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Bachelorarbeit

Determining Carbon Dioxide Footprint using Data Center Simulators

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Abstract

The modern world relies more and more on highly available software and digital data. To make this possible, the demands on *Data Centers* are increasing to provide the services in the required quality. This is associated with an increase in their power consumption and thus also their Carbon Dioxide (CO_2) emissions. Today, they are already among the largest consumers of electricity and producers of CO_2. Due to climate change and the set target of limiting global warming to a maximum of 2° Celsius, the aim is to reduce CO_2 emissions. To calculate the CO_2 footprint of *Data Centers*, *Data Center Simulators* are already used in their planning phases. Simulators provide operators with important information about the future *Data Center* and show room for improvement.

This thesis deals with the calculation of the CO_2 footprint of *Data Centers*, the associated factors and provides an extended approach to the calculation of the CO_2 footprint. Using a *life cycle assessment* approach, it is shown how the carbon footprint of *Data Centers* can be comprehensively calculated. For this purpose, several *life cycle stages* are determined that contribute to the CO_2 footprint during the life cycle of a *Data Center*. Based on the *life cycle stages*, requirements for simulators are developed and, with the help of these, four current *Data Center Simulators* are evaluated in their ability to calculate a CO_2 footprint. Since current simulators calculate the CO_2 footprint only partially and incompletely, the analysis of this work shows the need for a new simulator. Based on the analyzed *life cycle stages*, a new simulator is therefore designed. The subsequent evaluation of the simulator implemented as a *proof-of-concept* against the established requirements shows that the CO_2 emissions of a *Data Center* can be comprehensively calculated with the demonstrated concept. In addition, a case study is carried out based on the High-Performance Computing Center Stuttgart and compared with the environmental statement of the HLRS.

Kurzfassung

Die moderne Welt verlässt sich in vielen Bereichen immer mehr auf hochverfügbare Software und digitale Daten. Um dies zu ermöglichen steigen die Anforderungen an *Data Center* für die Bereitstellung der Dienste in der entsprechend geforderten Qualität. Damit verbunden erhöht sich ihr Stromverbrauch und auch ihr CO_2 Ausstoß. Bereits heute zählen sie zu den größten Stromverbrauchern und CO_2-Produzenten. Auf Grund des Klimawandels und dem gesetzten Ziel die globale Erwärmung auf maximal 2° Celsius zu beschränken, wird eine Verringerung des CO_2-Ausstoßes angestrebt. Um den CO_2-Fußabdruck von *Data Centern* zu berechnen, werden bereits in deren Planungsphasen *Data Center Simulatoren* eingesetzt. Diese liefern den Betreibern wichtige Informationen über das zukünftige Data Center und zeigen Raum für Verbesserungen auf.

Diese Thesis beschäftigt sich mit der Berechnung des CO_2 Fußabdruckes von *Data Centern*, den zugehörigen Faktoren und liefert einen erweiterten Ansatz zur Berechnung des CO_2-Fußabdruckes. Mit Hilfe eines *Life Cycle Assessment* Ansatzes wird gezeigt, wie der CO_2-Fußabdruck von *Data Centern* umfassend berechnet werden kann. Dazu werden mehrere *Life Cycle Stages* bestimmt, die während des Lebenszyklus eines *Data Centers* zum CO_2-Fußabdruck beitragen. Anhand der Life Cycle Stages werden Anforderungen an Simulatoren entwickelt und mit Hilfe dieser vier aktuelle *Data Center Simulatoren*, in ihrer Fähigkeit einen CO_2-Fußabdruck zu berechnen, bewertet. Da bisherige Simulatoren den CO_2-Fußabdrucks allerdings nur teilweise und unvollständig berechnen, zeigt die Analyse dieser Arbeit die Notwendigkeit eines neuen Simulators. Anhand der analysierten *Life Cycle Stages* wird daher ein neuer Simulator entworfen. Die anschließende Evaluation des als *Proof-of-Concept* implementierten Simulators gegen die aufgestellten Anforderungen zeigt, dass mit dem aufgezeigten Konzept der CO_2 Ausstoß eines *Data Centers* umfassend berechnet werden kann. Zusätzlich wird anhand des Höchstleistungsrechenzentrum Stuttgart ein Fallbeispiel durchgeführt und mit der Umwelterklärung des HLRS verglichen.

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Acronyms

CEF Carbon Emission Factor. 32

CO_2 Carbon Dioxide. 3

CO_2e Carbon Dioxide equivalent. 34

CUE Carbon Usage Effectiveness. 32

DC Data Center. 17

DCS Data Center Simulator. 18

ETS Emission Trading System. 17

g Gram. 37

GUI Graphical User Interface. 57

HLRS High-Performance Computing Center Stuttgart. 11

IPCC Intergovernmental Panel on Climate Change. 29

kWh Kilowatt Hour. 11

LCA Life Cycle Assessment. 23

LCI Life Cycle Inventory Analysis. 28

LCIA Life Cycle Impact Assessment. 28

m^2 Square meter. 34

m^3 Cubic meter. 41

MTBF Mean Time Between Failure. 43

PUE Power Usage Effectiveness. 31

U Unit. 26

UPS Uninterruptible Power Supply. 26

WUE Water Usage Effectiveness. 32

1 Introduction

The modern world is highly dependent on Data Centers (DCs). As the Internet becomes an increasingly important factor around the world and cloud computing is used not only privately but especially in modern businesses, this dependence will increase in the foreseeable future. In the last two years, during the global Covid19 pandemic, we have seen a sharp increase in the use of video-on-demand services such as YouTube, Netflix or Amazon Prime; video calling, e.g. Zoom and Jitsi; collaboration software such as Microsoft Teams or Nextcloud; and many cloud storage services such as Microsoft OneDrive or Dropbox. Network traffic used for these services increased by a total of 20% in just a few days, with some services such as video conferencing services generating up to 200% more traffic [FGL+21].

While the demand for such services is steadily growing, the need for high performance goes hand in hand with this development. Clearly, for most DC operators, the efficiency and performance of a DC is the primary concern. The downsizing of modern chips for data center servers is being used to accommodate more and more servers in a DC. As server density and cooling requirements increase, so does the need for cooling and power.

Over the past two decades, high-performance DCs have become one of the largest energy consumers in the world. In 2017, DCs were responsible for up to 3% of global energy consumption and it is estimated that DCs will be responsible for up to 4.5% in 2025[LWX+20].

In the past, the increase in power consumption was often considered only as a cost factor. However, with the increasing concern about climate change and the targets set by international organizations such as the UN or the EU, as well as legislation in countries such as the United States or Germany, power demand and the CO_2 emissions associated with power production DC are increasingly seen as one of the biggest problems in achieving the goal of limiting global warming to 1.5° Celsius. One of the main goals for the future will be to minimize the impact of DCs on the environment by reducing CO_2 emissions. However, while the direct CO_2 emissions of a DC are easy to measure, calculating the total CO_2 footprint requires taking into account the entire supply chain, direct emissions, and construction and disposal.

In addition, CO_2 emissions will also become an important cost factor or source of revenue in the future. Many countries around the world are currently developing or have already introduced CO_2 emission allowances. Typically, CO_2 allowances are measured in price per ton of CO_2. For example, the OECD has introduced an Emission Trading System (ETS) that is used to trade CO_2 allowances. Companies that emit CO_2 must purchase the allowances and are then allowed to emit CO_2 based on the allowances. However, it is also possible to sell unused allowances, which can become a huge source of revenue. Tesla, for example, sold $1.4 billion worth of CO_2 allowances in 2020 and is expected to sell $1.3 billion to $2 billion worth of allowances in 2021. [Tru21].

But even though some companies are already making big profits on CO_2 certificates or paying a lot for them, the certificates are currently quite cheap. In 2019, the price per ton of CO_2 in the EU was around € 26[WC+20]. This price is expected to rise in the future as governments around the world rapidly reduce the number of CO_2 allowances. But other countries besides ETS favor a different approach to CO_2 emissions. For example, Switzerland (up to €100 / ton) and Sweden (up to €120 / ton) [WC+20] introduced a CO_2 tax that is simply a cost to companies and is intended to curb CO2 emissions simply by making it cheaper to produce less CO_2. [WC+20]

With the ever growing need for high-performance DC and the move towards greater sustainability around the globe, it is also becoming increasingly important to consider sustainability at the planning stage of a DC. To simplify calculations in the planning phase, Data Center Simulator (DCS) can be used to quickly test different plans and evaluate which plan is most suitable. Often DCSs do not consider the sustainability of a DC and focus mainly on cost savings and performance improvement. Few simulators specialize in sustainability and only some of them calculate CO_2 emissions. But even fewer consider the CO_2 footprint over the life cycle of a DC. [GKK20] The goal of this work is to develop a simulator that not only considers the CO_2 emissions of a DC, but estimates the total CO_2 footprint over the life cycle of a DC.

The CO_2 footprint of a data center includes a wide range of CO_2 emitters throughout the life cycle of a DC. To reflect the CO_2 footprint of a DC, the analysis of a DC must include several different factors and metrics. Therefore, to establish the basis for such a calculation of the CO_2 footprint, this thesis addresses the following research questions:

RQ1 What factors influence the CO_2 footprint?

RQ2 How do simulators calculate the CO_2 footprint?

RQ3 How can the calculation in simulators be improved?

To answer these questions, a wide range of different factors are considered in this paper. To identify these factors, the CO_2 footprint of a data center over its entire life cycle can be divided into different stages: the manufacturing, packaging, transportation, storage, operation, and disposal. [Bou11]

Although this work takes into account a wide range of different factors, it cannot consider every aspect of the life cycle of a DC. The phase of storage and packaging cannot be considered in this work due to a lack of data and the variety of material.For both, the CO_2 emission depends heavily on the individual parts and on the details of these parts such as capacity, type of storage plate, type of packaging and more. Therefore, it wasn't possible to determine a general approach for the calculation of these stages.

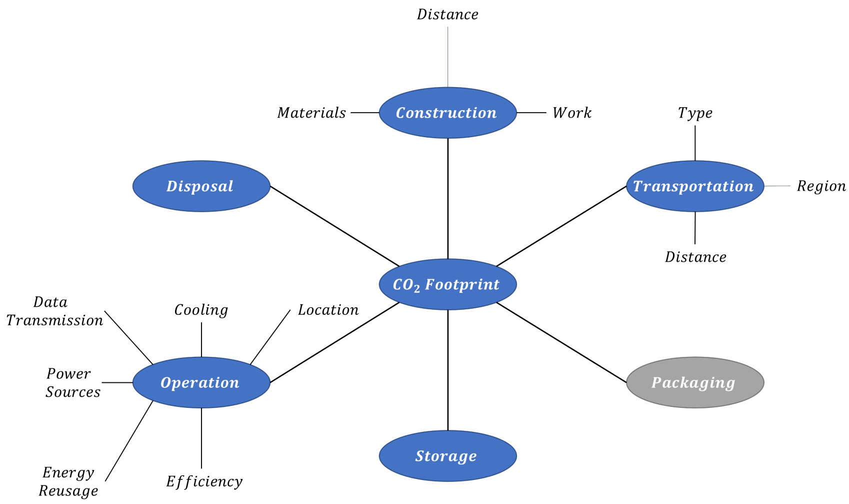

Figure 1.1: CO_2 footprint: Stages and contributors

As previously stated, this work and the simulator focus on four different stages (see Figure 1.1): the construction, the operation, the transportation and the disposal:

- Construction Stage
  In the Construction Stage, the main contributor to the carbon footprint is the construction of the data center building and the manufacturing of parts such as servers, cooling, etc.
- Operation Stage
  In the Operating Stage, several factors, divided into external and internal factors, must be taken into account with regard to the carbon footprint. As an internal factor, we need to consider energy generation by the DC itself using renewable energy sources such as solar panels or wind turbines, as well as the use of energy for cooling, server operations, etc. Important external factors are the location of a data center and, related to this, the CO_2 emissions of the data center's suppliers. Location plays a major role in cooling energy consumption and cooling demand due to the different climate zones. It is also important for the mix of energy sources and CO_2 emissions associated with energy generation. Another factor is the replacement of servers, etc., and the associated carbon footprint.
- Transportation
  The transport phase comprises two areas that must be treated separately: data transmission and freight transport. Data centers are responsible for 97 % [LWX+20] of traffic in networks. To capture data transmission emissions, we examine the energy consumption of data networks and estimate the CO_2 emissions of data networks. Freight traffic on the other hand includes the transportation of hardware such as servers by cargo ship, truck, or train.
- Disposal
  At the end of its lifecycle, a data center must be disposed of. This thesis provides a brief overview of the estimated CO_2 emissions from the disposal of the building and equipment.

The impact of the individual phases on the carbon footprint must also be taken into account. While in normal office buildings the construction phase is one of the main emitters of CO_2, data centers have a very different CO_2 emissions profile as they consume up to 40 times more energy during operation. [Bou11]

As a result of this work, a simulator for calculating the CO_2 footprint of a data center is presented. For the calculation in the simulator, this work also takes a brief look at existing metrics that can be used to compare the results.

This work and the simulator also focus exclusively on the CO_2 footprint of the data center life cycle. Other environmental impacts, such as energy efficiency, water consumption or heat dissipation, are not considered in this work.

In order to analyze the problem presented and to answer the research questions, this thesis is structured as follows:

- **Chapter 2: Methodology**

  This chapter deals with the methodology of this thesis. It presents a list of requirements for the calculation of the carbon footprint and links them to the research questions presented in the introduction.

- **Chapter 3: Background**

  This chapter addresses the background of this work and describes basics about DCSs and sustainability of DCs.

- **Chapter 4: Related Work**

  Related work on the footprint of DCSs and CO_2 is discussed in this chapter, providing an overview of existing research.

- **Chapter 5: Carbon Dioxide footprint**

  Chapter 5 takes a closer look on the CO_2 footprint. What impacts the CO_2 footprint of a data center, are there approaches from other industries we can take into account and how the influences of the CO_2 footprint can be separated into different "building blocks"to simplify the calculation and usage. Based on these factors, requirements for DCS are then developed, that must be met in order to calculate the CO_2 footprint as completely as possible.

- **Chapter 6: Analysis of Data Center Simulators**

  In chapter 6, several simulators are presented and analyzed. In the course of the analysis, the requirements from chapter 5 are used to evaluate whether they calculate the CO_2 footprint as completely as possible.

- **Chapter 7: Design and Implementation**

  Chapter 7 covers the design and implementation of the new DCS that will be developed in this thesis. It discusses how the factors identified in the chapters before can be used in the new simulator. Further the general architecture and special code pieces which are important to understand the functionality of the simulator are described.

- **Chapter 8: Evaluation and Discussion**

  In chapter 8, the results of the thesis and the designed simulator are examined in more detail. For this purpose, the simulator is evaluated based on the requirements from Chapter 5 and, in addition, the calculation of the CO_2 footprint is evaluated based on a case study and compared with existing data.

  Subsequently, the results of the thesis will be discussed in more detail. In addition, it is once again highlighted how the thesis answers the research questions and then an outlook on the future work is given.

- **Chapter 9: Summary**

  The last chapter contains a summary of the complete thesis. Here, the most important parts of the thesis are presented again in a compact way.

2 Methodology

Based on the research questions presented in Chapter 1, this thesis addresses the calculation of the CO_2 footprint for DC as part of DCS. The global trend towards more sustainability is driving DC operators to consider the CO_2 footprint in their planning phase. As a result, operators are interested in calculating the CO_2 emissions of their DC as part of the DCS. But while there are many DCS that consider various aspects of sustainability, CO_2 emissions seem to be a less considered or calculated issue. This chapter describes the methodology used to identify CO_2 emitters in the life cycle of a DC, whether and how these emitters are considered in current DCS, and what opportunities exist to improve calculations in DCS.

In order to identify the stages of a DCs life cycle, existing Life Cycle Assessments (LCAs) based on ISO 14040 [06a] and 14044 [06b] are analyzed and stages extracted. RQ1 is used to identify the factors of each stage and discuss their impact on CO_2 emissions. Each phase of the life cycle of a DC is examined individually. The description of each phase incorporates current research on calculating the impact on the carbon footprint. Therefore, for each phase it is analyzed which aspects have to be considered and how they can be used for the calculation of the total CO_2 footprint of a DC. Based on the results of these investigations, requirements are identified in chapter 5.2 to analyze and evaluate existing DCS in chapter 4. These requirements form the basis for an improved DCS focused on CO_2 emissions in Chapter 7.

With the requirements found for RQ1, it is possible to analyze existing simulators and evaluate whether they are able to calculate a realistic carbon footprint. To answer RQ2, this paper provides an overview of existing simulators, describes their functions, and evaluates whether or not they meet the requirements found. From the results, it can be deduced to what extent the different simulators are able to provide a good estimate of the DC'S carbon footprint.

From the analysis of existing simulators with regard to CO_2 emissions, the need for action in improving or expanding simulators is elaborated. Within the scope of the design chapter, an overall concept for DCS is presented. This concept focuses on the best possible determination of the CO_2 footprint in DC simulations. It incorporates and combines approaches from the evaluated work in the previous chapters. The goal is to achieve a closed-form approach that meets the requirements to the greatest extent possible.

Subsequently, an exemplary implementation is carried out to evaluate the concept. The details of the technical realization are described and the implementation is explained in more detail.

Afterwards, this work evaluates whether the designed and implemented DCS meet the requirements to estimate the CO_2 footprint of the life cycle of a DC. In addition, a case study is calculated using data from a real DC and the results are compared as far as possible. A discussion and outlook follows, briefly describing the answers to the research questions and discussing future work.

Finally, the last chapter summarizes the thesis and the insights gained.

In this chapter, the methodology of this thesis was presented. In order to answer the research questions and develop a DCS that calculates the CO_2 footprint of a DC, the factors that influence the CO_2 footprint are identified and described. These factors can be used to describe requirements that will be used to evaluate existing simulators. Improvements over current calculations and simulators are then identified to design and implement an improved simulator. This simulator will consider as broad a range as possible to provide a good estimate of the carbon footprint. The simulator will be evaluated and compared to existing simulators and potential improvements will also be identified.

Before presenting the analysis of the existing work, the next chapter begins with the basics necessary for the understanding of this thesis. Besides the terminology, this chapter also includes the basics of sustainability and data centers.

3 Background

As described previously, this chapter provides further background on DCs and DC sustainability before analyzing related work in the next chapter. It provides a quick general overview of basic knowledge and will go deeper into specific parts, that are relevant for the further understanding and calculation of the CO_2 footprint.

3.1 Data Centers

While in its early days the Internet was primarily intended as a network for the exchange of information between universities and researchers around the world [LCC+97], today it is a part of everyday life. So while the first websites were just static pages that didn't allow for user interaction, websites became more and more complex as technology advanced. With this development, data volumes also grew immeasurably as services and applications increasingly used collaboratively and data needed to be shared. While cloud computing was originally used to store and access data independently of the client system, it evolved into one of the fastest evolving sub-sectors of computing, with streaming services, collaboration services, and even operating system hosting. With the advent of Internet 2.0 and cloud computing, it is now necessary to have sufficient performance and high availability, which requires powerful data centers.

Data centers are currently used in many different sizes, ranging from a small server room with only a few servers for local businesses to the data warehouses operated by large companies such as Google, Amazon, Facebook or Microsoft. The basics of all data centers, regardless of size or purpose, are the same. A data center consists of a number of servers organized in server racks, a cooling system, power systems and water storage [BHR18]:

- Cooling System
  The cooling system is depending on the size of a DC, the cooling architecture and other factors. While small server rooms, that only contain a few server racks may not need a separate cooling system, enterprise DCs need a individual cooling system to handle the heat emissions.
- Power System
  Similar to the Cooling System, the Power System is depending on the size and other individual factors of a DC. Enterprise DCs have their own electrical system installed, which uses backup generators for power outages, transformers and a distribution network to supply the server racks.
- Water Storage
  Based on the type of cooling, a DC needs huge amounts of water. The water is either used in separate chillers or can also directly absorb the water and be chilled individually.

- Server Rack
  A rack, also called server cabinet, is a rack with a mounting grid in which servers, switches, routers, bridges, storage modules and other network components are installed. In addition, there are cable ducts, etc., and increasingly sensors, lockable doors, and ventilation and cooling equipment.

An overview of the main components is shown in Figure 3.1:

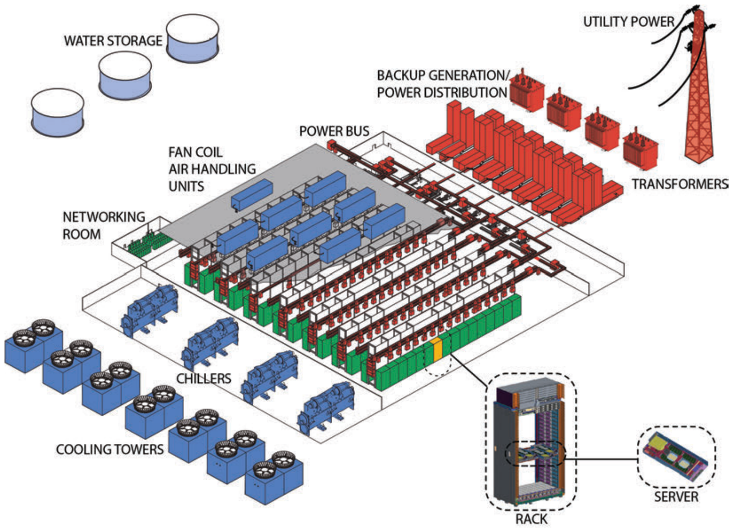

Figure 3.1: Main Components Data Center. From [BHR18]

As shown in Figure 3.2 server racks consist of a series of network switches, a power conversion section, a battery pack and a configurable payload bay. The configurable payload bay usually contains several rack servers. The available size in a server rack is measured in Unit (U). One U is a standardized unit for the height of e.g. servers that can be installed in a server rack and is equal to 44.45 mm. A server rack is typically up to 106,68 cm high by 48.26 cm wide. A server element is measured in absolute numbers and specified in multiples of 1U, typically between 1 and 4U. The number of servers is limited not only by the size of the usable space, but also by the available power supply.

However, while the basic configuration is always the same, the similarity stops when the size of the data center increases. Larger data centers have many more dependencies on their environment and require very different planning than a small server room.

To ensure the function, a DC uses Uninterruptible Power Supplys (UPSs) as part of its power supply system. A UPS has three basic functions:

- Switch to generators or utility power to catch possible power failures
- Energy storage to cover the time needed to switch to power generators
- Catch power spikes in the normal power supply

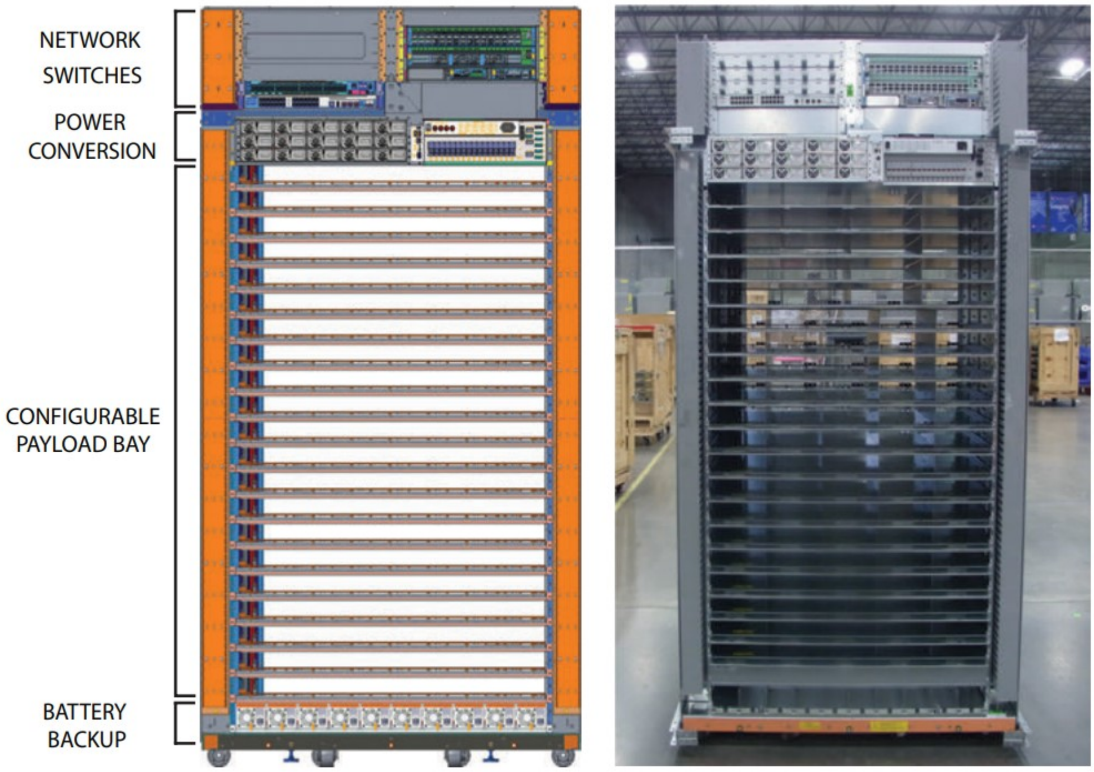

Figure 3.2: Server Rack. From [BHR18]

Based on the size of the DC and the number of servers in use, the UPS can either be part of the server rack, in small DCs, or have their own location in the DC area.

Since different customers and applications have their own requirements for data center availability and performance, a classification of data centers is used. The four levels of tier classification, developed by the Uptime Institute [Ins21], are used to evaluate the resilience of a data center and have the following criteria:

- The **Tier 1** level is the basic level of the Tier classification and has the lowest requirements. A DC graded with the Tier 1 level must have a UPS, an area for IT systems, cooling equipment running 24/7, and a power generator for possible power failures.
- **Tier 2** is the next level of the Tier classification system and ensures that the DC has redundancies for power and cooling. To get the Tier 2 classification a DC must fulfill a list of requirements concerning the facility, like engine generators, energy storage, chillers, cooling module, UPS modules etc.
- To certify the **Tier 3** level, a DC must be capable of maintaining hardware during the operation. Maintenance or replacement of individual hardware must not impact other hardware and must also be secured by redundancy.
- The **Tier 4** level adds higher fault tolerance to a DC. Redundant hardware must be physically isolated from the counterpart. Therefore individual events at one location doesn't interfere with the redundancy and the DC can work without disturbance.

While these Tier-levels increase fault tolerance and maintainability, they also increase the energy requirements of a DC, and thus CO_2 emissions, because they contain multiple redundant systems.

To support the design of a new DC or the evaluation of an existing DC, operators can use simulations. While there are simulators that handle different aspects regarding DCs, the DCS relevant for this thesis will be further discussed in Chapter 6.

3.2 Life Cycle Assessment

A LCA is a method for assessing the impact that an object, a company, or, as in this thesis, a DC has on its environment. In this regard, ISO standards 14040 [06a] and 14044 [06b] describe the process and content of an LCA analysis. According to these standards, an LCA contains the following components:

- **Defining the extent and aim of the assessment**
  The extent of LCAs can vary greatly and is strongly dependent on the desired level of detail and the aim of the study. The ISO standards do not set a clear definition here, but provide a guideline for determining the objectives and extent of the analysis. Among other things, the functions, the system itself and influences on the system should be determined. In addition, it should be defined which data are necessary and in which quality they are available. To limit the extent of the survey multiple stages of an objects life cycle should be defined to further investigate.
- **Life Cycle Inventory Analysis (LCI)**
  The LCI is part of the LCA and focuses on the collection and evaluation of data within the LCA. It specifies how data should be collected and that all calculations and evaluations need to be documented and must be comprehensible. Also it offers guidelines regarding the quality of data that should be considered during the collection.
- **Life Cycle Impact Assessment (LCIA)**
  Another component of a LCA is the LCIA. According to ISO 14040 [06a], a LCIA consists of four mandatory components:
  - *"selection of impact categories, category indicators and characterization models"* [06a]
  - *"assignment of LCI results to selected impact categories (classification)"* [06a]
  - *"calculation of category indicator results"* [06a]
  - *"resulting data after characterization"* [06a]

  The ISO 14040 also lists further, optional components that can be added to the LCIA if needed.
- **Life cycle interpretation**
  As final part of the LCA it is now necessary to evaluate and interpret the results of the LCI and LCIA. Within the interpretation issues should be identified and also *"conclusions, limitations, and recommendations"* [06a] are part of the last component.

[06a][06b]

Since data centers have been used in a very fluctuating manner up to now and are dissolved again after only a few years due to outdated technologies, data center simulators should consider the complete life cycle and thus represent a tool for LCA. There are already many approaches to consider data centers from a life cycle perspective. According to a life cycle analysis for data centers, the following stages can be identified [Bou11][ABD+12]:

Stage 1 Manufacturing
: The manufacturing includes the production of hardware for the DC as well as the construction of the building.

Stage 2 Packaging
: The Packaging Stage covers the emissions of the packaging for freight transported towards the DC

Stage 3 Transportation
: The Transportation Stage covers the emissions produced during the transportation of the hardware towards the DC.

Stage 4 Storage
: The emissions connected to the DC's hardware storage is covered within the Storage Stage.

Stage 5 Operation
: The Operation Stage covers all emissions that are produced to enable the operation of the data center.

Stage 6 Disposal
: At the end of it's life cycle the DC must be composed, and, depending if there is a further usage planed, the building must be demolished. This stage covers the emissions produced during the disposal and demolition.

3.3 Carbon Dioxide Footprint

While many DCS deal with the performance or energy consumption of DCs, sustainability is becoming increasingly important. But sustainability is a broad field with many different aspects that need to be considered, e.g. water consumption or use of resources.

One of the most important aspects of sustainability are greenhouse gas emissions, which are a key factor in global warming. Greenhouse gases are also a mixture of elements, but CO_2 is the greenhouse gas that has the greatest impact. According to Ritchie and Roser [RR20], global CO_2 emissions have increased from 25.53 billion metric tons of CO_2 in 2000 to a peak of 36.70 billion metric tons of CO_2 in 2019, with a slight decline to 34.81 billion metric tons in 2020, as shown in Figure 3.3.

With the goal of limiting the global warming between 1.5 and 2 degree Celsius of the Paris Agreement from 2015 [Paris15] in mind, more and more countries and organizations, like the Intergovernmental Panel on Climate Change (IPCC), are now looking to limit the CO_2 emissions. But while the direct emissions of an object is often quite easy to evaluate, it is not showing the complete emissions connected to it. The emissions of suppliers and others contractors must also be considered, if the complete influence shall be calculated, the so called CO_2 footprint.

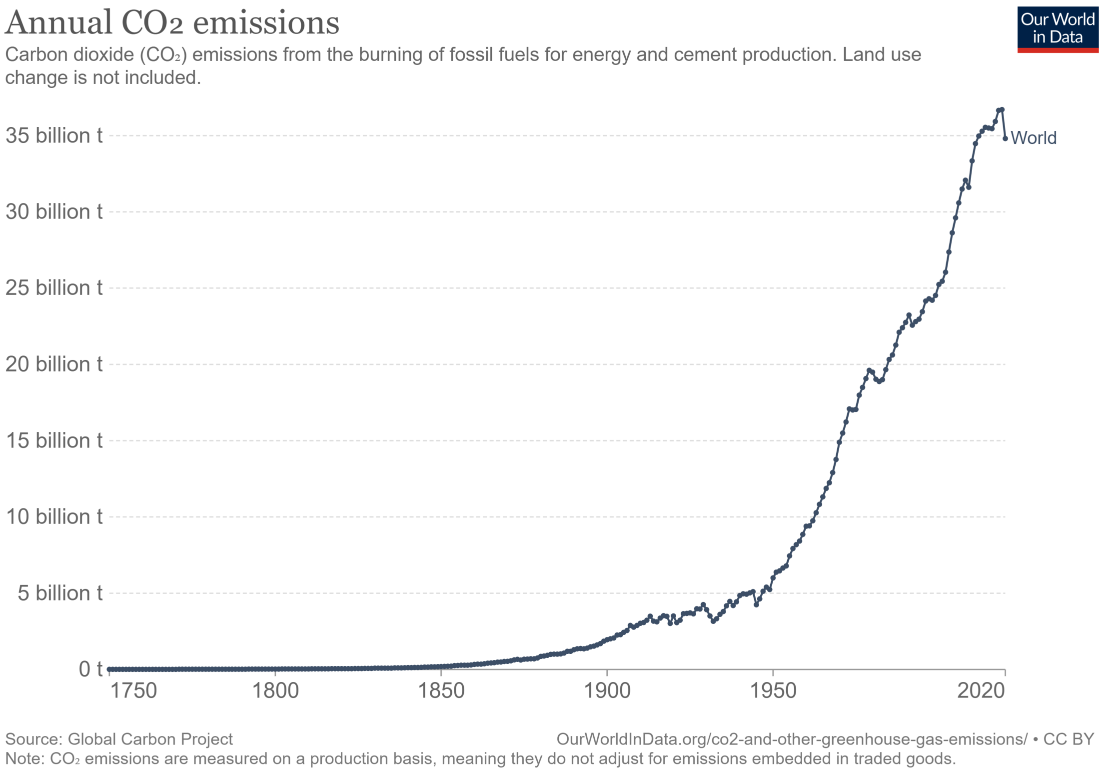

Figure 3.3: Annual global CO_2 emissions [RR20]

The CO_2 footprint not only includes the direct emissions of an object or building, but also takes into account the entire life cycle of an object. To assess the CO_2 footprint appropriately, the LCA approach can help identify emitters of CO_2, that are not directly related to the life cycle stage approach. However, to limit the scope, certain boundaries are required to account for life-cycle emissions of CO_2. Therefore, a CO_2 LCA should focus on three areas [PAP11]:

- direct emissions by the DC
- indirect emissions connected to the DC
- embodied emissions, such as emissions of building material

Within the different phases and within the given limits, all polluters should be evaluated if and how much CO_2 they emit.

In this chapter, different background knowledge about data centers, data center simulators and the carbon footprint was presented. It described how a DC is basically built and which energy consumers belong to it, what the LCA is and general knowledge about CO_2 emissions and the CO_2 footprint.

4 Related Work

With the increasing need of high performance DCs and the rapid growth in numbers of DCs the sustainability and also the CO_2 emissions become more and more important. Therefore, during the last decades many papers and studies were published to survey the current sustainability and to develop new approaches towards a more sustainable DC. In the following chapter an overview over the related work will be provided.

4.1 The Green Grid - Sustainability Metrics

As a global association working towards an efficient usage of energy and low CO_2 emissions of DCs, the Green Grid [Gri21], founded in 2007, developed multiple metrics that help to evaluate the emissions of a DC and other factors that influence those emissions.

Power Usage Effectiveness (PUE)

One important metric towards energy and carbon efficiency of DCs is the PUE, developed by the Green Grid, and discussed by Enrique Jaureqguialzo and Emerson Spain [Jau11]. The metric measures the energy efficiency of a DC and can also be used to calculate the carbon efficiency, as shown below. The PUE is calculated by the annual energy consumption of the whole facility and of the IT (IT load):

$$(4.1)\quad PUE = \frac{\text{total annual amount of energy consumption (facility) } [kWh]}{\text{annual IT load } [kWh]}$$

Based on the truncation rules for equations, the result value is a pure numerical value without any unit. The best possible value to aim for is a PUE of 1, since in this case no additional energy is required on top of the energy consumed by the IT. As it is easy to calculate, the PUE can indicate whether or not the DC is working efficiently and if there is room for improvement.

Carbon Usage Effectiveness (CUE)

Azevedo et al. [APPT10] developed a metric called Carbon Usage Effectiveness (CUE), that describes energy usage in conjunction with carbon emissions. Depending on known parameters, the CUE can be calculated in two different ways, both taking into account total CO_2 emissions of Energy and IT Equipment Energy:

$$(4.2)\quad CUE = \frac{\text{Total } CO_2 \text{ emissions Data Center[kg} CO_2]}{\text{IT Equipment Energy [kWh]}}$$

$$(4.3)\quad CUE = CarbonEmissionFactor(CEF) \cdot PUE$$
$$= \frac{CO_2 \text{ emitted [kg } CO_2]}{\text{Unit of Energy [kWh]}} \cdot \frac{\text{Total Data Center Energy [kWh]}}{\text{IT Equipment Energy [kWh]}}$$

Opposite to other metrics, like the unit-less PUE, the CUE is measured in kg CO_2/kWh. Since the optimal value at 0.0 kg CO_2/kWh means that the DC grid emits no CO2, it follows that the lower the value, the more efficient the DC grid.

While the CUE provides a metric for the direct CO_2 emissions, it does not consider the complete life cycle of a DC and strictly focuses on the Operation Stage. Therefore, the CUE provides a helpful and easy to use metric for operators to evaluate the current CO_2 emissions and can show potential for improvements, limited to the Operation Stage and the direct emissions.

Water Usage Effectiveness (WUE)

Another metric developed by Azevedo et al. [ABP11] focuses on Water Usage Effectiveness (WUE). Since the WUE value itself does not directly consider DC's CO_2 emissions, it only serves to identify potential improvements in water consumption and thus the overall sustainability of a DC. Similar to the PUE and CUE the WUE is also easy to calculate:

$$(4.4)\quad WUE = \frac{\text{Annual Site Water Usage [l]}}{\text{IT Equipment Energy [kWh]}}$$

Measured in liters per kWh, the minimum and thus optimum value of the WUE is 1. Since there is no upper limit, the same as for PUE and CUE applies here: The lower the value, the more efficient the DC generator is in terms of water consumption.

Since the WUE does not provide a direct measurement of CO_2, it provides an easy-to-calculate metric for current efficiency. The WUE is a good indicator of whether or not the emissions caused by water consumption can be optimized.

4.2 Data Center Carbon Footprint Components

Life Cycle Assessment - The ISO Standards 14040 and 14044 [06a] [06b] are describing the workflow, prerequisites and phases of a LCA. In his article Finkbeiner [Fin09] describes the benefits and risks of applying these standards to measure carbon footprints. While the ISO-standards are not setting strict rules towards measuring and accounting in a LCA, an LCA-analysis requires different stages to consider the complete life cycle emissions of an object.

Carbon Footprint - Pandey et al. [PAP11] surveyed different approaches to measure and calculate the carbon footprint. While there are different approaches necessary, based on the field of activity, they strongly rely on LCA-approaches and a set of boundaries to limit the calculations necessary:

- Direct emissions
- Embodied emissions in purchased energy
- Indirect emissions, e.g. transport disposal

This thesis relays on the LCA approach and the limits above to calculate the CO_2 footprint of DCs.

Electrical Carbon Footprint - Dennis Bouley of Schneider Electric discussed in his white paper No. 66 [Bou11] how the electrical carbon footprint of a data center can be estimated. He identifies three different key factors, that should be considered, for calculating the electrical CO_2 footprint:

1. Location
   As one of the key factors Bouley determines the location of the data center. Based on the country, where the data center is located, there are different CO_2 emissions based on the energy mix of the country. To claim this difference, Bouley exemplarily points out the energy mix of the USA versus France. While the USA are strongly relying on oil, gas and coal to produce energy, France relies mainly on nuclear energy which emits no CO_2. Together with the other energy sources, this difference results in a much lower carbon emission per kWh in France than in the USA.
2. IT Load
   Besides the location, Bouley also identifies the IT load as a key factor to calculate the electrical CO_2 footprint. He uses the IT load as a factor to identify the power consumption of the DC, which can be used to calculate the CO_2 footprint together with the PUE.
3. Electrical Efficiency
   As third and last key factor Bouley lists the electrical efficiency of the DC. Since DC plants are usually oversized to cover potential faults or extreme workloads, their energy consumption is usually higher than necessary. This makes the energy efficiency of the equipment a crucial factor that can strongly influence the CO_2 emissions of the DC.

After identifying the three key factors, Bouley also lists four different simulators that can be used to calculate the the estimated electrical carbon footprint:

- Data Center Power Sizing Calculator
- Data Center Efficiency Calculator
- IT Carbon & Energy Allocation Calculator
- Data Center Carbon Calculator

In the white paper, Bouley describes the three factors to calculate the electrical CO_2 footprint of a DC. But while he states different stages of DC life cycle, the calculations only focus on the Operation Stage. Not considering the other stages in his calculation, Bouley gives no indication of how they can be taken into account to calculate an overall CO_2 footprint.

Furthermore, there are also some issues regarding the key factors for the electrical CO_2 footprint of a DC. While the location of the data center is important to the energy mix, IT load and electrical efficiency are only two aspects that contribute to total power consumption. However, in order to calculate the total power consumption, other factors must also be taken into account that are not directly related to the energy consumption of the IT system, such as the consumption for lighting.

While the white paper introduces multiple stages of a DC's life cycle and lists factors that are necessary to be considered within a CO_2 calculation in a DCS, it does only consider the Operation Stage and focuses on the impacts of the IT towards the CO_2 emissions. Therefore it is only of limited use towards calculating the overall CO_2 footprint, but shows possible modules that should be considered within the calculations of the Operation Stage's CO_2 emissions.

Energy Consumption - Liu et al. [LWX+20] developed a methodology to calculate the energy consumption of a DC in the Pan-Arctic region. In their paper they describe different prediction methods for DCs in the US and Europe and afterwards developed their calculation which is based on the network traffic produced by a DC. In the analysis Liu et al. show, that the PUE of different DCs decreases the higher the latitude of the DC gets. According to them, this can be traced back to the climatic advantages of the region. While Liu et al introduce a method to calculate the energy consumption based on network traffic, this method does have it's problems. As they intent to show the benefits of relocating a data center in the Pan-Arctic region, they only calculate the benefits based on the PUE and the network traffic produced by the DC. Using a polynomial model, this calculation leaves room for inaccuracy.

Energy Consumption - Shaikh et al. [SUEA20] developed another method to calculate the CO_2 footprint of DCs based on the Green Grid's PUE. They estimate the total CO_2 footprint of a DC by offsetting the energy consumption of the DC against the different stages, each proportionally taken into account. While they do consider the PUE and different stages of a DC's life cycle, it seems like they only use sweeping statements to calculate the CO_2 footprint as it is only based on the energy consumption alone. Therefore the method of Shaikh et al. will only provide rough estimates of a DC CO_2 footprint, that does not consider individual conditions of a DC, transportation of hardware, or construction of a DC.

Location - Shebabi et al. [SMP+11] , like Bouley, also discuss the impact of the location and the data center design in their paper. They distinguish four different sizes of DCs; server rooms (23 Square meter (m^2)), localized DCs (47m^2), mid-tier DCs (232 m^2), enterprise DCs (465 m^2); and evaluate the PUE of different variants of these DCs based on location. The calculated PUE show a clear benefit of enterprise DCs against the other variants. The use of economizers can drastically lower the PUE. Later in their paper they also describe how the location influences the CO_2 emissions of DCs, ranging from 9 g Carbon Dioxide equivalent (CO_2e) per kWh in Seattle (WA) up to 188 gCO_2e per kWh in Dallas (TX). While Shebabi et al. differentiate between location and style of DCs, they only consider the emissions of the energy supply in operation and therefore do not consider the whole DC's life cycle.

Construction Material - Walhagen et al. [WGM11] **as well as Lauring et al.** [LMP00] deal with emissions of construction materials like steal, wood or glass. With their research, they provide data about emissions per material and also estimations for different building types. Some other research by **Biswas** [Bis14] **and Lee et al.** [LTK18] surveyed the carbon emissions produced during construction work in different settings. Combining all four studies, gained insights lay the basics to calculate the carbon emissions of the Construction Stage in this thesis which will be further discussed in Chapter 5.

Water production - Shimizu et al. [SDT12] described the CO_2 emissions of water supply in Japan. Considering different pumping types, the sewer system and other factors that influence the emissions of the water supply, they calculated an average value. By using the findings of Shimizu et al. it is possible to take the water consumption of a DC into account to calculate the CO_2 footprint as discussed in Chapter 5.

Network Connection - Baliga et al. [BAH+09] consider the CO_2 emissions of the network connection as an additional factor during DC operation. In their paper they analyze the energy consumption of a network based on the network structure and types. Based on this Baliga et al. calculated the energy consumption per byte of a network connection.

Transport Methods - McKinnon [McK07] **and Kim and Van Wee** [KV14] evaluated the CO_2 emissions of several transport methods. Differentiating the emissions of cargo ships, passenger and cargo planes, trucks and cargo trains, McKinnon as well as Kim and Van Wee described the CO_2 emissions of each transport type based on the freight weight and the distance traveled. While McKinnon evaluates each type by it's own, Kim and Van Wee surveyed the transport in supply chains, that uses different transport types. Both lists average values of four transport types in their surveys, so taking them into account covers CO_2 emissions of the Transportation Stage.

4.3 Carbon Footprint Calculations in Data Center Simulators

The previous section has described some of the existing research, that aims to analyze the CO_2 footprint in general and of the different aspects for specific areas. But while CO_2 emissions and the footprint of data centers are gaining more and more importance in research, simulators for calculating CO_2 emissions are quite rare, and those for calculating the CO_2 footprint are even rarer. While different simulators will be analyzed in Chapter 6, this section will focus on studies and research in simulators considering the CO_2 emissions.

Often, CO_2 emissions and CO_2 footprint are only considered as part of sustainability simulators, for example in [Oma19]. In it, Omar describes the application of different sustainability metrics and how they can be used in a simulator. Based on his analysis, he developed a simulator that calculates selected metrics for data centers. In terms of CO_2 emissions, Omar calculates only the PUE and CUE, taking into account only the CO_2 emissions caused by electricity consumption. Thus, again, only a portion of the complete CO_2 footprint is calculated, as no emissions outside of electricity supply are considered.

While Omar's approach is more general, other simulators are designed more specific. So most simulators only cover one specific aspect of a DC and strongly focus the calculation on that. Schneider Electrics Carbon Footprint Calculator [Ele21] presented above, strongly focuses on the calculation of the PUE and the emissions of the energy consumption. While this approach delivers valuable data, it does also not cover the DC's whole footprint.

In summary, the papers presented in this section address different parts of a DC's carbon footprint. GreenGrid's PUE, CUE, and WUE metrics provide an indication of whether or not a DC is operating efficiently. Based on the general LCA approach of the ISO standards, the work in Sections 4.2 and 4.3 each focuses on only a few stages or typical approaches, thus lacking a calculation of the entire carbon footprint. As they only deal with different aspects influencing the CO_2 emissions, none of them provides a fully comprehensive picture. Instead they only cover single stages of a DC's life cycle or a general way to calculate an unspecified CO_2 footprint.

Challenging the research questions of this work, the analyzed related work and current research clearly shows the need for an overall calculation of CO_2 footprint of DC covering the different factors and stages. The combination of the different research forms the basis for the development of a complete approach in the following chapters. Chapter 5 will now further evaluate the aspects of CO_2 footprint calculation and how they can be considered in a simulator to calculate an overall CO_2 footprint.

5 Carbon Dioxide footprint of Data Centers

As shown in precious chapters, DCs are structured by a lot of physical and technical components. Most aspects of DCs, energy consumption, cooling, and performance, can be simulated by so called DCSs in order to support DC operators in the planning phase of DCs. But most simulators miss to consider CO_2 footprint in their calculations. As already stated, CO_2 emissions are becoming increasingly relevant for DC operators as high emissions lead to additional costs.

With this background knowledge it is now possible to go into the calculation of the CO_2 footprint of a DC more in detail. As LCA in Chapter 3 already analyzed different stages of a DCs life cycle, this chapter identifies the corresponding factors of CO_2 emissions in the several stages. Based on these factors it is possible to define requirements to evaluate and compare different DCSs. At the end of this chapter requirements are listed and structured in categories.

5.1 Aspects of Carbon Emission of Data Centers

As previously described this thesis focuses on four stages to get a broad overview over the CO_2 footprint of a DC:

- Construction
- Operation
- Transportation
- Disposal

In the following subsections each stage will be investigated separately. As a result, the factors influencing the CO_2 footprint are identified and quantified for each stage.

5.1.1 Construction Stage

The construction of a data center is one of the first stages contributing to the CO_2 footprint during a DC's life cycle. While the Construction Stage isn't as important as in the construction of a office building, it is nonetheless one of the major contributors on a DCs CO_2 footprint.

Materials
During the Construction Stage one of the main emitters of CO_2 is the material used in the construction process. In their case study, Wallhagen et al. [WGM11] give an overview over the CO_2 emissions of different materials and their impact on a case study regarding an office building in Sweden, see Table 5.1. In their study they list the green house gas emissions as equivalents of CO_2. This numbers can simply be converted into Gram (g) of CO_2 emissions.

Materials	gCO_2/kg
Concrete reinforced	132
Aluminum	11,135
Glass	605
Gypsum	300
Insulation (Cellulose Fibre)	281
Insulation (Polystyrene)	1803
Insulation (Rockwool)	1460
Polyethene	2137
Steel (EU-Mix)	1082
Wood	112

Table 5.1: Estimated CO_2 emission in g per kg and material. Adapted from [WGM11]

Further Wallhagen et al. [WGM11] also calculated the average CO_2 equivalent per m^2 with $3.0g\ CO_2/m^2$. In another paper, Lauring et al. [LMP00] however described different types of building with average values from $0.8g\ CO_2/m^2$ up to $2.8g\ CO_2/m^2$ based on the construction type of buildings. From this it can be derived, that Wallhagen et al. [WGM11] provided an average value for heavy buildings such as office buildings or data center. Thus, a CO_2 equivalent per square meter of 3.0 grams for data centers is assumed for the following work.

Origin of construction material
Besides the type of construction material there is another factor connected to the material, that impacts the CO_2 emissions: the origin of the construction material. While most of the emissions of transporting the material is covered within the material emissions, the transportation of the material from the storage to the construction side must be considered separately and the CO_2 emissions of it must be calculated as part of the transportation stage. If no detailed weight of construction material is given, the weight can be estimated at 3081.35 kg per m^2 [OEF20]

Construction Process of DCs
In the Construction Stage not only the emissions of material must be considered, but also the construction process itself Lee et al. [LTK18] provide an analysis of a construction process of Apartment Housing and estimate that the construction emits $3290g\ CO_2/m^2$ in total, which splits up into $320g\ CO_2/m^2$ for fuel consumption and 2970 CO_2/m^2 for electricity usage.[LTK18]

Biswas [Bis14] provides a study on a university building of the Curtin University in Australia with $4020m^2$. In his study he calculated that during the life cycle of the building it will emit during the "mining, construction and usage stage"14, 229 tonnes CO_2-equivalent. He estimates that the Construction Stage in total is responsible for 2% of the emissions. [Bis14]

The emission per m^2 during the Construction Stage can therefore be calculated as follows

$$\frac{14,229t\ CO^2\ x\ 0.02}{4020\ m^2} = 0.071t\ CO_2/m^2 = 71000g\ CO_2/m^2 \tag{5.1}$$

With the two calculations providing a range for the CO_2 emissions between $3290g\ CO_2/m^2$ and $71000g\ CO_2/m^2$, it must be considered that Lee et al. surveyed a apartment housing complex, while Biswas investigated a university building which is nearer to a data center as the housing

energy sources	min g CO_2eq/kWh	maximal g CO_2eq/kWh	median g CO_2eq/kWh
Coal	740	910	820
Gas	410	490	650
Biomass	160	260	200
Geothermal	18	190	89
Hydropower	1.0	2200	24
Nuclear	3.7	110	12
Concentrated Solar Power	8.8	63	27
Wind onshore	7.0	56	11
Wind offshore	8.0	35	12

Table 5.2: CO_2 emissions of energy sources per kWh. Adapted from [SBF+14]

complex. Also Biswas provides more detailed data, which makes his study more comprehensible. Therefore the calculation of the university building provides the better values to use for a DC and promises the better estimation of the CO_2 emissions during the construction works.

5.1.2 Operation Stage

During the operation of a data center there are multiple factors that influence the CO_2 footprint strongly. Some of them are directly contributing to the footprint, while others are influencing the contributors.

Energy Sources

One of the direct contributors are the external power suppliers, which are also one of the most important external factors. Based on the sources used for the energy production, the impact on the CO_2 footprint can be calculated by the energy usage of the DC. Therefore it is important to know, whether fossil energy sources (such as Oil, Gas or Coal), or CO2 neutral sources (like nuclear power or renewable energy sources e.g. wind or solar power) are used to produce the energy.

In 2014 the *Working Group 3* of the IPCC [SBF+14] published an analysis of the emissions of different energy sources based on hundreds of studies all around the world. The report offers an overview of different energy sources and their emission in CO_2 equivalents per kWh. Table 5.2 shows the results of the analysis of the *Working Group 3*.

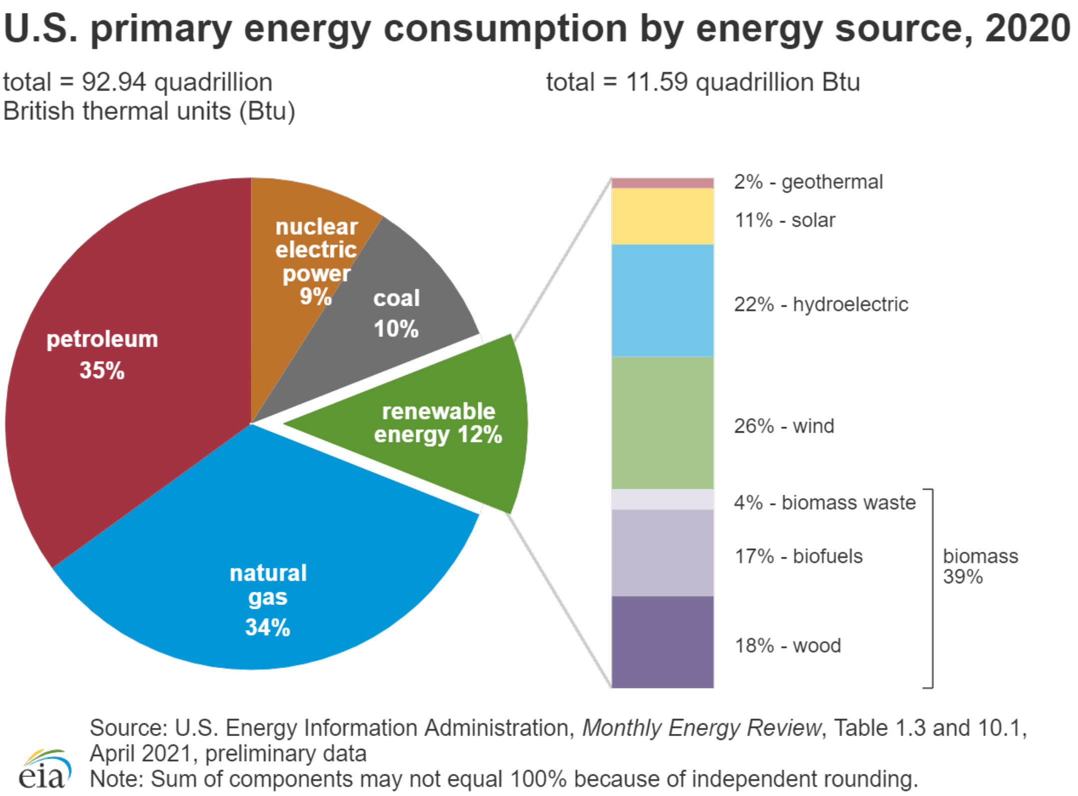

Figure 5.1: Energy mix in the United States [Adm21]

Energy Mix

But to calculate the CO_2 emissions of the energy supply not only the emissions of the production by type must be considered but also the available energy mix. The energy mix is strongly dependent on the region in which the energy is used. Figure 5.1 shows the energy mix of the United States in April 2021 provided by the U.S. Energy Information Administration [Adm21]. Figure 5.2 shows the energy mix available in Germany in 2020. [Bun21]

But while external power suppliers are mostly still the only power supply used by DCs, it became easy to produce energy for a DC with the development in the renewable energy sector. If a data center operates wind turbines or solar panels, it can improve its sustainability. The more renewable energy a data center uses, the more the direct CO_2 emissions can be reduced. Also, if it produces its own energy, a DC can reduce its dependence on external energy suppliers or, at best, become independent. To take the self produced energy and the matching CO_2 emissions into account, the emissions from rooftop PV systems and onshore wind turbines are taken into account as listed in Table 5.2.

Water Supply

With the energy supply being one of the important direct contributors to the DC's CO_2 footprint, the cooling technique of a data center has one of the highest potentials to save energy and can decrease the CO_2 footprint drastically. Typically data centers use two different types of cooling: air or water. While the impact of air cooling is simply the energy consumed by the cooling, the water cooling also needs a water supply and impacts the complete water usage of a data center.

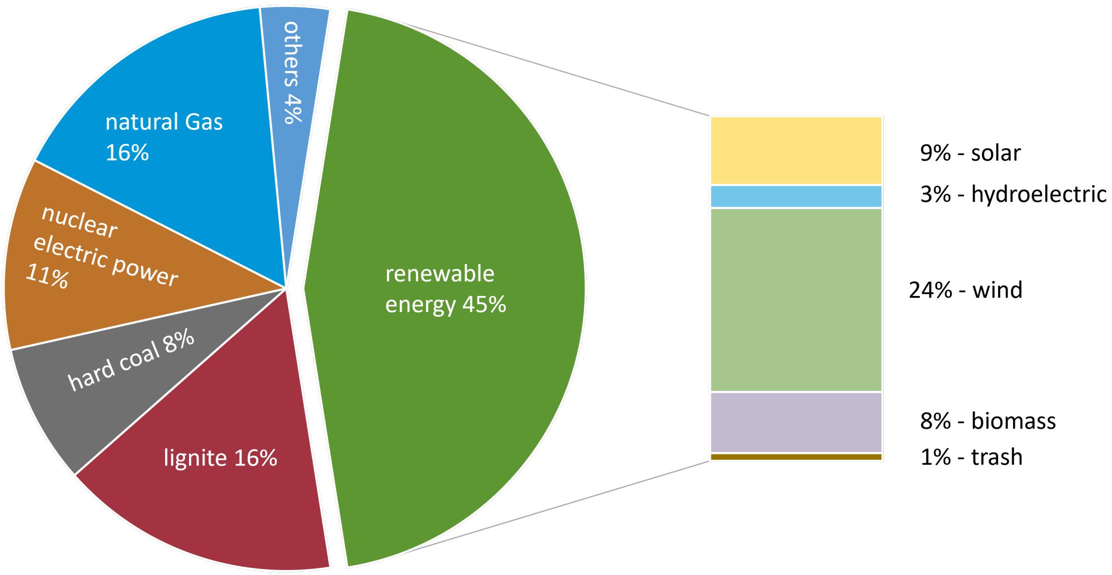

Figure 5.2: Energy mix in Germany. Adapted from [Bun21]

Which leads to another factor: the water supply of the data center. Based on their cooling technique DCs need huge amounts of water to cool their server and hardware. But while the water itself is an important factor for sustainability, it has also an impact on the CO_2 footprint of the data center. To identify and quantify the influence of the water supply on the CO_2 footprint, it is important to investigate the water production process and the types of energy used.

Shimizu et al. [SDT12] found that for each Cubic meter (m^3) of water produced and consumed, 0.376 kg CO_2/m^3 are emitted. While this number is an overall value it is important to mention that the CO_2 emissions can be minimized by using hydro-, wind- or solar powered water pumping stations.

To identify and quantify the water usage, and whether it is efficient, the WUE can be used. While it doesn't directly affect the CO_2 footprint of a DC, the WUE (Chapter 4.1) can be helpful to identify possibilities to minimize the water usage and therefore indirectly the CO_2 emissions of the water supply.

Efficiency

Another factor to minimize the CO_2 emissions of a data center is the efficiency of it. To identify whether there are possibilities to cut the need of energy the PUE is a metric that is easy to calculate and will give a quick overview whether or not the DC works effective regarding it's energy consumption. Like the PUE it is also possible to use the CUE and WUE as indicators how efficiently the DC is working.

Network Traffic

The factors above are more or less a direct influence of the DC's footprint. But during the operation a DC also needs the data networks around the world to deliver its services. To determine the CO_2 emissions of the network traffic the typical energy consumption of network traffic must be identified.

Baliga et al. [BAH+09] estimated, that the energy consumption per bit is between 2 and 4 microjules (μJ) for high access rates and will decline even further. As DCs have a huge amount of network traffic it is better to measure the energy consumption based on gigabytes instead of bits, the stated energy consumption of 1 bit leads to an energy consumption between 0.005 and 0.010 kWh per GB.

$$1GB = 8589934592\ bit \tag{5.2}$$

$$1kWh = 3600\ kJ \tag{5.3}$$

$$8589934592 \cdot 2 = 17,179,869,184\ \mu J = 17.180\ kJ = 0.005\ kWh \tag{5.4}$$

$$8589934592 \cdot 4 = 34,359,738,368\ \mu J = 34.360\ kJ = 0.010\ kWh \tag{5.5}$$

Location

The location of a data center doesn't contribute to the CO_2 emissions directly, but it does have a major influence on the supplies and requirements of a DC. The location influences the energy needed for cooling, the type of cooling a DC uses, the energy mixture that is available, and the type of regenerative energy sources that can be used.

Also, the location of the network traffic determines the CO_2 emissions of energy sources that are available at the location the data transmission happens. Therefore we can identify the CO_2 emissions that are produced during the network usage in one specific location as described in Section 5.1.2. With the energy mix, the network traffic and the energy consumption it is possible to calculate the CO_2 emissions of the network traffic and determine the impact on the CO_2 footprint of the data center.

5.1.3 Transportation Stage

In the Transportation Stage the type of transport, the distance and also the weight of the freight must be considered to estimate the CO_2 emissions. Typically the emissions of freight are measured in g CO_2 per tonnes km, the weight of freight is therefore considered in each definition.

First, the CO_2 footprint of the transportation is highly depending on the type of transport. Transporting freight via cargo ship, truck, train or plane each has a different impact on the CO_2 emission during the transportation and is also depending on the used loading capacity of each transportation type.

Transportation by Cargo Ship

With Taiwan being one of the major producers of server hardware, it is safe to assume, that a major part of the freight is transported via cargo ship. The typical load factor of a cargo ship lies between 40% and 100% and averages around 85%. [McK07] As this thesis and simulator aims to calculate the estimated CO_2 footprint of the complete life cycle of a DC, it offers to use the average load factor and the corresponding CO_2 emission, which is given as 6.21 g CO_2 per tonne km [McK07].

Type of transport	$(g\ CO_2)/(tonne\ km)$
cargo ship	6.21
cargo train	49
truck	138
plane	768

Table 5.3: CO_2 emissions by transportation type - ascending, adapted from [McK07] and [KV14]

Transportation by Truck and Train

But while the transportation via ship is typically the major part of the travel distance, the transportation on land needs also be taken into account. To get an overview of the CO_2 emissions of the land based transport over the complete DC's life cycle it is necessary to investigate two different transportation types: transportation by truck and by cargo train. Like the load factor of cargo ships the load factor of trucks and cargo trains also is something between 40% and 100%. For a truck the average load factor is about 85% [McK07] which leads to a average CO_2 emission of $138 \frac{g\ CO_2}{tonne\ km}$ [KV14]. For a cargo train the average load factor is about 65%, which results in a CO_2 emission of $49 \frac{g\ CO_2}{tonne\ km}$ [KV14].

Transportation by Plane

The transportation by plane is harder to estimate. This is due to the fact that the major freight transportation done by plane is transported with passenger flights, e.g. about 70% in the United Kingdom. Alan McKinnon [McK07] lists three different CO_2 emission ratios for international cargo flights: 637, 800, 867 g CO_2 per tonne km. To estimate the CO_2 emissions the average of these three values will be used, which is about 768 g CO_2 per tonne km. [KV14][McK07]

5.1.4 Disposal Stage

During the life cycle of a DC hardware must be replaced and disposed. Also, at the end of the life cycle the DC itself must be disposed. The Disposal Stage covers the CO_2 emissions that appear during those processes.

Hardware Disposal

Server Hardware has an average Mean Time Between Failure (MTBF) of 45,500 hours or 5.19 years [Sys19]. This means, that during an expected life cycle of a data center, which is about 10 years, the hardware will be renewed at least 1 time to prevent hardware failure. But while the replacement of hardware is a major part during a DC's life cycle, there is no data about the CO_2 emissions of the disposal of hardware.

Building Disposal

The disposal of the building instead can be quantified. Pun and Liu [PL06] as well as Moncaster and Simons [MS13] are describing the estimates of the demolition of a building. While Pun and Liu takes the disposal as a reverse of the construction process, Moncaster and Simons estimate the CO_2 emissions of the disposal process as about 21% of the total CO_2 emission of a office buildings life cycle.

Due to the fact that the CO_2 emissions of a DC are much higher than the emissions of an office building, the method of Moncaster and Simons is not capable to estimate the emissions of the Disposal Stage. The method of Pun and Liu otherwise is an easy way to roughly estimate the impact of the disposal towards the complete CO_2 footprint of a DC.

Therefore the CO_2 emissions for the construction material as presented in Table 5.1 can be taken into account for the disposal of the material.

Based on Pun and Liu [PL06] it is also possible to estimate the CO_2 emissions of the disposal work. As they take the emissions of construction into account, the CO_2 emissions of the buildings disposal can be calculated the same way as the emission of the construction process presented in section 5.1.1.

Summary

In the sections above the different stages of a DC and how they can be calculated are presented. The Construction Stage covers the emissions of the construction material, the construction process and, if necessary, of the transportation of the material. In the Operation Stage the energy production, the cooling technique, the water usage and the efficiency and location of the data center are considered to calculate the emitted CO_2. Besides the directly connected emissions the Operation Stage also covers the CO_2 emissions that are connected to the data transmission on data networks. The Transportation Stage then gives an overview over the emissions emitted during the freight transport based on the type of transport, the covered distance, and the weight of the freight. At the end of the life cycle the Disposal Stage becomes important. The Disposal Stage covers the CO_2 emissions that appear during the disposal of the building and the accompanying work.

With the knowledge about the CO_2 emissions appearing in the four stages and how they contribute to the DC's footprint, it is now possible to name requirements, that must be fulfilled by a simulator to give a general overview over a DC's CO_2 footprint.

5.2 Requirements

In the section above the factors contributing to the CO_2 footprint of a DC are summarized. Based on the various factors that occur in the four phases, the requirements for the DCS can be established. The requirements are used to evaluate the simulator's calculations with regard to the CO_2 footprint. The following section lists requirements that later can be used to determine whether or not a simulator calculates a general overview and also can be used as a guideline to consider each aspect necessary to calculate the CO_2 footprint as good as possible.

5.2.1 Requirements Construction Stage

Chapter 5.1 described ways to calculate the emissions of a DC with the help of four different stages of a DC's life cycle - the Construction Stage, the Operation Stage, the Transportation Stage and the Disposal Stage. With the knowledge of how to calculate the emissions of the Construction Stage this section now names three requirements that must be considered in a DCS to cover the whole CO_2 emissions of the Construction Stage.

C1 *Construction material*
The emissions of the construction process are highly depending of the material used. As presented in Table 5.1 the emissions of the material can be calculated based on the quantity used. To cover the total CO_2 emissions of the construction process it is necessary that a simulator considers the amount of each material used during the construction process. Alternatively the Simulator can also use a more general approach by calculating the material emissions based on the construction area.

C2 *Emissions of the construction process*
Besides the material the next big factor in the Construction Stage is the construction process itself. The work and energy used during it can be taken into account to calculate the CO_2 emissions as presented in Section 5.1.1. Therefore the CO_2 emissions of the construction process need to be considered within each DCS.

C3 *Origin of the construction material*
As described in Section 5.1.1 it is also necessary to consider the origin of the construction material to decide whether or not the emissions of the transportation are already covered in requirements C1 or C2. A DCS therefore must be able to calculate the transportation emissions individually.

These three requirements - the construction material, the construction process and the origin of the material enable a DCS to calculate the Construction Stage's impact on the CO_2 footprint of a DC.

5.2.2 Requirements Operation Stage

In addition to the requirements for the Construction Stage, requirements for the Operation Stage are developed and elaborated in this section. In this chapter requirements regarding the Operation Stage will be developed and elaborated. As the Operation Stage produces the biggest amount of CO_2 emissions, these requirements have to be considered in simulations in order to calculate a realistic CO_2 footprint.

O1 *External power sources*
As described in Section 5.1.2 DCs are heavily reliable on external power sources. To cover the CO_2 emissions of the energy production it is necessary to determine the energy sources used and how they contribute to the CO_2 footprint. A DCS that aims to calculate the CO_2 footprint of a DC's life cycle must be able to consider the energy mix and the emissions produced by each energy source individually.

O2 *Internal power sources*
Besides the external power supply, nowadays it is possible for DCs to produce parts of their energy need by themselves. To take the emissions into account, that appear during the local energy production, it is therefore necessary for a DCS to cover the energy sources used internally and how they contribute to the DC's CO_2 footprint.

O3 *Cooling technique*
The cooling is one of the main energy consumers of a DC. Therefore the cooling technique has a major impact on the CO_2 footprint. But besides the emissions of the energy consumption, cooling also has an influence on the water usage of the DC. With the water production also

emitting CO_2 the cooling technique has a huge potential to save CO_2. A DCS considering the cooling technique therefore can show how an improvement in the cooling can improve the DC's sustainability by limiting the CO_2 emissions.

O4 *Water usage*
As mentioned above the water usage also contributes to the CO_2 emissions of a DC. To cover those emissions a DCS must be capable to consider the water usage and calculate the emissions that appear in this process.

O5 *Data Center efficiency*
The efficiency of a data center is another factor that needs to be considered by a DCS. With the PUE, CUE and WUE it is possible to show the effectiveness of a DC and also if there is potential for improvement.

O6 *Location of the Data Center*
The location of a DC influences the energy mix, availability of water, and other factors presented in Section 5.1.2. A DCS that considers the location therefore is able to influence the planing process of a DC by determining whether the chosen location offers a good availability of energy, water and other resources and also show possible improvements in the CO_2 footprint based on the location.

DT1 *Energy consumption network traffic*
Without the network connection a DC's utility is very limited. But the transmission of data needs energy and also contributes to the CO_2 footprint of a DC. A DCS therefore needs to consider the data traffic produced by the DC.

DT2 *Available energy mixture*
The emission of the data transmission does not only rely on the amount of data sent, but also on the available energy mixture in the region the transmission happens. To calculate the CO_2 emissions of the data transmission a DC therefore must consider the available energy mixture and the emission of the individual energy sources.

With the knowledge of how to calculate the CO_2 emissions of the Construction Stage, this section provided requirements for DCS that helps calculating the total CO_2 footprint of a DC. The external and internal power supply, the cooling technique, water usage, reuse of energy, the efficiency and the location are all factors that contribute directly or indirectly to the CO_2 emissions of a DC. Together with the requirements towards data transmission - the amount of network traffic, the available energy mixture, and the time of network transmission - these requirements ensure that the CO_2 emissions of the Operation Stage are observed and considered in the DC's CO_2 footprint.

5.2.3 Requirements Transportation Stage

With DCs scattered all around the world, the transportation of freight has a big impact on the CO_2 footprint of a DC, as presented in Chapter 5. While the section before covered the emissions of the Operation Stage and named matching requirements, this section now consider the requirements of the Transportation Stage, that must be met by a DCS to calculate the transports CO_2 emissions.

FT1 *Type of transport*
With the globalized industry the CO_2 emissions of freight transport need to be considered. The type of transport is one of the major variables that influence the emissions of the transportation stage. A DCS therefore must determine whether the freight is transported by cargo ship, truck, train or plane.

FT2 *Distance of transport*
Together with the type of transport the other important factor is the distance the freight is transported. A DCS that connects the distance and the type of transport is able to calculate a more exact CO_2 footprint.

The type of transport, the distance traveled and the region the freight goes through are important factors in the Transportation Stage to measure the CO_2 emissions. Therefore, those three points must also be met by the DC to cover the influence on the DC's CO_2 footprint.

5.2.4 Requirements Disposal Stage

As the final part of a DC's life cycle the Disposal Stage has a big impact on it's CO_2 footprint. As described in Chapter 5 the Disposal Stage is the counter part of the Construction Stage and covers similar topics. This means that a DCS must met the following requirements to consider the disposal completely:

D1 *CO_2 emission of disposing hardware*
As described in Section 5.1.4 the hardware of a DC must typically be replaced within 5 to 6 years, due to reaching its end of life. The emissions of disposing hardware therefore is a factor that needs to be considered in a DCS focusing on the CO_2 footprint.

D2 *CO_2 emission of disposing a building*
Also Section 5.1.4 describes how the emissions of demolishing a building can be calculated. With the easy to measure and calculate CO_2 emissions, a DCS must consider the disposal to get an overall overview of a DC's CO_2 footprint.

D3 *CO_2 emission of disposal process*
Besides the emission of the materials it is also necessary to consider the emission of the demolishing an disposal process. A DCS only can deliver an overall overview if the process is considered and taken into account. Together with the emissions of the material the disposal process delivers the complete CO_2 emissions of disposing a DC.

With this chapter describing the requirements that enables a DCS to calculate the emissions of the Disposal Stage - hardware disposing, emissions of demolishing a building and the required work - all requirements regarding the four different stages are named. If a simulator meets most of the requirements of the construction, operation, transportation and Disposal Stages it will give a broad overview over the total CO_2 footprint at the end of a DC's life cycle.

5.3 Overview

This chapter discussed how the carbon emissions of a DC's life cycle can be calculated and based on that calculation what requirements a DCS must fulfill to cover each stage. With the influences of the Construction Stage (material, work, origin), the factors of the Operation Stage (external/internal power production, cooling, water usage, energy reuse, energy efficiency and the data transmission factors (amount of data, energy mix, and rime of transmission) both stages must be considered in the CO_2 footprint calculation. Also the impacts of the transportation stage (type, distance, region) and of the Disposal Stage (hardware, disposing a building and disposal process) are necessary to be considered in a DCS calculating the CO_2 footprint. At the end, this chapter provided a quick overview of all requirements in Table 5.4 that helps to evaluate if a DCS meets all requirements or not.

Stage		Requirement
Construction	C1	Construction material
	C2	Construction process
	C3	Origin of material
Operation	O1	External Power Sources
	O2	Internal Power Sources
	O3	Cooling technique
	O4	Water usage
	O5	Data Center efficiency
	O6	Location of the Data Center
	DT1	Energy consumption network traffic
	DT2	Available energy mixture
Transportation	T1	Type of transport
	T2	Distance of Transport
Disposal	D1	*CO_2 emission of disposing hardware*
	D2	*CO_2 emission of disposing a building*
	D3	*CO_2 emission of the disposal process*

Table 5.4: Simulator Requirements

6 Analysis of Data Center Simulators

With the increasing interest in sustainability of DCs, operators need to consider this aspect in the planning phase or check whether existing DCs have to be improved in order to comply current regulations. This is why researchers and operators become more and more interested and demand the estimation of the CO_2 footprint as part of DCS calculations.

As stated before, there are several aspects to calculate the total carbon footprint of a DC based on four phases. The impacts of the Construction, Operation, Transportation and Disposal Stages all contribute significantly to the carbon footprint of the life cycle of a DC. Based on these findings, the requirements established (Chapter 5.2) can be used to analyze existing DCSs to determine if they are capable of determining a DC's CO_2 footprint.

In this chapter, already existing DCS will be evaluated to show whether or not they are capable of estimating the CO_2 footprint of a DC. For this evaluation the requirements presented in Chapter 5.2 will be used to show which simulator considers which part of the four stages of a DC's life cycle.

6.1 DCNSim

Developed by Yang Liu and Jogesh Muppala from the Hong Kong University of Science and Technology, the Data Center Network Simulator (DCNSim) offers the simulation of a DC's network and aims to evaluate the performance of it. Based on the event simulator SimJava, the simulator enables the users to evaluate and compare specific network architectures and the routing of packages within. To perform the necessary calculation DCNSim offers the user multiple different traffic patterns but also enables the user to use a unique traffic pattern with a traffic pattern generator. It's main purpose is to calculate the maximum throughput of a DC network, the so called ABT, but is also used to calculate the average path length, or rate of routing failures. [LM13]

Like previously introduced, the network connection of a DC plays an important part in the calculation of the DC's CO_2 footprint, DCNSim seemed to be a simulator that may help to calculate the networks CO_2 emissions. But while it considers the network of a data center, it does not calculate any CO_2 emissions produced by it and does not meet any of the requirements as presented in Table 6.1.

Stage		Fulfilled
Construction	C1	No
	C2	No
Operation	O1	No
	O2	No
	O3	No
	O4	No
	O5	No
	O6	No
	DT1	No
	DT2	No
Transportation	T1	No
	T2	No
Disposal	D1	No
	D2	No
	D3	No

Table 6.1: Evaluation - Simulator Requirements: DCNSim

6.2 DCSim

```
- -- HOSTS --
-    nHosts: 1
- Active Hosts
-    max: 1.0
-    mean: 0.95
-    min: 0.0
-    CPU util: 4.035%
-    MEM util: 6.25%
- Data Centre
-    CPU util: 3.833%
-    MEM util: 5.938%
- Power
-    consumed: 0.025kWh
-    max: 153.852Ws
-    mean: 152.216Ws
-    min: 148.0Ws
-    efficiency: 5.017cpu/watt
```

Figure 6.1: DCSim - calculation results

DCSim is a data center simulator developed by Michael Tighe, et al. from the University of Western Ohio [TKBL12]. It simulates different abstraction levels of a DC - VMs, Hosts, Racks, Cluster, and Data Center. Being an extensible data center simulator it is meant to deliver a framework to test "DC management techniques and algorithms"[TKBL14]. Therefore it is also capable to simulate management policies for a data center and evaluate their behavior in stress situations, for example when a host has a unusually high utilization and VMs must be transferred to another host. Also, it only covers a small part of a DC and describes percentages for CPU utilization and a number of active hosts.

Aiming on the Operation Stage on a DC's life cycle with management policies based on utilization of the different components DCSIM only covers the energy efficiency by calculation the PUE and the efficiency per watt. No other requirements are fulfilled as presented in Table 6.2.

Stage		Fulfilled
Construction	C1	No
	C2	No
Operation	O1	No
	O2	No
	O3	No
	O4	No
	O5	Yes
	O6	No
	DT1	No
	DT2	No
Transportation	T1	No
	T2	No
Disposal	D1	No
	D2	No
	D3	No

Table 6.2: Evaluation - Simulator Requirements: DCSim

6.3 CoolSim

CoolSim [Mod21] is a DCS of the company Applied Math Modeling Inc. It's main focus is to simulate the air flow within a DC, as presented in Figure 6.2, and it is therefore mainly a computational fluid dynamics simulator that describes the heat flow within DCSs.

To simulate the air flow, CoolSim offers a virtual server room and enables the user to place models of server racks and other objects freely within the virtual room, to recreate individual settings and offer a unique calculation. By simulating the air flow, CoolSim focuses on the Operation Stage of a DC's life cycle and does not consider other stages.

But besides it main purpose CoolSim also provides other results like the PUE and the total facility power, which enables the user to perform a rough evaluation of the simulation. Besides that, CoolSim does not provide any further aspects to fulfill the requirements and does not offer any calculation towards the CO_2 emissions :

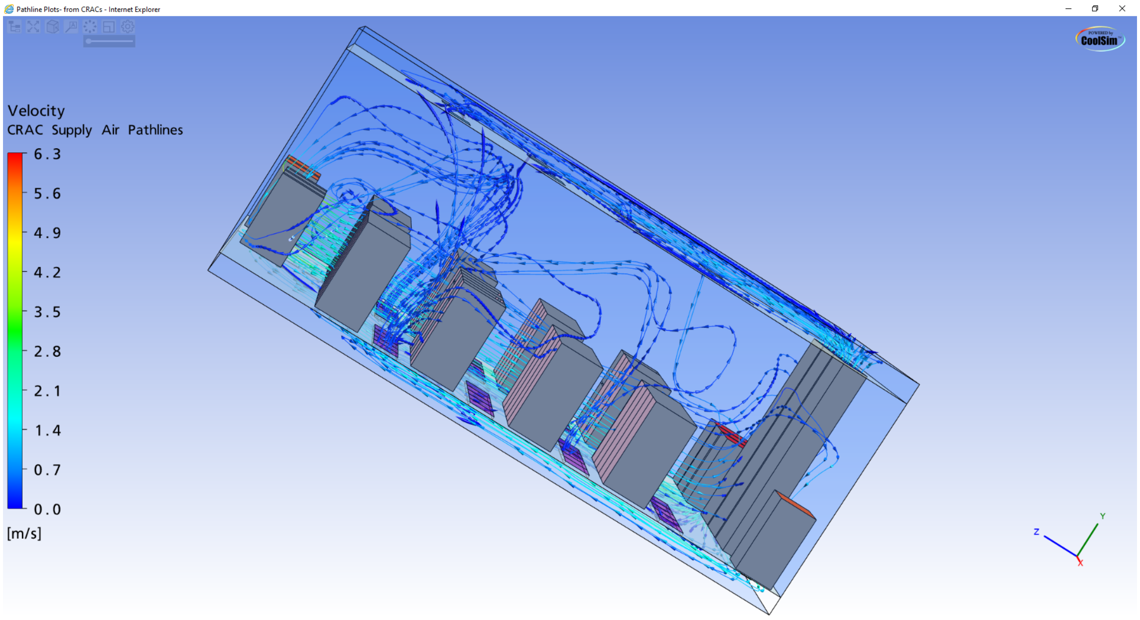

Figure 6.2: CoolSim Air Flow result

Stage		Fulfilled
Construction	C1	No
	C2	No
Operation	O1	No
	O2	No
	O3	No
	O4	No
	O5	Yes
	O6	No
	DT1	No
	DT2	No
Transportation	T1	No
	T2	No
Disposal	D1	No
	D2	No
	D3	No

Table 6.3: Evaluation - Simulator Requirements: CoolSim

6.4 Schneider Electric - Data Center Footprint Calculator

Schneider Electric's Data Center Footprint Calculator [Ele21] is a simulator that calculates the CO_2 emissions based on three different variables: location, efficiency and load. For the location they consider the continent and the country to calculate the CO_2 emissions footprint and the avoided CO_2 emissions. For the efficiency the simulator uses the PUE and offers the possibility to compare two

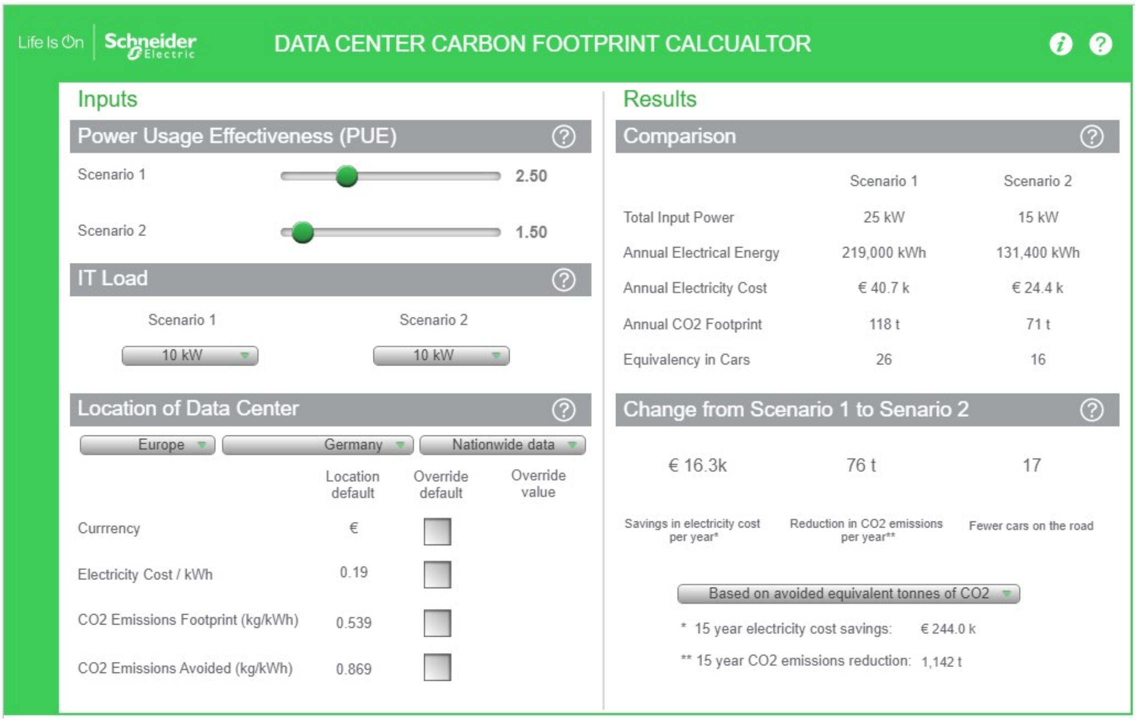

Figure 6.3: Schneider Electric - Data Center Carbon Footprint Calculator [Ele21]

different scenarios with different PUE and IT Load. Out of the requirements of chapter 5.2, the Data Center Footprint calculator focuses on the Operation Stage and ignores the other stages as shown in Table 6.4. Also within the Operation Stage the simulator only considers three requirements:

O1 *External Power Sources*
While the simulator doesn't directly distinguish between different energy sources, it does consider the external power sources overall. To calculate the CO_2 emissions of the external power sources, simulator does consider the CO_2 emissions of the available energy mixture per kWh in the specified location.

O5 *DC efficiency*
Schneider Electric's Data Center Footprint Calculator does consider the efficiency of a DC. The simulator uses the PUE to take the efficiency into account and also compare different PUE scores and their effect on the CO_2 emission.

O6 *Location*
The simulator uses the location of the DC to get values for the CO_2 emissions of the energy supply. It does not consider different energy sources but takes an average value of a country as metric. While this method simplifies the calculation and roughly delivers a value for the energy supply's carbon emission, it is not possible to consider different regional settings or the use of renewable energy.

While the simulator of Schneider Electric covers the CO_2 emissions of a DC, it does only consider a small aspect of a DC's life cycle and even there focuses on small and easy to calculate aspects. It only covers three of the 15 requirements presented in chapter 5.2 and will only provide a quick overview over possible CO_2 emissions and savings for one year of operation, based on the energy supplier's CO_2 emissions.

Stage		Fulfilled
Construction	C1	No
	C2	No
Operation	O1	Yes
	O2	No
	O3	No
	O4	No
	O5	Yes
	O6	Yes
	DT1	No
	DT2	No
Transportation	T1	No
	T2	No
Disposal	D1	No
	D2	No
	D3	No

Table 6.4: Evaluation - Simulator Requirements: Schneider Electric Data Center Footprint Calculator

6.5 Analysis Results

After the analysis of DCNSim, DCSim, CoolSim, and Schneider Electric's calculator it is safe to say that none of the simulators met the requirements to calculate the CO_2 footprint of a DC' life cycle. While DCNSim does not fulfill any of our requirements at all, DCSim and CoolSim do also meet one requirement. With two out of the 18 requirements fulfilled Schneider Electric's is the only simulator that does calculate direct CO_2 emissions of a DC and estimate an annual CO_2 footprint. But also Schneider Electric's calculator only focuses on the Operation Stage with the energy consumption and the emissions of the energy production.

Out of the four analyzed simulators none considers the construction, transportation, or Disposal Stage. This means that none of this simulators is capable of delivering an estimation of the overall CO_2 footprint of a DC. Even the best of the evaluated simulators only considered the Operation Stage and within this stage only a single emission source or impact on the emissions.

This result shows that to estimate the overall CO_2 footprint of a DC, it is necessary to develop a new simulator, that is capable to calculate the emissions of the four stages and therefore covers the complete life cycle of a DC. In the following chapter a simulator will be designed, that fulfills the presented requirements. Besides the design and the calculation details, the chapter will also describe the implementation of the simulator.

7 Design and Implementation

As analyzing existing simulators showed, that none of them fully consider all aspects of CO_2 footprint calculations, gained insights and elaborated requirements are used to design a DCS. Although Schneider Electric's Data Center Carbon Footprint Calculator considered some of the requirements, the simulator only is capable to estimate a small amount of CO_2 emissions.

Aiming to calculate the CO_2 footprint as extensive as possible, the newly designed simulator takes all four stages into account. To create the most value for operators, also suggestions for potential improvements of the CO_2 footprint are designed as part of the simulators calculation logic, using the Green Grids CUE, PUE, and WUE. Afterwards details and characteristics of implementing the simulator are shown.

7.1 Design

To implement a simulator, that is capable of estimating the CO_2 footprint of a DC, four different stages of the DC's life cycle must be consider: the Construction, Operation, Transportation and Disposal Stage. Each of these stages requires different user inputs and different data sets to calculate the CO_2 emissions based on the identified aspects and requirements in Chapter 5. This section will provide the basic idea for the simulator, the design choice towards the different calculations and how the calculations will later be implemented.

In order to provide the relevant information for operators, the simulators user interface is designed to calculate the CO_2 footprint either for specific stages or for the overall footprint. To support the user best, the simulators user interface provides a guided walk-through. To sketch a useful interface the following subsections cover the needed inputs, data sets, calculations and necessary outputs of each stage. The overall concept of the CO_2 footprint calculation in the DCS is collected and a visualization for the simulator Graphical User Interface (GUI) is proposed.

7.1.1 Construction Stage

As stated in Chapter 5.1.1, in the Construction Stage three different aspects need to be considered and summed up: the construction material, the origin of the construction material and the construction process itself.

Construction Material
The material used in the construction process of data centers causes CO_2 emissions. Table 5.1 provided an overview of the emissions of commonly used construction material per kg.

To calculate the emissions of construction material, the data of all materials including weight information is required as input. For each material, the weight (m) is multiplied by the deposited emissions per kg CO_2. Subsequently, all results are summed up.

The emissions of the construction material will be calculated as follows:

$$(7.1)\quad CO2_{Material-Construction} = \sum m_{Material} * CO2_{Material}$$

Transportation Construction
While in the part above, the emissions of the raw material is calculated, it is also necessary to consider the origin of the material. As stated in Chapter 5.1.1, it is necessary calculate the emissions of the transportation. The simulator will therefore ask the user to enter the distance between the storage of the construction material and the construction side. Based on the distance, the area of the DC (A) in m^2 and the emissions of the transport by truck (0.138 kg CO_2 per tonne km, see Chapter 5.1) the emissions of the transportation will be calculated as follows:

$$(7.2)\quad CO2_{Transport-Construction} = 0.138 \frac{kg\ CO_2}{tonne\ km} \cdot A_{DC} \cdot 3.08135 \frac{t}{m^2} \cdot distance$$

Construction Work
As described earlier the construction work's CO_2 emissions can be estimated based on the area of the data center with about 71 kg CO_2/m^2. The user therefore has to enter the expected area (A) in m^2 of the DC. With this information, the simulator then is capable to calculate the emissions of the construction work.

$$(7.3)\quad CO2_{Work-Construction} = A_{DC} * 71 \frac{kg\ CO_2}{m^2}$$

Combined CO_2 emissions of the Construction Stage
In the end, the simulator will then sum up the CO_2 emissions of each individual aspect and return the value of CO_2 emitted within the Construction Stage. This value then will be showed in the GUI of the simulator and within the Construction Page a doughnut chart will show the shares of each aspect.

$$(7.4)\quad CO2_{Construction} = CO2_{Material-Construction} + CO2_{Transport-Construction} + CO2_{Work-Construction}$$

As this section covers the Construction Stage of a DC's life cycle, it considers the CO_2 emissions of the material, the origin of the material, and the work process. Each aspect is calculated individually and considered in the overall CO_2 footprint of the DC.

7.1.2 Operation Stage

The previous section described the calculations, that will be performed by the simulator to cover the emissions of the Construction Stage using the individual emissions of the construction material, it's origin and the construction work. With the Construction Stage covered, this subsection shows how the calculations necessary for the Operation Stage is covered.

Distinguishing between the necessary emissions to operate the data center and the network connection, this stage covers external and internal factors and also factors, that do not contribute directly to the emission, but may influence them.

Power Supply

The most important part of the Operation Stage is the power supply of the DC. With the ongoing development of modern renewable power producers, such as wind or solar energy, the power supply must consider whether or not it is external or internal. To calculate the emissions of the power supply, the simulator asks for the average power consumption (W) in kWh and the location of the DC. With the location the simulator will be able to calculate the emissions based on the energy mixture in the specified region. But to cover individual aspects, that are not considered with the country's energy mixture, the user will also be able to state the emissions of the energy mixture individual. The emissions will then be calculated with the median emissions stated in Table 5.2.

$$(7.5) \quad CO2_{Power} = \sum W_{EnergySource} * CO2_{EnergySource}$$

Water Consumption

Furthermore the cooling technique of the DC has to be considered in the Operation Stage. While it does not contribute directly to the emissions, it affects the energy and water consumption of the DC and can indicate potential to improve the CO_2 emissions. The DCS will therefore ask for the type of cooling used in the simulated DC. Together with metrics like the CUE and WUE it is then possible to point out possible potential to save water or energy and therefore limit the CO_2 emissions of either the energy or the water supply.

As stated in Chapter 5.1.2 the CO_2 emitted during the water pumping can be calculated based on the water usage. On average about 0.376 kg CO_2 are emitted to produce one m^3 of water. The DCS therefore is able to calculate the CO_2 emissions based on the water consumption (V) of the DC:

$$(7.6) \quad CO2_{Water} = V_{Water} * 0.376 \frac{kg\ CO_2}{m^3}$$

Data Transmission

Besides the CO_2 emissions connected directly to the operation of the DC also the network transmission of the data contributes to the CO_2 footprint. As DC are typically used to provide services all around the world, they are connected to the internet to transmit their data. With the energy consumption per Gigabyte and the CO_2 emissions of the power suppliers known (as presented in Chapter 5.1.2), it is possible to calculate the CO_2 emissions of the data transmission. The DCS will therefore ask the typical network throughput of the data center and the location of the network traffic:

$$(7.7)\quad CO2_{Transmission} = \frac{1}{2}\sum_{i=1}^{2} GB_{Data} * x_i * CO2_{EnergyMix}$$

$$x_1 = 0.005\frac{kWh}{GB}, x_2 = 0.010\frac{kWh}{GB}$$

Overall Emissions

The overall emissions of the Operation Stage will then be calculated by add the emissions of each part of the stage:

$$(7.8)\quad CO2_{Operation} = CO2_{Power} + CO2_{Water} + CO2_{Transmission}$$

7.1.3 Transportation Stage

With the calculation of the CO_2 emissions of the construction and Operation Stage a major part of the CO_2 footprint of a data centers life cycle is covered. But nonetheless it is important to also cover the Transportation stage, to consider the CO_2 emitted during the transport of freight via ship, truck, train or plane.

Calculation

Based on the Table 5.3 it is possible to calculate the CO_2 emitted during each part of the freight transport. The DCS will therefore ask for the distance traveled by each type and the weight of the transport. This allows to roughly estimate the overall emissions of the transport as follows:

$$(7.9)\quad CO2_{Plane} = weight_{freight} \cdot distance_{plane} \cdot 0.768$$

$$(7.10)\quad CO2_{CargoShip} = weight_{freight} \cdot distance_{ship} \cdot 0.00621$$

$$(7.11)\quad CO2_{Truck} = weight_{freight} \cdot distance_{truck} \cdot 0.138$$

$$(7.12)\quad CO2_{Train} = weight_{freight} \cdot distance_{train} \cdot 0.049$$

$$(7.13)\quad CO2_{Transport} = CO2_{CargoShip} + CO2_{Plane} + CO2_{Train} + CO2_{Truck}$$

7.1.4 Disposal Stage

Finally, the Disposal Stage will be taken into account to cover the complete CO_2 footprint of the DC. As stated in Chapter 5 the Disposal Stage can be calculated similar to the Construction Stage. Therefore, the DCS will ask the user to input the values of used construction material and the area of the DC, if they are not already given in the Construction stage.

Calculation

Similar to the Construction Stage, the CO_2 emissions are calculated as follows:

(7.14)

$$CO2_{Material-Disposal} = \sum m_{Material} * CO2_{Material}$$

(7.15)

$$CO2_{Work-Disposal} = A_{DC} * 71000\frac{g}{m^2}$$

(7.16)

$$CO2_{Disposal} = CO2_{Material-Disposal} + CO2_{Transport-Disposal} + CO2_{Work-Disposal}$$

7.1.5 Overall CO_2 footprint

In the previous sections the design and the calculations necessary to cover each Stage were described. With covering the CO_2 emissions of the material, the origin of the material and the process in the Construction and Disposal Stage, the CO_2 emissions of the power supply, water supply and data transmission in the Operation Stage, and the CO_2 emissions based on transport type, weight, distance and location in the Transportation Stage a broad spectrum of CO_2 emitters are identified and considered within the DCS.

The DCS is therefore capable to calculate the overall CO_2 footprint based on the emissions of all four stages:

(7.17)

$$CO_2 = CO2_{Construction} + CO2_{Operation} + CO2_{Transport} + CO2_{Disposal}$$

7.2 Implementation

After designing a simulator to determine the overall CO_2 emissions of a data center, this chapter describes a possible implementation in a proof of concept. The contents and formulas described above are implemented so that the concept can be evaluated and compared with other solutions.

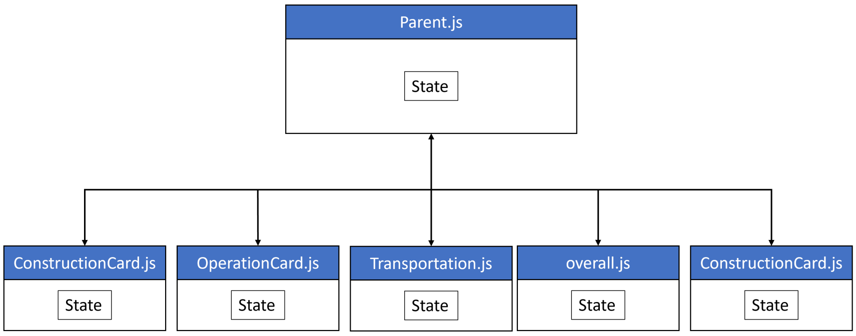

Figure 7.1: Architecture

7.2.1 Prototype construction

The Prototype was realized by a REACT app [Inc21] with chart.js [21a] and React-Bootstrap [21b]. This solution enables a platform-independent usage and could be hosted as web-app in future. As all logic as part of the front end code is executed client-side, this is a lightweight approach. Computation being performed direct on client system, makes them fast and performant without additional connections. Since no separate data storage is required for the prototype, the data is temporally stored in the state of the React app. As shown in Figure 7.1 the React-App consists of a parent.js and multiple card.js. As the input and calculations values are saved in the state of the parent.js, the values are passed from the parent to the card when necessary. This ensures, that the values are consistent during the usage of the app.

The parent.js is used to organize the Stage and Chart Cards. While it does not provide any logic, it provides the state variables for all card classes and callback operations for all classes to update the state variables. Further the parent.js class provides a header with the buttons to navigate through the life cycle stage.

The following subsections will now provide an overview over the individual cards and the source code.

7.2.2 Stage Cards

Within the simulator React Bootstrap Cards are used as an modifiable approach, that enables fast customization. In the simulator two different types of Cards are used: one to offer the needed forms to get the user input and the other one to display the visualization as doughnut chart.

Each of the four stages described above, has it's unique card, that offers the necessary input fields to collect the data required for the calculations of the individual CO_2 emissions. Based on the requirements of each individual stage, the stage card offers input fields that are either more general or very specific.

Each of the stage cards contains the GUI as well as the logic within its Javascript file. To provide the GUI of the card, each stage card uses the React Bootstrap Card component with it's own header, body and footer depending on the individual requirements of the stage. Within the Card component the input fields are provided using React Bootstrap Forms. Each Form offers a placeholder in case there is no value entered or the value is zero.

Construction Card

The construction card provides the state and input fields for the numbers that are necessary to calculate the emissions of the Construction Stage.

The input fields can be selected depending on the desired level of detail. If the user only wants a general calculation of the emissions, input fields for the transport distance of the materials (in km) and the building area (in m^2) of the data center are requested. A flat value of 3g per square meter area is then used to calculate the emissions for the building materials. Alternatively, if the user wants a more precise calculation, there is an option to additionally specify the weight of the materials used individually. In this case, the data from the table 5.1 is used for the exact calculation.

State
Within the construction card, the state holds four different variables:

- Array - constructionMaterial
  The array constructionMaterial contains the values entered for the ten individual materials given and inherits it values from the parent.js's constructionMaterial array. If the detailed view is not used, the array is not needed and remains in its initial state consisting of zeros.
- Variable - distance
  The distance variable saves the transport distance entered and inherits it's and inherits the constant values to calculate distance from parent.js. This ensures that after changing the life cycle stage the values will be saved and can later be changed.
- Variable - constructionArea
  The constructionArea variable saves the construction area of the DC. As the variable above it inherits it's values from the parent.js class and its constructionDistance.
- Variable - detailedActive
  The detailedActive variable is a boolean value to dis- or enable further input fields. If false, the user doesn't use the detailed view, the constructionMaterial array turns in its initial state and flat value of calcChanges class is used with inserted constructionArea to calculate material emissions.

View

As previous stated, each card contains its React Bootstrap components to provide the GUI. Listing 7.1 shows exemplary code for the ConstructionCard showing the implementation of the card header, body and footer and the first input field of the construction card. Figure 7.2 shows the detailed and normal view of the ConstructionCard.

Listing 7.1 Exemplary React-Code in ConstructionCard.js

```
render() {
    return (
        <div>
            <Card style={{ color: '#000', height: "75vh"}}>
                <Card.Header>
                    <Card.Title>Construction Stage</Card.Title>
                </Card.Header>
                <Card.Body>
                  <Form>
                      {this.state.detailedActive &&
                      <div>
                      <Form.Text>Construction Material</Form.Text>
                            <Row>
                                <Col md>
                                    <Form.Text>Concrete</Form.Text>
                                </Col>
                                <Col md>
                                    <Form.Group>
                                        <Form.Control
                                            id="concrete"
                                            type="number"
                                            placeholder="Concrete [kg]"
                                            value={this.state.constructionMaterial[0] === 0 && null}
                                            value={this.state.constructionMaterial[0] !== 0 &&
                                        this.state.constructionMaterial[0]}
                                            onChange={e => {
                                                this.changeBGColor(e.target.value, e.target.id);
                                                this.setState(update(this.state, {
                                                    constructionMaterial: {
                                                        [0]: {$set: e.target.value}}
                                                    }))
                                            }}
                                        />
                                    </Form.Group>
                                </Col>
                            </Row>
                            .
                            .
                            .
                <Card.Footer>
                        <Row>
                            <Col>
                                {!this.state.detailedActive && <Button variant="primary"
                                        onClick={this.onDetailedActive}>Detailed Input</Button>}
                                {this.state.detailedActive && <Button variant="primary"
                                        onClick={this.onDetailedActive}>Hide Details</Button>}
                            </Col>
                            <Col>
                                <Button variant="primary" onClick={this.onSubmit}>Calculate</Button>
                            </Col>
                        </Row>
                 </Card.Footer>
                </Card.Body>
            </Card>
        </div>
    )
}
```

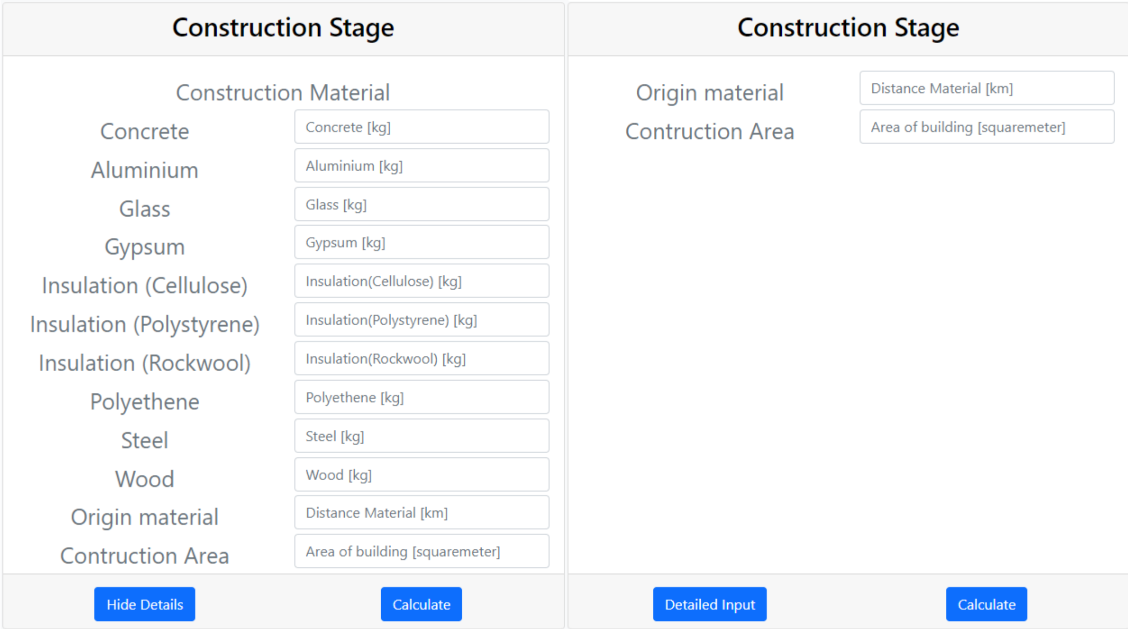

Figure 7.2: Detailed and normal view of the ConstructionCard

Logic

Within the calcChanges function of the constructionCard.js the class calculates the emissions of the construction material, the transport distance, the construction work and the total emissions of the Construction Stage according to equations 7.1, 7.3, 7.4 as shown in Listing 7.2. The calcChanges function uses the parameters material, distance and area provided from the state of the constructionCard.js and will return the emissions of each part as well as the total emissions. Afterwards, the constructionCard.js will forward them to the parent.js to be safed.

Listing 7.2 Logic Function within ConstrcutionCard.js

```
/**
 *
 * @param {*} material - array containing the weight of used construction material, 0s if not used
 * @param {*} distance - var containing the distance between material storage
 * @param {*} area - var containing the area of the constructed building
 * @param {*} detailedCalc - var - boolean whether or not detailed material weights are used
 * @returns
 */

calcChanges(material, distance, area, detailedCalc) {

/**set emissions per source, order: [concrete, aluminium, glass, gypsum, insulation(cellulose),
 * insulation(polystyrene), insulation(rockwool), polyethene, steel, wood]
 */
var emissionsPerMaterial = [0.132,11.135, 0.605, 0.300, 0.281, 1.803, 1.460, 2.137, 1.082, 0.112];

// total emissions[0] and emissions of material[1], distance[2] and work[3]
var emissions = [0,0,0,0];

/**
 * if detailed entries: calculate kWh per material and weight
 * else calculate with average value of 0.003 kg CO_2 per m^2
 */
if(detailedCalc){
    for(var i=0; i<material.length; i++){
        emissions[1] = emissions[1] + (material[i]*emissionsPerMaterial[i]);
    }
} else{
    emissions[1] = area * 0.003;
}

/**
 * calculate emissions based on distance
 * CO_2 Emissions Truck 0.138 kgco2 per tonne and km
 * weight per m^2: 3081,35kg
 * if detailed weight given calculate with given weight, else with estimate based on area and weight per m^2
 */

if(detailedCalc){
    var totalWeight = 0;
    for(var i=0; i<material.length; i++){
        totalWeight = totalWeight + material[i];
    }
    totalWeight = totalWeight/1000;
    emissions[2] = 0.138*totalWeight*distance;
}else{
    emissions[2] = 0.138*3.08135*area*distance;
}

/**
 * emissions for construction work
 * 1 m^2 == 71 kg CO_2
 */
emissions[3] = (area * 71);

emissions[0] = emissions[1] + emissions[2] + emissions[3];
emissions.map(v => v.toFixed(3));
return emissions;
}
```

Operation Card

The operation card provides the forms and logic that are necessary to calculate the emissions connected to the operation of the DC.

State

The state of the OperationCard.js contains the following variables:

- Variable - powerConsumption
  Containing the value for the power consumption in kWh of the DC, this variable inherits it's initial value from the parent.js.
- Variable - itLoad
  The itLoad variable contains the value of the IT load in kWh. It inherits its initial value from the parent.js and is used to calculate the PUE, CUE and WUE.
- Variable - individualCO2
  Containing individual values for the CO_2 emissions per kWh, this Variable is used to enable calculations if the CO_2 values is not within the normal energy mix of the specific country. If not set, this value will be 0.
- Variable - waterConsumption
  This variable saves the amount of Water in m^3 consumed by the DC and inherits it's initial value from the parent.js.
- Variable - dataTransmission
  The dataTransmission contains the amount of data traffic produced by the DC in GB. Similar to the other variables the initial value is inherited from the parent.js.
- Variable - location
  The location variable contains the location of the data center. As the variables above, this variable also inherits it's initial state from the parent.js.
- Variable - lifeSpan
  As last variable in the OperationCards state, the lifespan variables saves the planed lifespan of the DC and is used to extrapolate the CO_2 emissions of the Operation Stage which are calculated per year.

View

The operation card provides the input forms to get the data for the power and water consumption, the data transmission rate and the location of the DC. Figure 7.3 shows the initial view of the operation card.

Logic

Within the calcChanges Class, the emissions of the Operation Stage are calculated based on the calculations 7.5, 7.6, 7.7 and 7.8 and uses power consumption, water consumption, IT load, individual CO_2, data throughput and the location of the DC as parameters. In the end, the function returns an array containing the overall emissions, the emissions for the power consumption, water consumption, data transmission, and the values of PUE, CUE and WUE.

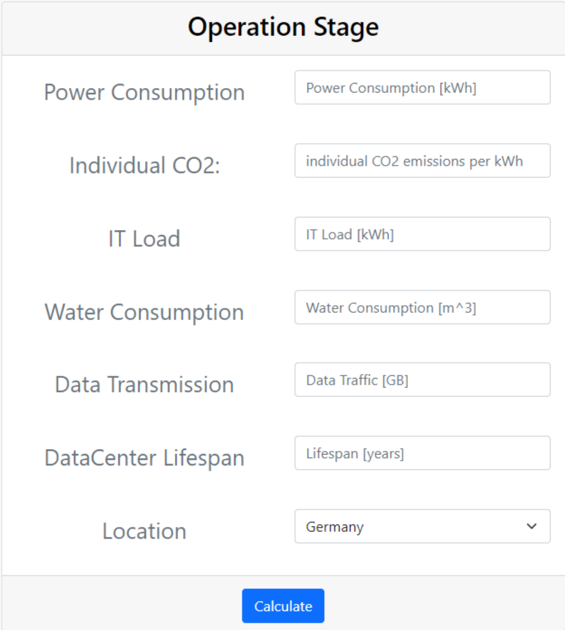

Figure 7.3: GUI of the Operation Card

Transportation Card

The Transportation Card provides the forms and logic for the transportation stage of a DC's life cycle.

State

In the state of the TransportationCard.js the following values are saved:

- Variable - weight
  The weight variable contains the weight of the transported freight and inherits from the parent.js's transportWeight variable.
- Variable - distancePlane
  Covering the distance freight is transported via plane, the distancePlane variable inherits it's initial value from the parent.js's transport array.
- Variable - distanceShip
  The distanceShip variable contains the distance the freight is transported by cargo ship. Similar to the distancePlane variable, it inherits its initial value from the transport array of parent.js
- Variable - distanceTruck
  To save the distance freight is transported on the road, the distanceTruck variable saves the corresponding value. Like the distancePlane and distanceShip variable it inherits it's initial value from the transport array of parent.js

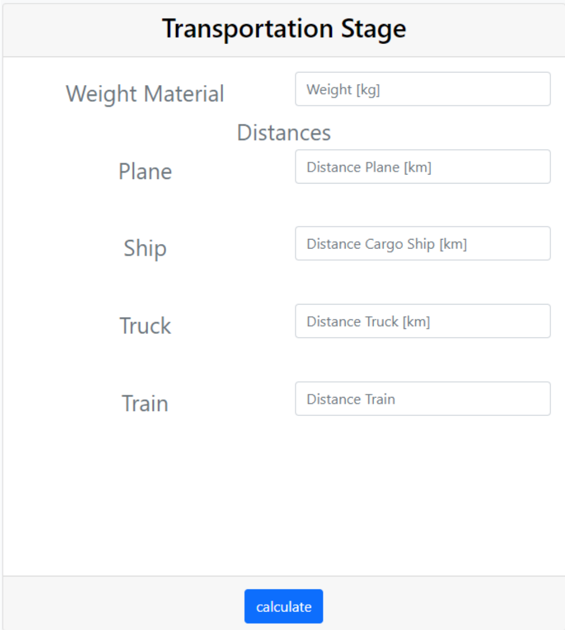

Figure 7.4: Transportation Card of the CO2Sim

- Variable - distanceTrain
  The last variable of the TransportCard.js is the distanceTrain, covering the distance freight is transported via cargo trains. Same as the previous three variables the initial value is inherited from the transport array of the parent.js.

View

The Transportation Card provides Input Forms to enter the values for the transport weight and the distances freight is transported by plane, ship, truck or train. Figure 7.4 shows the initial state of the Transportation Card.

Logic

To calculate the emissions for each of the four transport types and the total transport emissions the calcChanges function uses the parameters weight, distancePlane, distanceShip, distanceTruck and distanceTrain, as shown in listing 7.3. The calculations follows the equations 7.9, 7.10, 7.11, 7.11 and 7.13. After the calculations the function returns an array containing the total emissions and the emissions of all transport types, which will then be forwarded to the parent.js.

Listing 7.3 Logic Function within TransportationCard.js

```
/**
   *
   * @param {*} weight - weight of the freight in tonne
   * @param {*} distancePlane - distance transport by plane in km
   * @param {*} distanceShip  - distance transport by ship in km
   * @param {*} distanceTruck  - distance transport by truck in km
   * @param {*} distanceTrain  - distance transport by train in km
   * @returns - array containing emissions [overall, plane, ship truck, train] in kgCO_2
   */
  calcChanges(weight, distancePlane, distanceShip, distanceTruck, distanceTrain) {

  // emissions overall[0], plane [1], ship [2], truck[3], train[4]
  var emissions = [0,0,0,0,0];
  //emissions per weight [tonne] and distance plane [0], ship [1], truck[2], train[3] in kg
  var emissionsPerType = [0.768, 0.00621, 0.138, 0.049];

  //calculate emissions plane
  emissions[1] = emissionsPerType[0]*weight*distancePlane;

  //calculate emissions ship
  emissions[2] = emissionsPerType[1]*weight*distanceShip;

  //calculate emissions truck
  emissions[3] = emissionsPerType[2]*weight*distanceTruck

  //calculate emissions train
  emissions[4] = emissionsPerType[3]*weight*distanceTrain

  //total emissions
  emissions[0] = emissions[1] + emissions[2] + emissions[3] + emissions[4];

  //map values to 3 decimals max
  emissions.map(v => v.toFixed(3));

  return emissions;
  }
```

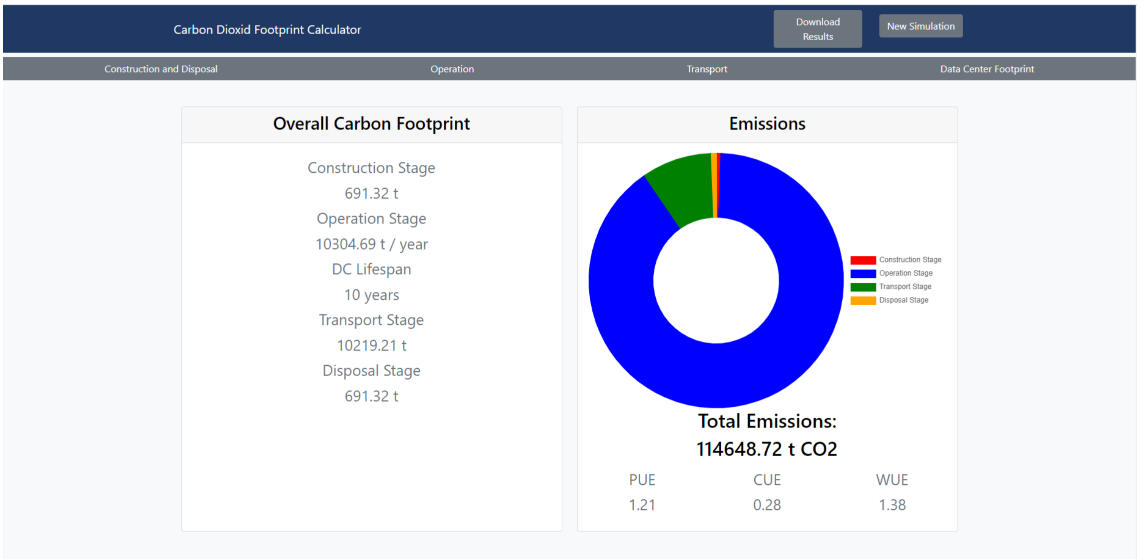

Figure 7.5: Overview of the Overall Footprint Card together with the Chart Card

7.2.3 Overall Footprint Card

As final card the overall Footprint Card provides the user with an overview of the emissions previously calculated and the total CO_2 footprint of the DC. Offering no input options, the card only shows previous calculations. Further a doughnut chart provides an overview over the share the different life cycle stage have on the CO_2 footprint and also the values of the PUE, WUE and CUE, as shown in Figure 7.5.

8 Evaluation and Discussion

In the previous chapters, the basics and requirements to calculate the CO_2 footprint of a DC using a DCS were discussed. Additionally, existing simulators were analyzed and found to not meet the necessary requirements to calculate the full CO_2 footprint. For this reason, a new simulator was designed and analyzed in the further parts of the thesis, which should fulfill as many requirements as possible.

In order to verify this, this chapter evaluates the designed simulator using the criteria from Chapter 5 and compares it to the existing simulators from Chapter 6. Furthermore, the simulator is compared to real data using an example evaluation, where possible. At the end of this chapter, the research questions are discussed and an outlook on further improvements or future extensions of the designed simulator is given.

8.1 Comparison

In the first section of this chapter, the simulator developed during the thesis is analyzed and compared with the other simulators from Chapter 6. For this purpose, this chapter examines whether and how many requirements the new simulator fulfills and how it compares to the other simulators.

8.1.1 Requirements Evaluation

As in Chapter 6, the requirements are evaluated on the basis of the individual life cycle stages of a DC. Likewise, the evaluation is structured according to the stages and their associated requirements.

Construction Stage

To calculate the emissions of the Construction Stage, the simulators are required to cover three areas:

C1 Construction Material: fulfilled

C2 Emissions of the Construction Process: fulfilled

C3 Origin of the Construction Material: fulfilled

The new simulator fulfills all of these three requirements. It is able to record the emissions of the building material both on the basis of exact weight data of individual building materials and to calculate them on the basis of the building area. Here, the user can select which of the two methods is preferred and provide corresponding data. The building area is also used to make a rough calculation of the emissions caused by the actual construction work. Emissions from material transport are calculated by entering the distance traveled and recorded accordingly. To give a quick overview of the total CO_2 emissions, the sum of all emissions is displayed at the end and a doughnut chart is used to show the shares of the individual areas.

Operation Stage

In order to capture emissions from ongoing operations and incorporate them into the calculation of the carbon footprint, the following requirements are placed on the simulator:

O1 External Power Sources: fulfilled

O2 Internal Power Sources: fulfilled

O3 Cooling: fulfilled

O4 Water Usage: fulfilled

O6 Data Center efficiency: fulfilled

O7 Location of the Data Center: fulfilled

DT1 Energy Consumption Network traffic: fulfilled

DT2 Available Energy Mixture: fulfilled

As in the Construction Stage, the simulator also meets all requirements in the Operation Stage. By recording the complete electricity consumption through the simulator and recording the location, both the internal and external CO_2 emissions are calculated by the simulator. The calculation is based on the electricity mix in the selected country and the CO_2 emissions of each energy source per kWh. Water consumption and the resulting emissions are recorded and calculated based on the user's input. Water consumption is additionally also taken into account when calculating the effectiveness of the DC. Together with the total electricity consumption and the IT Load, the values of PUE, CUE and WUE are thus be calculated and displayed to the user. By querying the location and the amount of data transmitted, the emissions of network usage is also determined by the designed simulator.

Transportation Stage

To capture the full CO_2 footprint, emissions from deliveries to the DC must also be considered. Therefore, the following requirements cover CO_2 emissions of the Transportation Stage for DC:

FT1 Type of transport: fulfilled

FT2 Distance of transport: fulfilled

The simulator acquires the type of transport, as well as the weight of goods and the distance traveled per type of transport. It thus fulfills all requirements and calculates the CO_2 emissions of the Transportation Stage. The emissions are given both in total and broken down by transport type, so the user can evaluate and find improvements on transportation.

Disposal Stage

The final stage of the life cycle of an DC is the Disposal Stage. In order to capture the emissions generated during the demolition of the building, the following requirements are placed on the simulator:

D1 CO_2 Emissions of disposing hardware: not fulfilled

D2 CO_2 Emissions of disposing a building: fulfilled

D3 CO_2 Emissions of disposal process: fulfilled

Opposed to the other stages, the simulator can not fulfill all requirements towards the Disposal Stage, due to lack of data. Within the scope of this work, no usable data basis on the disposal of hardware, especially of data centers, could be determined. For this reason, it was not possible to cover this aspect via the simulator.

Overview

Table 8.1 shows the requirements the simulator has fulfilled. Even though it did not meet all the requirements, the simulator is clearly better at capturing the footprint compared to the other simulators (see Chapter 6) that did not meet any (DCNSim) or only one (DCSim, CoolSim) or at best three (Schneider Electric's Data Center Footprint Calculator). So, the designed simulator CO2Sim can be seen as a valuable addition to existing simulators and thus be taken into account to calculate the aspect of CO_2 emissions.

Stage		Fulfilled
Construction	C1	Yes
	C2	Yes
Operation	O1	Yes
	O2	Yes
	O3	Yes
	O4	Yes
	O5	Yes
	O6	Yes
	DT1	Yes
	DT2	Yes
Transportation	T1	Yes
	T2	Yes
Disposal	D1	No
	D2	Yes
	D3	Yes

Table 8.1: Evaluation - Simulator Requirements CO2Sim

After the quantitative evaluation of the requirements in this section, the following section deals with a qualitative analysis of the simulator based on a case study.

8.1.2 Example High-Performance Computing Center Stuttgart

The HLRS, a data center of the University of Stuttgart, [HLR21a] is used as a case study for the qualitative analysis of the simulator. Part of the HLRS is the supercomputer Hawk [HLR21b], which is ranked 24th in the TOP500 list of fastest supercomputers as of November 2021 [Gmb21].

The HLRS regularly publishes environmental statements that provide necessary data for input to the simulator and comparative data for output. For this case study the environmental report of 2019 [BLF+20] is used as basis.

The necessary data of the HLRS environmental report to compare simulators output is listed in Table 8.2.

Label	Value
Area	6089.53 m^2
Power Consumption	28406000 kWh
IT Load	23476033 kWh
Water Usage	32512 m^3

Table 8.2: Data HLRS - adapted from [BLF+20]

The environmental report does not provide any data on network usage or data that can be used as a basis for transport days. However, a rough order of magnitude for the weight of the hardware used can be derived from the Hawk supercomputer [HLR21b] data: The Hawk supercomputer uses the HPE Apollo 6500 Gen10 Plus system, HPE ProLiant DL385 Gen10 servers and matching racks. From the HPE Apollo 6500 Gen10 Plus System [Ent21a] datasheet, it can be seen, that the system can reach a maximum weight of 98.4kg and a height of 6U. The HPE ProLiant DL385 Gen10 server has a height of 2U and a maximum weight of 24.7kg [Ent21c]. A matching server rack is the HPE 42U G2 Enterprise shock rack, which has a slot area of 42U and a maximum payload of 1361kg. The rack itself weighs a maximum of 237kg [Ent21b].

According to the information on the website [HLR21b], Hawk uses 48 (44 ProLiant + 4 Apollo 6500) server racks on which the hardware is distributed. Extrapolated, this results in a weight for a server rack with ProLiant servers or Apollo 6500 Gen10 systems of:

$$Weight_{Rack(ProLiant)} = 21 \cdot 24.7kg + 237kg = 755.7kg \tag{8.1}$$

$$Weight_{Rack(Apollo6500)} = 7 \cdot 98.4kg + 237kg = 925kg \tag{8.2}$$

With these assumptions, we can determine the total weight of the Hawk supercomputer:

$$\begin{aligned} Weight_{Hawk} &= 44 \cdot Rack_{ProLiant} + 4 \cdot Weight_{Rack(Apollo6500)} \\ &= 44 \cdot 755.7kg + 4 \cdot 925kg = 36950kg \end{aligned} \tag{8.3}$$

With this data, it is also possible to extrapolate other systems of the HLRS, the NEC Cluster (16 racks [8 CPU + 8 GPU]) and the Cray CS-Storm (16 racks [8 GPU, 8 CPU]). For this purpose, the Apollo 6500 rack is assumed for GPU systems and the ProLiant rack for CPU systems.

$$Weight_{NEC} = 8 \cdot 755.7kg + 8 \cdot 925kg = 13445.6kg \tag{8.4}$$

$$Weight_{CS-Storm} = 8 \cdot 755.7kg + 8 \cdot 925kg = 13445.6kg \tag{8.5}$$

The complete hardware weight of the HLRS-Hardware is therefore assumed as follows and used within the simulator:

$$(8.6)\quad \begin{aligned} Weight_{HLRS} &= Weight_{Hawk} + Weight_{NEC} + Weight_{CS-Storm} \\ &= 36950kg + 13445.6kg + 13445.6kg = 63841.2kg \end{aligned}$$

For the data transmission a throughput of 200 GB/min is assumed, which leads to a data transmission per year of:

$$(8.7)\quad Transmission = 200\frac{GB}{min} \cdot 60min \cdot 24 \cdot 365 = 105,120,000\frac{GB}{Year}$$

To calculate the emissions of the Transportation Stage, we also need the distance traveled during transportation. For this case study, we assume that the hardware is shipped from Kaohisung, Taiwan, as Taiwan being one of the main producers of such hardware, via Hamburg to the HLRS in Stuttgart. So distances in Table 8.3 are assumed for the simulation.

Transport Type	Value
Plane	0 km
Cargo Ship	18,820.024 km (via Suez Canal)
Truck	100 km
Train	600 km

Table 8.3: Assumed Distances for Hardware Transportation

With these data and assumptions, it is now possible to compare the results of the simulator compared to the real values of the environmental report of the HLRS [BLF+20] as shown in Table 8.4 and Table 8.5

The Data of Tabels 8.4 and 8.5 show the CO_2 emissions data calculated by the new simulator and given by [BLF+20]. Also, the environmental report provides only few of the data calculated by the simulator. An additional peculiarity is also that the Environmental Report shows an individual CO_2 value of 0.233 kg CO_2/kWh for the electricity mix of the University of Stuttgart. This value is about half of the average CO_2 value of the generally available electricity mix in Germany.

Taking this into account, it can be seen that the simulator calculates the CO_2 emission correctly, as the HLRS environmental report value of 6618.60 t CO_2 and the simulator calculated a value of 6618.598.91 t CO_2 for Power Consumption. Furthermore, one can compare the GreenGrid metrics PUE, CUE and WUE, as shown in Table 8.5. The PUE is exactly the same here. The CUE value is different by a factor of 1.33 and the WUE by a factor of 1.25. Further, the environmental report does not provide a calculation of the CUE and WUE but instead only lists the results. The most probable source of error is the IT load, since this could only be derived from the information in the environmental report and was not specified. However, since the PUE is correct and also based on the IT load, this cannot be clearly determined as the source of error and it remains unclear why the values differ.

Category	Emissions (CO2Sim)	Emissions(HLRS report)
Construction & Disposal Stage		
Construction Work	432.356 t CO_2	–
Construction Material	0.018 t CO_2	–
Transport Distance	258.942 t CO_2	–
Construction (total)	691.32 t CO_2	–
Operation Stage		
Power Consumption / year	6618.598 t CO_2	6618.60 t CO_2
Water Consumption / year	12.224 t CO_2	–
Data Transmission / year	3 673.865 t CO_2	–
Operation (total) / year	10304.69 t CO_2	–
Transportation Stage		
Plane	–	–
Cargo Ship	7.461 t CO_2	–
Truck	0.881 t CO_2	–
Train	1.876 t CO_2	–
Transportation (total)	10.218 t CO_2	–
CO_2 Footprint		
Total	104439.73 t CO_2	6618.60 t CO_2

Table 8.4: Comparison CO_2 emissions CO2Sim to HLRS environmental report [BLF+20]

Metric	Value (CO2Sim)	Value(HLRS report)
Construction & Disposal Stage		
PUE	1.21	1.21
CUE	0.28 kg CO_2/kWh	0.21 kg CO_2/kWh
WUE	1.38 l/kWh	1.10 l/kWh

Table 8.5: Comparison Green Grid Metrics: CO2Sim to HLRS environmental report [BLF+20]

As no other emissions are listed, it is not possible to compare the data of other stages than the Operation Stage. Furthermore, in the scope of this work, no other simulators could be evaluated, that calculates the CO_2 footprint in this extend. But based on the above comparisons, it can be assumed that the simulator calculates reliably in the other stages as well and is capable to estimate the complete CO_2 footprint of a DC.

8.1.3 Summary

This subsection showed that the simulator developed in this thesis both outperforms other simulators and can correctly calculate the CO_2 footprint. Other simulators focus solely on CO_2 emissions from electricity consumption and meet only a few (maximum three) of the requirements for calculating the CO_2 footprint. The newly developed simulator, on the other hand, was able to meet all but one of the requirements, demonstrating that it can perform a comprehensive calculation of the CO_2 footprint of a DC. In the qualitative analysis, the simulator also showed that the output values are realistic and comparable to the data from the case study. The simulator is thus able to make a comprehensive and coherent calculation of the CO_2 footprint and can make a useful contribution in the analysis and planning of DC.

8.2 Discussion and Outlook

In the course of this work, it was highlighted how a LCA approach can be used in the calculation of the CO_2 footprint and how the individual sections can help to perform the necessary calculations in a DCS. Based on this, requirements were then set and current DCS were tested against these requirements. In addition, based on the LCA approach and the individual stages, a simulator was developed, that meets the established requirements and enables a comprehensive calculation of the CO_2 footprint of a DCS. The following section discusses, as outcome of this work, the research questions in detail.

8.2.1 Results and Conclusion

In the course of this thesis, a DCS was developed that calculates the CO_2 footprint much more extensively than other simulators. This section will now discuss the underlying research questions:

RQ1 What factors influence the CO_2 footprint?

The CO_2 footprint of a DC describes the DC emissions directly or indirectly associated with the DC that occur during its life cycle. To capture this footprint as completely as possible, a LCA is necessary. Based on the LCA approach in Chapter 3.2, several stages were identified that allow a more detailed analysis of CO_2 emissions. Within each stage, causes of CO_2 emissions could then be identified and analyzed:

- Manufacturing / Construction Stage

  Within the Manufacturing and Construction Stage, several factors have been identified that influence the CO_2 emissions. These are mainly related to the construction of the DC. The first factor identified is the materials used in the construction of the DC. Two pathways were identified by which the CO_2 emissions contained in the material could be calculated. One way is to directly calculate the CO_2 emissions by the individual weight of the different construction materials. Table 5.1 thereby shows which CO_2 emissions per kg are associated with the respective material. Alternatively, it is also possible to determine the emissions of the building materials based on the area of the data center. The second factor that contributes significantly to Construction Stage emissions is the construction work itself. Based on the area of the building, it is possible to obtain a lump sum value for the CO_2 emissions from the construction work. The final factor contributing to the total CO_2 emissions of the Construction Stage is the transportation of the construction materials. Unlike later in the Transportation Stage, in the Construction Stage it is only necessary to analyze the direct transportation warehouse and construction site, since the emissions beyond that are already accounted for in the construction material values. Depending on the weight of the building material, the CO_2 emissions of the transport can be calculated. If the weight of the material is not specified, a rough estimate of the weight of the material can be made on the basis of the surface area and the corresponding CO_2 emission calculated as a result.

- Packaging Stage

  The next stage is the Packaging Stage and the CO_2 emissions of the packaging contained therein. In the scope of this thesis, not enough data was available to make a closer analysis possible. This is due to the fact that, depending on the individual packaging of an object, there are different levels of CO_2 emissions. Without the appropriate data, it was not possible to provide a detailed breakdown of the packaging stage. The aspect of packaging should be challenged in future work.

- Operation Stage

  The Operation Stage is the most important stage in the life cycle of a data center in terms of its CO_2 footprint. Due to the high energy requirements of a DC and its approximate useful life of 10 years, a large portion of the CO_2 footprint occurs during the Operation Stage. In the course of this work, it was possible to identify several factors of the Operation Stage that have an influence on the CO_2 footprint. First and foremost among these is the power consumption of a DC. Together with the location of the data center, it is possible to calculate the CO_2 emissions generated by electricity consumption. Another major influence on the CO_2 footprint is the water consumption of the DC. The CO_2 emissions generated by extraction and supply are major contributors to the CO_2 footprint. The final factor identified as significantly affecting the CO_2 footprint is the network connectivity of a DC. Here, the power consumption of the network contributes to the CO_2 footprint of the Operation Stage.

- Storage Stage

  The Storage Stage of a DC was identified as the fourth stage. The Storage Stage handles the storage of material, etc. In the scope of this thesis. it was not possible to find sufficient data sets that would have allowed a more detailed analysis of the storage stage and could be used in a general approach. So this should also be further investigated in a future work.

- Transportation Stage

  Another important stage with regard to the CO_2 footprint is the Transportation Stage. Essentially, there are 3 factors that influence the CO_2 emissions: the weight of the freight, the type of transport and the distance covered. Based on this information, it is then possible to determine the CO_2 emissions of the respective transport type and to record a total CO_2 emission of the Transportation Stage.

- Disposal Stage

  The Disposal Stage was identified as the last stage contributing to the CO_2 footprint in the life cycle of a DC. Within the Disposal Stage, the CO_2 output of the demolished materials, the demolition work, and the transport must be included in the CO_2 output of the Disposal Stage.

In summary, several factors influence the CO_2 emissions of a data center. Whereas some stages in a DC life cycle can be determined, for some stages there are not enough appropriate data to provide a detailed breakdown and further analysis. For this reason this work focused on the stages construction, operation, transportation and disposal of a DC life cycle. The determined factors and stages are the basis to evaluate how and to which extend existing simulators calculate the CO_2 footprint of DC in the next research question.

RQ2 How do simulators calculate the CO_2 footprint?

To determine how current DC calculate the CO_2 footprint, various requirements for the simulators were developed in Chapter 5.2. These are based on the life cycle stages of the LCA approach and the more detailed analysis of the individual stages in Chapter 5.1. A selection of simulators were analyzed: DCSim, DCNSim, CoolSim, Schneider Electric. In the course of the analysis, it was found that the simulators either do not analyze the CO_2 footprint at all (DCNSim) or only analyze it to a very limited extent (DCSim, CoolSim, Schneider Electric). DCSim and CoolSim only consider the efficiency of the DC, for this purpose both simulators use the PUE metric as well as other power consumption data.

As the only one of the simulators analyzed, Schneider Electric's Data Center Footprint Calculator also considers the DC emissions generated by the use of CO_2. However, the simulator is limited to the CO_2 emissions from the amount of electricity consumed and calculates this based on the IT Load entered by the user, the PUE and the location of the DC.

In summary, the analysis shows that none of the simulators presented calculates an overall footprint. As far as the simulators fulfill the requirements from 5.2, this is limited to the Operation Stage and especially the subcategories efficiency, location and power consumption. Thus, the simulators only calculate sub-areas of a full life cycle and cannot estimate the full footprint of a DC. However, as stated above, since there are far more factors to consider and calculate as part of the CO_2 footprint, calculations can be improved to get a more comprehensive picture of the CO_2 emissions of a DC.

RQ3 How can the calculation in simulators be improved?

In order to improve the calculation of the CO_2 footprint and obtain the most meaningful result, it is necessary to consider the stages of the LCA that have already been identified for 5.2:

- **Manufacturing / Construction Stage**

  Within the Construction Stage, both the construction work for the actual building and the manufacturing processes must be considered for the most complete coverage of CO_2 emissions.

  Manufacturing of Hardware - Hardware manufacturing includes the production of servers, graphics cards, server racks, cooling, etc. Due to the enormous amount of different systems, hardware manufacturers and individual configurations, it was not possible within the scope of this bachelor thesis, to find a meaningful calculation method that would have done justice to the variable equipment.

  Nevertheless, hardware manufacturing is an important CO_2 source and can contribute to the improvement of calculations in the future, provided that an appropriate method and data sources are found.

  Construction - In the case of construction work, the building materials, their transport and the actual work contribute to the CO_2 emissions in particular. With regard to the emissions of the construction materials, two approaches can be used in a simulator, depending on the data situation and the desired level of detail. It is possible, on the one hand, to determine the emissions of the individual substances on the basis of their weight; a more general approach, on the other hand, may be chosen if the weight and the different materials are not known. For this purpose, an approximate CO_2 emission of the materials used can be calculated by using a flat value per m^2.

Based on the determined weight, it is also possible to determine the CO_2 emissions of the transport. As already mentioned, only the route between the warehouse and the construction site needs to be determined, since the other CO_2 emissions are already included in the CO_2 value of the building materials.

The area also allows the emissions of the direct construction work to be recorded. Here, based on the m^2 number and a flat value for the CO_2 emission per m^2, a rough calculation of the CO_2 emission of the construction works can be made.

With these calculations, it is possible to obtain an overview of emissions from the construction work and thus improve the calculation of the CO_2 footprint of a DC.

- **Packaging Stage**

  Within the LCA, the Packaging Stage is the next stage to be covered for improved calculation of the CO_2 footprint of a DC. Similar to hardware manufacturing, due to individual packaging, material usage and different manufacturers, it was not possible in this thesis to find a general approach that takes all specifics into account. However, a DCS that calculates the packaging stage would cover an essential stage of a DC and thus improve the concrete calculation of the CO_2 footprint.

- **Operation Stage**

  A significant portion of the CO_2 footprint of a DC occurs during the Operation Stage. Within this stage, all emissions that a DC causes directly or indirectly during operation are recorded.

  Power Consumption - The first and largest factor is the electricity consumption of the DC. Here, to improve the calculation of the emissions, a selection of the location can be made as well as a detailed calculation of the emissions by the energy sources, proportionate to the electricity mix of the country. In connection with the complete electricity consumption of the DC it is then possible to calculate the absolute CO_2 emissions of the DC. Furthermore, it is also useful to allow an individual amount of CO_2 emissions per kWh. This allows especially DC, which have an independent electricity production or else a CO_2 value per kWh different from the general electricity consumption, to calculate your emissions by electricity consumption in detail.

  Water Consumption - In addition, the calculation of the CO_2 footprint can be improved by calculating the CO_2 emitted by water use. Here, using the amount of energy required in kWh per m^3 extracted, water usage and the electricity mix of the respective country, the CO_2 emitted can be calculated and thus accounted for in the CO_2 footprint of the data center.

  Data Transmission - Furthermore, the calculation can be improved if the network usage of the DC is recorded. By specifying the amount of data, the total power consumption can be calculated based on the required energy per GB. Again, using the electricity mix of the respective country and the corresponding CO_2 emissions per kWh, it is then possible to calculate the emissions of the data transmission.

Efficiency Metrics - Based on the above calculations and a query of the IT Load of the DC, it is also possible to use various efficiency metrics. While this is not a direct improvement to the calculation of the CO_2 footprint, it may indicate that improvements in efficiency and thus CO_2 output are possible. Simple metrics to show this directly are the PUE, WUE and CUE developed by the GreenGrid.

Lifespan - To simplify the calculation of the above factors, it makes sense to record them in relation to a year. This ensures a sufficient level of detail and at the same time it is not necessary to go into individual specific deviations. In order to take into account the total emissions of the Operation Stage in the life span of a DC, the value calculated for one year must be calculated against the life span. This then gives the total CO_2 emissions of the DC and allows the CO_2 footprint to be more accurately determined.

In summary, the calculation of CO_2 emissions can be improved in the Operation Stage by taking into account key points such as electricity consumption, water consumption and data transmission and calculating them based on the electricity mix and its emissions. Additionally, a lifetime consideration is needed to account for the complete CO_2 emissions of the Operation Stage over the lifetime of the DC. A good indicator whether improvements are possible in the future are the GreenGrid metrics. Even if these do not directly contribute to improving the calculation of CO_2 emissions, it is recommended to use these easy-to-calculate metrics.

- **Storage Stage**

  Another stage of the LCA of a DC that can contribute to the improvement of the CO_2 footprint is the storage stage. It was not possible to find sufficient data here to make an universal calculation of the CO_2 emissions of the Storage Stage. Nevertheless, based on the LCA approach, it can be said that an improvement in the calculation can be made if a simulator takes the storage stage into account.

- **Transportation Stage**

  The calculation of CO_2 emissions can also be improved by considering the Transportation Stage. In the Transportation Stage of a DC LCA, the CO_2 emissions associated with the transportation of hardware, etc. are taken into account. To calculate the CO_2 emissions, three factors must be taken into account: the type of transport, the weight of the freight and the distance.

  Types of Transportation - Four different groups were identified as the main types of transportation: Aircraft, cargo ships, trucks and freight trains. Depending on the type, different amounts of CO_2 emissions are generated. To enable a universal calculation, an average load factor was identified. Based on it, it is possible to determine the CO_2 emissions for each transport type per ton and distance.

  Weight and Distance - To enable calculation of CO_2 emissions, values based on weight and transport distance are used. The commonly used unit is kg CO_2 per tonne km.

- **Disposal Stage**

  As the last stage in the life cycle of an DC, the disposal stage must be considered. Here, as in the Construction Stage, there are two areas: Hardware Disposal and the Demolition of the Building. A simulator that calculates the disposal stage directly improves the calculation of the CO_2 footprint.

Disposal of Hardware

As in the Construction Stage, it was not possible to find sufficient data to enable a general approach towards calculating the emissions of hardware recycling within the scope of the bachelor thesis. Nevertheless, the calculation of the CO_2 footprint can be improved if a simulator can include the recycling of the hardware.

Disposal of the Building

A further improvement of the calculation of the CO_2 footprint is possible by considering the demolition of the building. The demolition of the building generates similar emissions as the construction. In the course of the thesis, it was found that the same steps and calculations can be used to calculate the CO_2 emissions of the building demolition as in the Construction Stage. If the corresponding calculation has been carried out, a separate calculation is therefore no longer necessary to record the resulting emissions.

In summary, in the analysis of the simulators it became clear that they calculate the CO_2 footprint only marginally and concentrate exclusively on the operation stage and the power consumption. An improvement of the calculations (**RQ3**) within DCS is possible by using the stages of the LCA approach and thus performing a much more comprehensive calculation of the CO_2 footprint. If the six stages are used with the above factors, a calculation can be made that includes all stages of the life cycle of a DC and thus takes into account both direct and indirect CO_2. The exemplarily implementation in chapter 7 and the evaluation, showed that the calculations can be improved.

Summary

Using the LCA to answer the **RQ1**, the different stages and factors that allow the CO_2 footprint to be calculated were identified. For **RQ2**, requirements were placed on simulators and existing simulators were tested against them. Since it was found that none of the simulators performed a comprehensive calculation of the CO_2 footprint, it became necessary to develop a custom simulator that could meet as many of the requirements as possible. As a basis for this, the findings regarding **RQ3** were used, in which it was shown how an improved calculation of the CO_2 footprint can be achieved by taking into account the individual stages and their factors.

8.2.2 Future Work

In the LCA, stages relevant for the calculation of the CO_2 were identified and further analyzed. As already stated, not all factors could be dealt with within the scope of this thesis, but should be further investigated in future work.

The most important remaining points concern the two life cycle stages, which could not be elaborated in more detail within the scope of this work, due to a lack of data and to much variety in materials. Both the Packaging Stage and the Storage Stage of the DC life cycle need to be further investigated to find out how and in which degree CO_2 is emitted and how it can be calculated with a general approach and implemented accordingly in the simulator.

Another point to improve in future work is the development of a general approach to calculate the production or recycling of hardware in the Manufacturing/Construction Stage or in the Disposal Stage. Therefore, an extension of the developed simulator is necessary.

Some more details, like refining the Transportation Stage for regional differences adding more countries and their electricity mixes to the Operation Stage, and a server-client solution for data storage and universal availability would further improve the simulator in future.

The simulator developed in this thesis can be seen as a basis for the calculation of a CO_2 footprint. Therefore, this approach can be further refined and extended in some places to achieve the best possible result.

9 Summary

It is impossible to imagine the modern world without data centers. The demands placed on them are constantly increasing. The trend worldwide is toward high-availability and high-performance web solutions, which places further demands on modern DC. But as requirements increase and the performance of DC increases as a result, so will power consumption and CO_2 emissions. Already in 2017, DC were among the largest consumers of energy, accounting for about 3% of the world's electricity consumption.

At the same time, the world is fighting against global warming which should be limited to a warming between 1.5° Celsius and 2° Celsius. The greenhouse gas CO_2 plays an important role in this process and it is becoming increasingly important to calculate the CO_2 footprint more accurately to reduce emissions. For DC, DCS are a good tool to calculate and plan the environmental impacts. Therefore, the calculation of CO_2 footprint of DC needs to be continuously improved to properly consider, and in the best, reduce the impact.

This thesis challenged current approaches on how to calculate the CO_2 footprint for DC. By presenting the LCA approach as a method to improve the calculation for DC, different stages can be derived for a DC life cycle. Analyzing each stage concerning the aspect of CO_2 emissions, a more comprehensive calculation approach of CO_2 emissions for DC was designed (see Chapter 5.1).

As the first stage to be considered, emissions are already caused in construction of DC. In the Construction Stage, the emissions of the entire construction process can be taken into account on the basis of the materials used, the area to be built on and the actual construction work.

The second stage identified in this thesis is the Operation Stage. As this stages causes the largest share of CO_2 emissions of a data center, all emissions associated with the operation of the DC are considered: the total power consumption, the IT load, the water consumption, the data transmission and the planned runtime, as well as the location of the DC.

The next stage considers the freight transport associated with the DC. Based on four different transport types, the weight of the freight and the respective distance traveled, the CO_2 emissions of the Transportation Stage can be calculated and included in the footprint.

The last stage considered in this paper is the Disposal Stage. Due to the high degree of similarity between the different stages, the emissions calculated in the Construction Stage can be used to calculate the Disposal Stage's share of the total carbon footprint.

Further stages identified (packaging and storage) could not be considered due to lack of data and approaches in this field. So, the calculation of these stages are addressed as open topics for future work.

After identifying and analyzing the different stages, suitable requirements were derived that can be used to analyze existing simulators (Chapter 5.2). The analysis of existing simulators revealed that they either do not calculate the CO_2 footprint at all or do so insufficiently. So, aiming to calculate a more comprehensive CO_2 footprint of DCs, a new approach was developed, that can cover as many requirements as possible (Chapter 6).

Therefore, in the course of this thesis, a new simulator was designed and implemented that considers all four stages, as an example to perform these calculations. It was shown how this simulator calculates the emissions of each stage and how the results are presented. (Chapter 7)

After completion of the new simulator, it was tested against the requirements and the DCS was able to fulfill all but one requirement. Subsequently, a case study was used to further investigate and highlight the practicality of the simulator. At the end, it was shown how the research question was answered in this thesis and an outlook on Future Work was provided. (Chapter 8)

Therefore, a new simulator was created as part of this thesis that takes into account all four stages in the calculation of the carbon footprint. For each stage, the calculations and results were presented. A prototype implementation showed that the requirements set could be met by the new simulator with one exception. Subsequently, a case study was conducted to further investigate and to illustrate the practicality of the simulator. Finally, the research questions were answered and an outlook on future work was given in Chapter 8.

As different factors influencing the CO_2 emission of a DC, an overall investigation of DC life cycle needs to be considered in calculation. Analyzed simulators only cover parts of the CO_2 footprint, so calculations can be improved. The designed simulator can be used as a supplement to existing simulators in order to cover the aspect of CO_2 emissions in more detail.

In consideration of global warming, the calculation and reduction of CO_2 footprints is becoming more and more important. It is likely that research into CO_2 emissions will continue to progress and data center simulators will also be further refined. This research and the resulting simulators, as they relate to DC, can help develop more efficient processes and reduce CO_2 footprints.

Bibliography

[06a] *Environmental management — Life cycle assessment — Principles and framework*. Standard. Geneva, CH: International Organization for Standardization, July 2006 (cit. on pp. 23, 28, 32).

[06b] *Environmental management — Life cycle assessment — Principles and framework*. Standard. Geneva, CH: International Organization for Standardization, July 2006 (cit. on pp. 23, 28, 32).

[21a] *Chart.js*. 2021. URL: https://www.chartjs.org/ (cit. on p. 62).

[21b] *React Bootstrap*. 2021. URL: https://react-bootstrap.github.io/ (cit. on p. 62).

[ABD+12] M. Aggar, M. Banks, J. Dietrich, B. Shatten, M. Stutz, E. Tong-Viet. "Data Centre Life Cycle Assessment Guidlines". In: *The Green Grid* (2012) (cit. on p. 29).

[ABP11] D. Azevedo, S. C. Belady, J. Pouchet. "Water usage effectiveness (WUE™): A green grid datacenter sustainability metric". In: *The Green Grid* (2011) (cit. on p. 32).

[Adm21] U. E. I. Administration. *U.S. Energy facts explained*. 2021. URL: https://www.eia.gov/energyexplained/us-energy-facts/ (cit. on p. 40).

[APPT10] D. Azevedo, M. Patterson, J. Pouchet, R. Tipley. "Carbon usage effectiveness (CUE): a green grid data center sustainability metric". In: *The green grid* 32 (2010) (cit. on p. 32).

[BAH+09] J. Baliga, R. Ayre, K. Hinton, W. V. Sorin, R. S. Tucker. "Energy consumption in optical IP networks". In: *Journal of Lightwave Technology* 27.13 (2009), pp. 2391–2403 (cit. on pp. 35, 42).

[BHR18] L. A. Barroso, U. Hölzle, P. Ranganathan. "The datacenter as a computer: Designing warehouse-scale machines". In: *Synthesis Lectures on Computer Architecture* 13.3 (2018), pp. i–189 (cit. on pp. 25–27).

[Bis14] W. K. Biswas. "Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia". In: *International Journal of Sustainable Built Environment* 3.2 (2014), pp. 179–186 (cit. on pp. 34, 38).

[BLF+20] M. Brodbeck, B. Lorenz, T. Fischer, N. Conrad, I. Wöckener. *Aktualisierte Umwelterklärung 2019*. Tech. rep. Geneva, CH: Höchstleitstungsrechenzentrum der Universität Stuttgart, 2020 (cit. on pp. 76–78).

[Bou11] D. Bouley. "Estimating a data center's electrical carbon footprint". In: *Schneider Electric White Paper Library* (2011), pp. 14–22 (cit. on pp. 18, 20, 29, 33).

[Bun21] D. S. Bundesamt. *Bruttostromerzeugung 2020*. 2021. URL: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Energie/_Grafik/_Interaktiv/bruttostromerzeugung-erneuerbare-energien.html (cit. on pp. 40, 41).

[Ele21] S. Electric. *Data Center Carbon Footprint Calculator*. 2021. URL: https://www.se.com/ww/en/work/solutions/system/s1/data-center-and-network-systems/trade-off-tools/data-center-carbon-footprint-comparison-calculator/ (cit. on pp. 35, 52, 53).

[Ent21a] H. P. Enterprise. *QuickSpecs HPE Apollo 6500 Gen10 Plus System*. 2021. URL: https://www.hpe.com/psnow/doc/a50002545enw.pdf (cit. on p. 76).

[Ent21b] H. P. Enterprise. *QuickSpecs HPE G2 Enterprise Series Racks*. 2021. URL: https://www.hpe.com/psnow/doc/a00002907enw.pdf (cit. on p. 76).

[Ent21c] H. P. Enterprise. *QuickSpecs HPE ProLiant DL385 Gen10 Plus v2 server*. 2021. URL: https://www.hpe.com/psnow/doc/a50002560enw (cit. on p. 76).

[FGL+21] A. Feldmann, O. Gasser, F. Lichtblau, E. Pujol, I. Poese, C. Dietzel, D. Wagner, M. Wichtlhuber, J. Tapiador, N. Vallina-Rodriguez, et al. "Implications of the COVID-19 Pandemic on the Internet Traffic". In: *Broadband Coverage in Germany; 15th ITG-Symposium*. VDE. 2021, pp. 1–5 (cit. on p. 17).

[Fin09] M. Finkbeiner. *Carbon footprinting—opportunities and threats*. 2009 (cit. on p. 32).

[GKK20] C. Goller, M. Keppler, D. Krakowiak. *A Qualitative Analysis of Data Center Simulators*. Tech. rep. Universität Stuttgart, Institute of Architecture of Application Systems - Service Computing, 2020 (cit. on p. 18).

[Gmb21] P. GmbH. *TOP500 List - November 2021*. 2021. URL: https://www.top500.org/lists/top500/list/2021/11/ (cit. on p. 75).

[Gri21] T. G. Grid. *About Us*. 2021. URL: https://www.thegreengrid.org/en/about-us (cit. on p. 31).

[HLR21a] HLRS. *About us*. 2021. URL: http://www.hlrs.de/about-us/ (cit. on p. 75).

[HLR21b] HLRS. *Systems - HPE Apollo (Hawk)*. 2021. URL: http://www.hlrs.de/systems/hpe-apollo-hawk/ (cit. on pp. 75, 76).

[Inc21] M. Inc. *React.js*. 2021. URL: https://reactjs.org/ (cit. on p. 62).

[Ins21] U. Institute. *TIER Classification System*. 2021. URL: https://uptimeinstitute.com/tiers (cit. on p. 27).

[Jau11] E. Jaureguialzo. "PUE: The Green Grid metric for evaluating the energy efficiency in DC (Data Center). Measurement method using the power demand". In: *2011 IEEE 33rd International Telecommunications Energy Conference (INTELEC)*. IEEE. 2011, pp. 1–8 (cit. on p. 31).

[KV14] N. S. Kim, B. Van Wee. "Toward a better methodology for assessing CO2 emissions for intermodal and truck-only freight systems: A European case study". In: *International Journal of Sustainable Transportation* 8.3 (2014), pp. 177–201 (cit. on pp. 35, 43).

[LCC+97] B. M. Leiner, V. G. Cerf, D. D. Clark, R. E. Kahn, L. Kleinrock, D. C. Lynch, J. Postel, L. G. Roberts, S. S. Wolff. "The past and future history of the Internet". In: *Communications of the ACM* 40.2 (1997), pp. 102–108 (cit. on p. 25).

[LM13] Y. Liu, J. Muppala. "DCNSim: A Data Center Network Simulator". In: *2013 IEEE 33rd International Conference on Distributed Computing Systems Workshops*. 2013, pp. 214–219. DOI: 10.1109/ICDCSW.2013.66 (cit. on p. 49).

[LMP00] M. Lauring, R. Marsh, E. H. Petersen. "Arkitektur og Miljø.: Form, konstruktion, materialer-og miljøpåvirkning." In: (2000) (cit. on pp. 34, 38).

[LTK18] J. Lee, S. Tae, R. Kim. "A study on the analysis of CO2 emissions of apartment housing in the construction process". In: *Sustainability* 10.2 (2018), p. 365 (cit. on pp. 34, 38).

[LWX+20] Y. Liu, X. Wei, J. Xiao, Z. Liu, Y. Xu, Y. Tian. "Energy consumption and emission mitigation prediction based on data center traffic and PUE for global data centers". In: *Global Energy Interconnection* 3.3 (2020), pp. 272–282 (cit. on pp. 17, 19, 34).

[McK07] A. McKinnon. "CO2 Emissions from Freight Transport in the UK". In: *Report prepared for the Climate Change Working Group of the Commission for Integrated Transport* 57 (2007) (cit. on pp. 35, 42, 43).

[Mod21] A. M. Modeling. *About CoolSim*. 2021. URL: https://www.coolsimsoftware.com/About-CoolSim/Why-CoolSim/CoolSim-History-and-Vision (cit. on p. 51).

[MS13] A. Moncaster, K. Symons. "A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards". In: *Energy and buildings* 66 (2013), pp. 514–523 (cit. on p. 43).

[OEF20] M. Ondová, A. Eštoková, M. Fabianová. "Reducing the carbon footprint in the foundations structures of masonry family houses". In: *Selected Scientific Papers-Journal of Civil Engineering* 15.2 (2020), pp. 55–62 (cit. on p. 38).

[Oma19] E. Omar. "Data center simulator for sustainable data centers". MA thesis. 2019 (cit. on p. 35).

[PAP11] D. Pandey, M. Agrawal, J. S. Pandey. "Carbon footprint: current methods of estimation". In: *Environmental monitoring and assessment* 178.1 (2011), pp. 135–160 (cit. on pp. 30, 33).

[Paris15] "Paris Agreement". In: *United Nations Treaty Collection, Chapter XXVII 7. d* () (cit. on p. 29).

[PL06] S. K. Pun, C. Liu. "A framework for material management in the building demolition industry". In: *Architectural Science Review* 49.4 (2006), pp. 391–398 (cit. on pp. 43, 44).

[RR20] H. Ritchie, M. Roser. "CO_2 and greenhouse gas emissions". In: *Our world in data* (2020) (cit. on pp. 29, 30).

[SBF+14] S. Schlömer, T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, et al. "Annex III: Technology-specific cost and performance parameters". In: *Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2014, pp. 1329–1356 (cit. on p. 39).

[SDT12] Y. Shimizu, S. Dejima, K. Toyosada. "The CO2 emission factor of water in Japan". In: *Water* 4.4 (2012), pp. 759–769 (cit. on pp. 35, 41).

[SMP+11] A. Shehabi, E. Masanet, H. Price, A. Horvath, W. W. Nazaroff. "Data center design and location: Consequences for electricity use and greenhouse-gas emissions". In: *Building and Environment* 46.5 (2011), pp. 990–998 (cit. on p. 34).

[SUEA20] A. Shaikh, M. Uddin, M. A. Elmagzoub, A. Alghamdi. "PEMC: Power Efficiency Measurement Calculator to Compute Power Efficiency and CO_2 Emissions in Cloud Data Centers". In: *IEEE Access* 8 (2020), pp. 195216–195228 (cit. on p. 34).

[Sys19] C. Systems. *Was ist die MTBF auf dem TMS-Appliance-Server?* 2019. URL: https://www.cisco.com/c/de_de/support/docs/conferencing/telepresence-management-suite-tms/112568-pqa-112568-00.html (cit. on p. 43).

[TKBL12] M. Tighe, G. Keller, M. Bauer, H. Lutfiyya. "DCSim: A data centre simulation tool for evaluating dynamic virtualized resource management". In: *2012 8th international conference on network and service management (cnsm) and 2012 workshop on systems virtualization management (svm)*. IEEE. 2012, pp. 385–392 (cit. on p. 50).

[TKBL14] M. Tighe, G. Keller, M. Bauer, H. Lutfiyya. *DCSim Wiki*. 2014. URL: https://github.com/digs-uwo/dcsim/wiki (cit. on p. 50).

[Tru21] C. Trudell. "Tesla Emissions-Credit Revenue May Boom Again in 2021: Analyst". In: *Bloomberg* (Jan. 2021). URL: https://www.bloomberg.com/news/articles/2021-01-27/tesla-credit-revenue-may-rise-to-2-billion-credit-suisse-says (cit. on p. 17).

[WC+20] P. J. Welfens, K. Celebi, et al. *CO2 allowance price dynamics and stock markets in EU countries: Empirical findings and global CO2-perspectives*. Tech. rep. Universitätsbibliothek Wuppertal, University Library, 2020 (cit. on p. 18).

[WGM11] M. Wallhagen, M. Glaumann, T. Malmqvist. "Basic building life cycle calculations to decrease contribution to climate change–Case study on an office building in Sweden". In: *Building and Environment* 46.10 (2011), pp. 1863–1871 (cit. on pp. 34, 37, 38).

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Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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