"), Energie Effizienzklasse Klasse D 2. Dell 24 Monitor – E2422H	5	1	HP BK114AA 2.4GHz USB wireless receiver	1	Logitech Maus M185 Wireless Mouse 1000 dpi
MTHEO_P_1													
MTHEO_P_2													

A12. Data Questionnaire Template – Building

Category	Item	Amount	Unit [adjust if necessary]	Specification, explanations	Number of employees who share specified item
Office supplies	Papier		kg/Year		
	[other; please add lines]				
Building supply (building 1) [please specify]	Gas		m3/Year		
	Oil		Litre/Year		
	Electricity		kWh/Year	specify voltage level if necessary	
	Fresh water		m3/Year		
	Service water		m3/Year		
	Nitrogen		kg/Year		
	Oxygen		kg/Year		
	Compressed air		kg/Year		
	[other; please add lines]		[…]		
			[…]		

A13. Data Questionnaire Template – ICT

Cateogry	Material/Equipment	Amount	Unit [please use other units if necessary]	Explanations e.g. on reference period, measurement uncertainties	Usage/life time of the relevant device in DLR [gray cells: not relevant]		Number of employees who use the service or equipment specified
					Amount	Unit	
Internet communication	Internet Bandwidth		Mbps				
	Internet Usage		Hours/Year				
	Power consumption for Internet communication		kWh/MB				
DLR server (local/central)	DLR server #1		Piece			Year	
	Power consumption for DLR server #1		kWh/Year				
	Emergency power generators		Piece			Year	
	Energy consumption of emergency power generators		Liters of diesel/year				
	[please insert additional lines, if needed]					Year	
Other information and communication devices	Printer (large)		Piece			Year	
	Toner consumption (color/black)		Number of cartridges / year				
	Power consumption printer (large)		kWh/year				
	Projector Screen		Piece			Year	
	Power consumption projector screen		kWh/year				
	Projectors		piece			Year	
	Power consumption projector		kWh/year				
	Other devices (such as routers, …)		piece			Year	
	Power consumption of other devices (e.g. router,…)		kWh/year				

A14. Data Source Category

Data Category	Data Name	Primary Data Source
Employee Working Profile	Working hours in DLR	HR dept.
	Working hours in the Project	Project Leader, Admin, Cost Accounting
	Period of Employement in the Project	
Commuting	Means of Transport	
Traveling	Means of Transport	Central Travel Management, DLR Travel Controlling dept., Admin
	Hotel stays	
Event held by DLR	Travelling of participants	Project Leader, Admin
	Hotel stays of participants	
	Energy consumption during event	Objektmanagement
Desktop Workstation	IT equipments	IT department
	Electricity consumptions of desktop workstation equipments	
Building	Energy consumption	Objektmanagement
ICT	Internet Data	IT department
	DLR Server Device	
	Other ICT equipments	
	Electricity consumption of ICT equipments	