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Masterarbeit

Energy and CO2 footprint of cloud/backend processing

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Abstract

Data centers are the backbone of the digital infrastructure and they are responsible for storing and processing large amounts of data. In 2023, global emissions from cloud computing made up from 2.5% to 3.7% of worldwide GHG, thereby exceeding emissions from commercial flights (2.4%). The demand for data centers is increasing exponentially due to high number of users (5.8 billion in October 2023) and rising demand for services and technologies such as streaming, cloud gaming, blockchain, artificial intelligence and machine learning. The emission in this data centers is caused by electricity consumption (to run the servers), water consumption (to run the servers) and the lifetime of the equipment. Many companies have outsourced their tech infrastructure thus their information is being managed more efficiently, but this measure does not remove completely their environmental impact. Different measures are currently being taken from the top three cloud providers: AWS, Microsoft Azure and GCP. AWS leads the list with over 30% market share and they have committed to reaching net zero emissions by 2040. They announced that they will inform their customers about their carbon footprint while continuing to improve emissions release. Azure team is also working to improve their climate impact and are currently trying on a 2-year-old experiment where they have submerged 800 servers on the ocean floor of the Scottish coast. On the other side, GPC, which has the least market share among these three, claims to have already reached net zero emissions. Apart from there, there are many software that are using different algorithm to measure the carbon footprint for data centers.

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Acronyms

ER error rate. 74

FR Fehlerrate. 74

RDBMS Relational Database Management System. 74

1 Introduction

1.1 Motivation

Climate change is one of the hottest topics of this century. GHG contribute the most in heating of the planet. It is estimated that data centers alone cause 3.7% of all greenhouse emissions, thus exceeding the emissions from commercial flights in 2022. The demands for IT services and technologies have been increasing with the advancements of machine learning, AI, cloud gaming, streaming etc. Data storage is estimated to reach 175ZB in 2025[Zho21]. This growth of data processing and data storage has improved the quality of our life, but at the same time hundreds of MtCO2 are released yearly from this. As of today, USA has the largest number of data centers in the world with more than 2000 sites, thus causing highest carbon footprint per country based. Figure 1.2 shows a distribution of data centers worldwide. While in the beginning of the century these data centers were not build thinking about their environmental impact, this has seemed to change in the recent years. There have been improvements in the way data centers are build, where they are build and there has been refinement in the hardware used. So the same algorithm can be executed in less power consumption. Many institutions have already migrated their services to clouds and decreasing their overall footprint. With big cloud providers like AWS, companies can decide where they want to host their services and can track their environmental effect while the
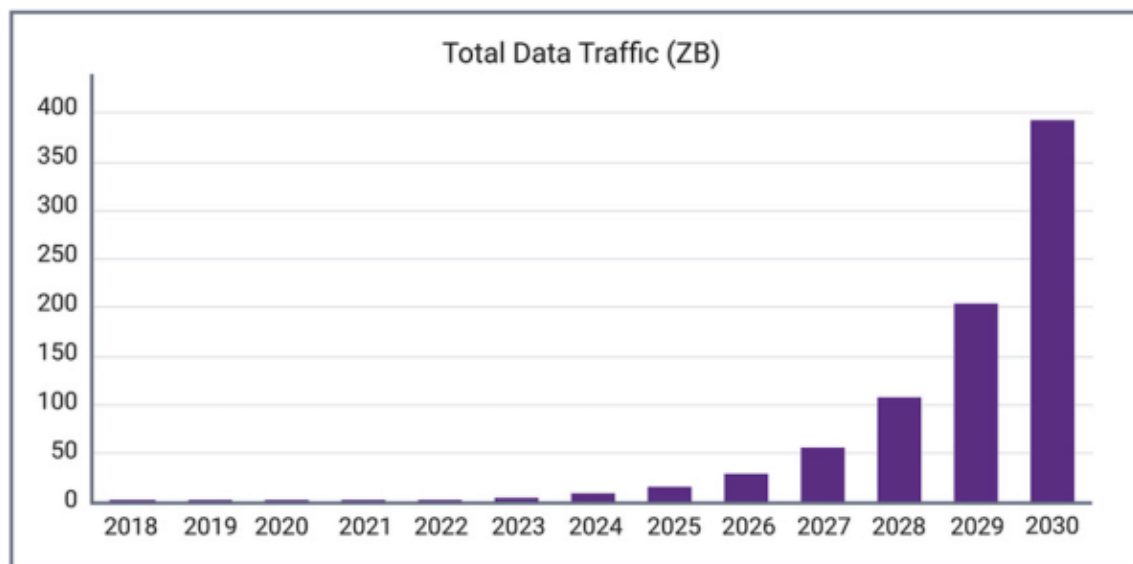
Figure 1.1: Total Data Traffic Forecast through 2030. Source: "Impact of AI on Electronics and Semiconductor Industries", IBS, April 2020
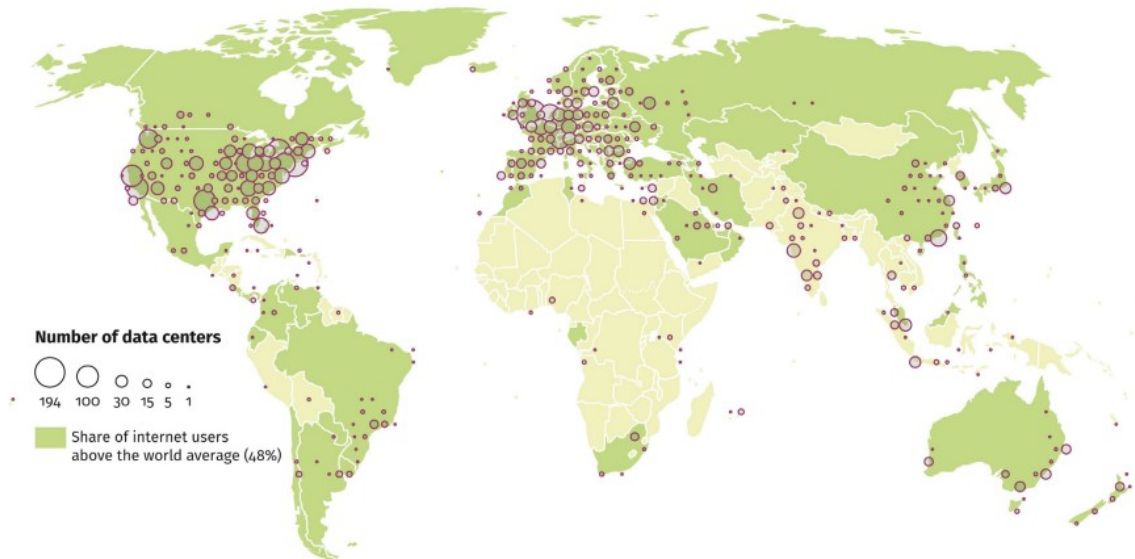
Figure 1.2: Data Center distribution worldwide; Source: Data Center Map

resources are being managed more efficiently.Big companies have advanced in reducing carbon release and Google today uses 100% green energy. But other smaller companies still do not have the right mastery energy management.

Instructions that that a computer what actions to perform are mainly softwares[24a]. Software does not consume energy by itself directly, it directs and influences the operations of hardware, therefore causing carbon emissions. In a survey committed by programmers, only 18% of them stated that they build these programs with efficiency in mind. Considerable work has been done in the development of software with sustainability at its core, thanks to the advancements made in Software Engineering for Sustainability (SE4S). Nevertheless, since this is a relatively new field of study, there is still a significant amount of work to be carried out in this area.

IT in some way has improved our lives in terms of: Life Satisfaction (Trust and Safety), Mobility (Culture and Sports), Integration (Sustainability) and Public Services[NLA19]. Now we can attend a company meeting from the comfort of our own homes instead of commuting to office and therefore lowering overall carbon release. Also there exist data centers that are just tackling the CO2 release itself. So, IT has done more good in terms of carbon emissions, but with the newest researches, the situation can be improved a lot still in terms of electricity production, space and thermal management. GeSISmarter report from 2020 stated the that greenhouse gas emissions can be reduced by 16.5% (9.1GtCO2) with effective use of IT[Cos19].

1.2 Problem Statement

In 2006, the British mathematician and entrepreneur Clive Humby coined the phrase "Data is the new oil" [Hum06]. Michael Palmer expanded on Humby's quote by saying, "like oil, data is valuable, but if unrefined it cannot really be used [Oil] has to be changed into gas, plastic, chemicals,

etc to create a valuable entity that drives profitable activity; so, data must be broken down and analyzed for it to have value"[Pal06]. As of March 2024 there are currently 10593 data centers worldwide with US leading this with 5381 data centers[24b].

Data centers constructed in the past did not take into consideration the environmental considerations. However, as the demand for various products, systems, and activities grew, it became evident that they had a significant carbon footprint. [ZZG+23a] concluded:

1. Approximately 20–40% of the energy consumed by DC can be reduced by optimizing IT equipment, including server layout adjustment, virtualization technology, and storage equipment improvement.

2. Approximately 15–27% of the energy consumed by DC can be reduced via research and development of advanced cooling technologies, including natural cooling and liquid cooling to achieve sustainability.

3. DCs' ECER strategies are affected by the differences in geographical location, natural resources and economic basis, and the single energy-saving method is difficult to meet the goal of zero-carbon emission.

4. The key challenges and potential opportunities in the future decarbonization path of DCs are summarized from the perspectives of policy reform, technological innovation, and resource diversification and management, which is great significance to the realization of zero-carbon DCs and the sustainable development of human society.

1.3 Structure

In the following, the structure is outlines as follows:

- Chapter 2 is the background of this all this and has three subpoints: Energy, Greenhouse Gases and Data Centers

- Chapter 3 is the Study Design along where I included my research questions and the methodology in my research used to find answers for those questions

- Chapter 4 is about all about Energy. In this chapter I studied separately the energy used for running servers and energy used for cooling

- Chapter 5 is the hardware footprint of data centers in years

- Chapter 6 is about Cloud and Virtualization and answers the research question 4

- Chapter 7 is about Energy saved from data centers and clouds and the concept of Carbon-Free Energy Data centers

- Chapter 8 - here there are the conclusions from my my research

Leading countries by number of data centers as of March 2024

Country	Number of data centers
United States	5,381
Germany	521
United Kingdom	514
China	449
Canada	336
France	315
Australia	307
Netherlands	307
Russia	297
Japan	251
Mexico	219
Italy	170
Brazil	168
India	163
Poland	152
Spain	144
Hong Kong	143
Switzerland	122
Singapore	120
Sweden	99
New Zealand	95
Indonesia	81
Belgium	81
23	79
24	79

Number of data centers

Source
Cloudscene
© Statista 2024

Additional Information:
Worldwide; March 2024

Figure 1.3: Leading countries by the number of data centers; Source Statista[24b]

2 Background

We start with providing insights into relevant background knowledge of this thesis. The relevant topics include: "data center", "data center carbon footprint", "data center energy consumption", "data center sustainability", "cloud efficiency", ënergy conservationänd ëmission reduction technology", ßerver thermal management", "cooling in data centers", "liquid cooling".

2.1 Energy

The energy consumption of servers serves as the fundamental metric for assessing power and heat flow within data centers. In these environments, the interplay between IT equipment and cooling systems is tightly intertwined due to thermal considerations. In the context of China, data centers have reached a notable level of energy consumption, with their combined usage ranging between 120 and 130 billion kWh. This accounts for approximately 2% of the total electricity consumption in the country. Similarly, in 2014, data centers in the United States consumed an estimated 70 billion kWh, representing roughly 1.8% of the nation's overall electricity usage.[JBY+20].

The data center's energy consumption primarily stems from two main components: IT equipment and cooling equipment, which collectively account for approximately 90% of the total energy usage[JBY+20]. Figure 2.2 provides an illustration of the dynamics of energy and air flows within a data center. This visual representation offers valuable insights into the aspects of data center operations and highlights the interplay between energy consumption and airflow management. IT equipment, including servers, storage devices, and networking infrastructure, represents a significant portion of the energy consumed within a data center. These electronic devices require power to operate efficiently and process the vast amounts of data they handle. The energy consumed by IT equipment is influenced by factors such as the number of devices, their processing power, and their utilization rates[KBB+16]. Additionally, cooling equipment plays a crucial role in maintaining optimal operating conditions within the data center environment. As IT equipment generates heat during operation, cooling systems, such as air conditioning units and precision cooling systems, are employed to regulate temperatures and prevent overheating. The energy consumed by cooling equipment is necessary to ensure the reliability and performance of the IT infrastructure[RZX+16].

Energy can be generated from various sources. Some of the most common methods of energy generation:

Fossil Fuels: Fossil fuels such as coal, oil, and natural gas are burned to produce heat, which is then used to generate electricity. This process is commonly used in power plants[RR17b].

Nuclear Energy: Nuclear power plants use a process called nuclear fission to generate heat. The heat produced by splitting atoms is used to create steam, which drives turbines and generates electricity[RRR23b].

Figure 2.1: Analysis of a typical 465 m2 data center, Source Emerson Network power[Eme15]

Renewable Sources: Renewable energy sources include solar, wind, hydroelectric, geothermal, and biomass. Solar energy is generated by converting sunlight into electricity using photovoltaic cells. Wind energy is harnessed by wind turbines that convert the kinetic energy of the wind into electricity. Hydroelectric power is generated by capturing the energy of flowing or falling water. Geothermal energy utilizes the heat from the Earth's interior to generate electricity. Biomass energy is produced by burning organic matter such as wood, agricultural crops, or waste materials[RRR20].

Hydropower: Hydropower is a specific type of renewable energy that generates electricity through the force or energy of moving water, such as rivers or waterfalls. It involves the use of dams or flow-through turbines to convert the kinetic energy of moving water into electrical energy[SBI+13].

Tidal and Wave Energy: Tidal energy is generated by harnessing the power of ocean tides, while wave energy is generated by capturing the energy of ocean waves. Both methods involve specialized technologies to convert the mechanical energy of water into electricity[KKAH17].

Fuel Cells: Fuel cells generate electricity through an electrochemical process, usually by combining hydrogen with oxygen to produce water and electricity. Fuel cells can use hydrogen derived from various sources, including natural gas, biomass, or renewable energy[MSS12].

It's important to note that the availability and utilization of different energy sources can vary depending on factors such as geographical location, technological advancements, and economic considerations[FFN+20][KOW+19][AKK15]. The transition toward renewable and sustainable energy sources is gaining momentum globally due to concerns about climate change and the finite nature of fossil fuel resources[QHR+19].
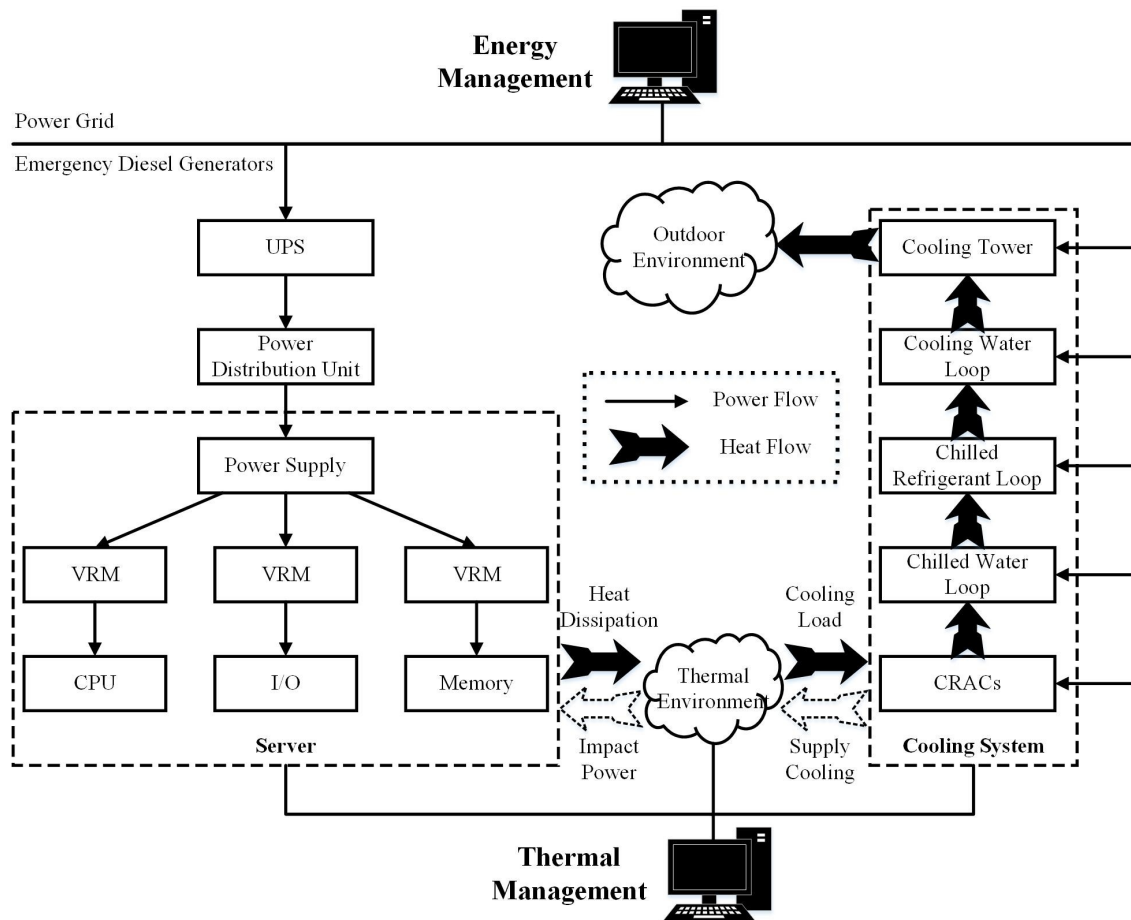
Figure 2.2: The power flow and heat flow in general data centers [JBY+20]

2.2 Greenhouse Gases

United Nations Climate Change Conference (COP26) held in Glasgow reached an agreement to ensure global net zero emissions by mid-century and to reduce global emissions by 45% by 2030[AM21].

Greenhouse gases are gases in the atmosphere that absorb and emit radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect. Carbon dioxide (chemical formula CO_2) is an important greenhouse gas, which contributes 9%–26% of the greenhouse effect.

The greenhouse gasses included in CO2e calculations are[Dio17]:

- Carbon dioxide (CO2)

- Nitrous oxide (N2O)

- Methane (CH4)

- Fluorinated Gases

Greenhouse gas emissions, 2022

Greenhouse gas emissions[1] include carbon dioxide, methane and nitrous oxide from all sources, including land-use change. They are measured in tonnes of carbon dioxide-equivalents[2] over a 100-year timescale.

Our World in Data

| No data | 0 t | 10 million t | 30 million t | 100 million t | 300 million t | 1 billion t | 3 billion t | 10 billion t |

Data source: Jones et al. (2024) OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY
Note: Land-use change emissions can be negative.

1. Greenhouse gas emissions: A greenhouse gas (GHG) is a gas that causes the atmosphere to warm by absorbing and emitting radiant energy. Greenhouse gases absorb radiation that is radiated by Earth, preventing this heat from escaping to space. Carbon dioxide (CO_2) is the most well-known greenhouse gas, but there are others including methane, nitrous oxide, and in fact, water vapor. Human-made emissions of greenhouse gases from fossil fuels, industry, and agriculture are the leading cause of global climate change. Greenhouse gas emissions measure the total amount of all greenhouse gases that are emitted. These are often quantified in carbon dioxide equivalents (CO_2eq) which take account of the amount of warming that each molecule of different gases creates.
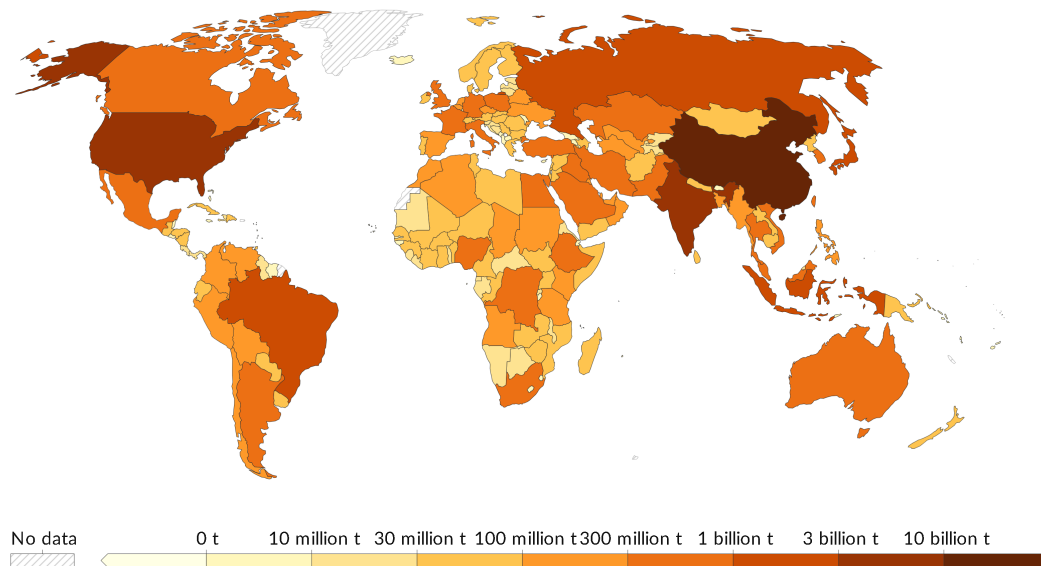
2. Carbon dioxide equivalents (CO_2eq): Carbon dioxide is the most important greenhouse gas, but not the only one. To capture all greenhouse gas emissions, researchers express them in "carbon dioxide equivalents" (CO_2eq). This takes all greenhouse gases into account, not just CO_2. To express all greenhouse gases in carbon dioxide equivalents (CO_2eq), each one is weighted by its global warming potential (GWP) value. GWP measures the amount of warming a gas creates compared to CO_2. CO_2 is given a GWP value of one. If a gas had a GWP of 10 then one kilogram of that gas would generate ten times the warming effect as one kilogram of CO_2. Carbon dioxide equivalents are calculated for each gas by multiplying the mass of emissions of a specific greenhouse gas by its GWP factor. This warming can be stated over different timescales. To calculate CO_2eq over 100 years, we'd multiply each gas by its GWP over a 100-year timescale (GWP100). Total greenhouse gas emissions – measured in CO_2eq – are then calculated by summing each gas' CO_2eq value.

Figure 2.3: Greenhouse gas emissions, 2022 [RRR23a]

A data center consumes significant amount of power and a mass of greenhouse gas is produced in the process of power generation. According to US Energy Information Administration[23], about 0.86 pounds (0.39 kg) of CO2 is released per kWh. Below is the descriptive map greenhouse emissions for each country.

Measuring CO2 emissions from data center computing presents challenges due to the intricate nature of data center infrastructure and the various factors that influence CO2 production, including data center efficiency and energy sources used[WK13]. [ABA21a] estimated that 720 million tons of CO2 emissions will be released by data centers only in 2030. The amount of CO2 generated by data centers is influenced by multiple factors, with data center efficiency and energy sources being key variables. These variables can vary significantly across different data centers, making it difficult to accurately measure CO2 emissions. Additionally, data centers are complex environments with

shared infrastructure utilized by multiple users and managed support systems, further complicating the precise calculation of CO_2 emissions attributed to individual applications, users, or computing servers.

2.3 Data Centers

A data center is a physical room, building or facility that houses IT infrastructure for building, running, and delivering applications and services, and for storing and managing the data associated with those applications and services[IBM24].

In Figure 2.4, we can observe the hierarchical structure of the data center (DC), which is divided into three distinct layers. Starting from the top layer, we find the core switches responsible for receiving data service instructions and transmitting them to the front-end servers through the network. Moving down to the middle layer, we encounter the aggregation switches, which serve as the connection point between the top and bottom layers. Their primary function is to facilitate the consolidation of data from various sources. Finally, at the base layer, we have the front-end and back-end servers. The front-end servers handle user instructions and requests, while the back-end servers allocate storage nodes[ZZG+23b].

The main objective of the DC is to effectively integrate and centralize network and storage resources using virtualization technology. This integration allows for efficient data processing. Additionally, the DC employs network node virtual functions to monitor, manage, and oversee the performance of individual nodes within the network. By leveraging these technologies, the DC is able to streamline operations and optimize resource allocation for enhanced performance[ZZG+23b].

Spending on data center systems is expected to see a notable jump in growth from 2023 (4%) to 2024 (10%), in large part due to planning for generative AI GenAI[STA24].
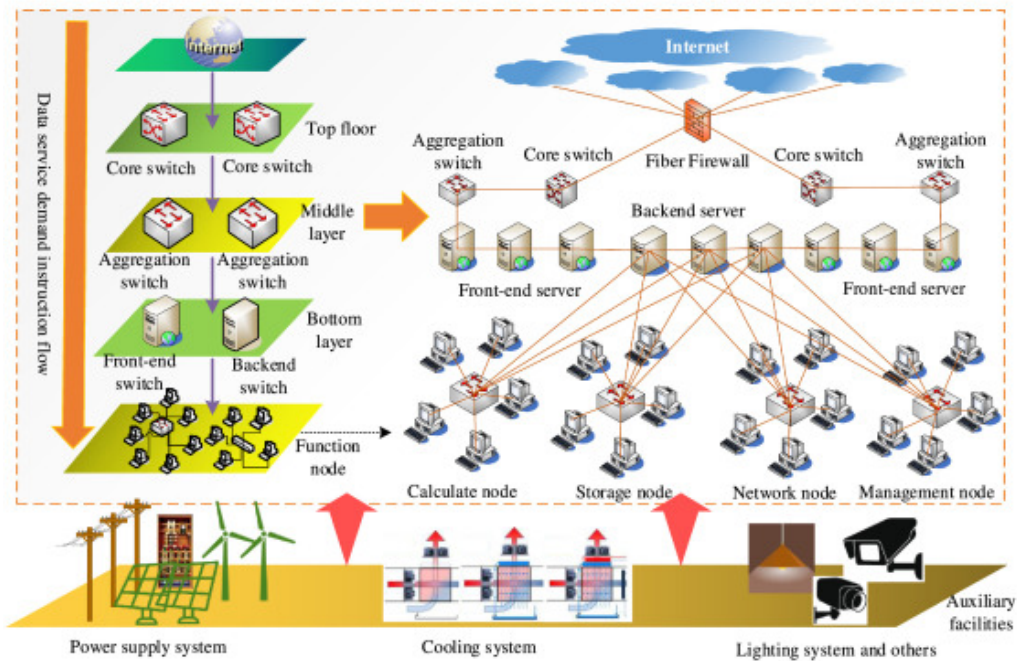
Figure 2.4: Diagrammatic representation of the DC's overall structure[ZZG+23b]

3 Study Design

3.1 Research Questions

RQ1 How much GHG do data centers currently produce, and what can be an estimate of the GHG production for the upcoming years?

RQ2 Study of the emission causes in data centers, focusing on factors like electricity, cooling and physical hardware fragments.

RQ3 Introduction to carbon footprint and study of the (existing) measures for the reduction of carbon footprint.

RQ4 How can outsourcing to cloud computing reduce the environmental impact?

RQ5 Study of the DCIM Software for carbon footprint measuring and evaluation of the software's accuracy via experiments.

3.2 Methodology

When I started conducting my research about energy and CO2 of cloud/backend processing, I saw that the most energy consumption comes from this massive server rooms that would process data non stop, called data centers. So I focused my study on data centers, their infrastructure and the energy that these rooms were consuming. Servers are the primary powerhouses within data centers. In this thesis I tried to include the latest publicly available research or development of the specific topic because some old papers were not relevant anymore. There were many old publications about data centers and their energy consumption, whose outcome was already applied in real life several times or their outcome was overridden. Papers and publications used in this thesis are related to electrical engineering, thermal engineering and climate change. As a resource for this thesis I also checked the activity of main cloud providers such as AWS, Google and Microsoft. Even though these companies are working independently from each other, they have all made huge advancements in their common goal to reach net zero carbon emissions.

4 Energy used from Data Centers

The US data centers handled about 300 million Terabyte of data that consumed around 8.3 billion kWh per year in 2016, hence 27.7 kWh per Terabyte with a carbon footprint of approximately 35 kg CO2 per Terabyte of data[Cor18].

According to a report published by the International Energy Agency[IEA23] in 2023, data centers worldwide were estimated to consume approximately 1-1.5% of the world's electricity. While this figure may seem relatively modest, it assumes significance when considering the overall global energy consumption. Additionally, as our reliance on digital services continues to grow and more devices become interconnected, the demand placed on data centers and their energy consumption is expected to increase[SJS15]. Compounding this issue is the fact that a significant portion of the energy used by data centers still comes from non-renewable sources[RRR24].

In areas where coal continues to be the primary source of electricity, the environmental impact of data center operations is particularly significant[FWH21]. Data centers powered by coal emit a disproportionately higher amount of carbon emissions compared to those running on cleaner energy sources. As a result, even though data centers may only account for a small percentage of global energy consumption, their contribution to greenhouse gas emissions raises valid concerns.

The power consumption of a data center is influenced by a variety of factors, including the hardware specifications and internal infrastructure, the computational workloads, the types of applications running, and the cooling requirements[DWF15]. These variables make the overall power usage difficult to measure precisely. Additionally, the power consumption of the IT equipment, cooling systems, and power conditioning infrastructure within the data center are all closely interrelated.

4.1 Energy used for running Servers

Servers are the primary powerhouses within data centers. They process vast amounts of data, ensuring that our emails, cloud applications, online games, and myriad other digital services function seamlessly[BL21]. Their constant activity means they're persistently consuming electricity[Inn20], and this continuous energy draw is a direct contributor to carbon emissions, especially if the electricity source is fossil fuel-based.

The total energy consumption of a server is the collective sum of the energy consumed by all its individual hardware components. This includes the energy used by the CPU(s), memory modules, storage drives, network interfaces, power supply, cooling fans, and any other active components within the server[ABA21b].

A depiction of electricity consumption is depicted in the figure 4.1 where it is clear that CPU consumes the most of energy with 32%.
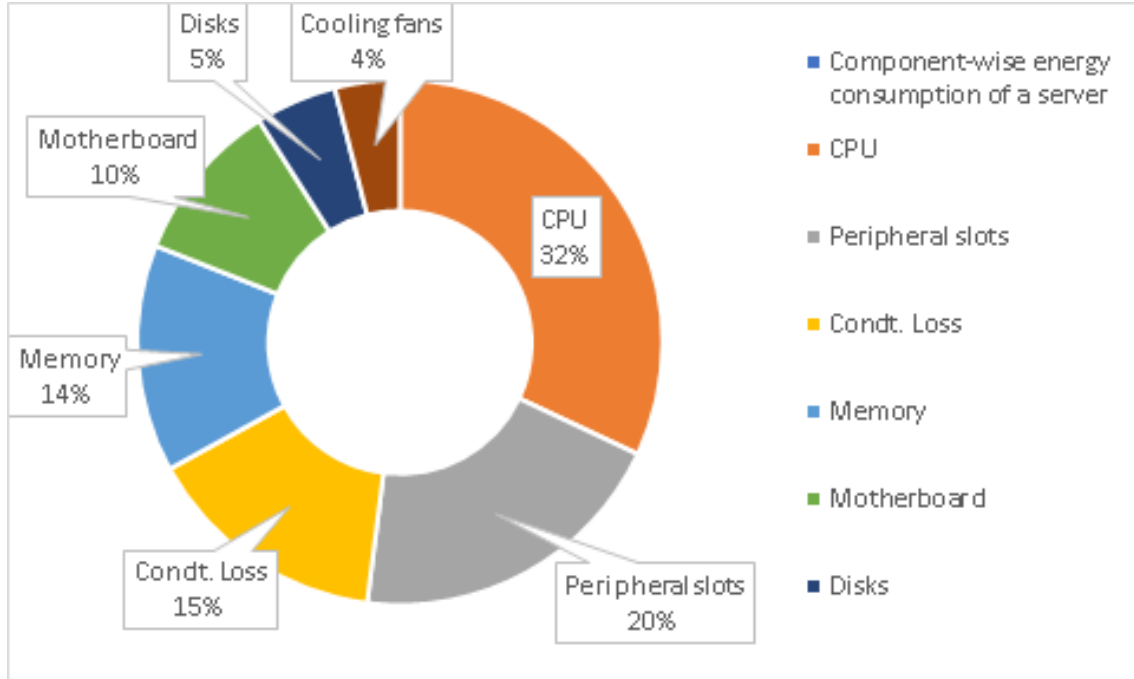
Figure 4.1: Component-wise energy consumption of a server; Source[ABA21b]

The energy consumption of each individual component is influenced by factors such as the component's power rating, utilization level, and operating conditions. The total server energy consumption can be calculated by measuring or estimating the power draw of each component and then adding them together. According to [CPR+15] total energy estimation of the system is calculated as below (E_{base} accounts for the un-addressable energy losses including the idle energy consumption of the server):

$$E_{total} = E_{base} + E_{cpu} + E_{disk} + E_{net} + E_{mem}$$

Monitoring the energy usage of individual server components can provide valuable insights into optimizing the server's overall energy efficiency. This can involve techniques like right-sizing hardware, implementing power management features, and optimizing workload distribution to reduce unnecessary energy consumption[LWZ+18]. An example would be the comparison between two different processors like ATOM and Xeon[ICC24]. The figure 4.2 shows power consumption comparison of two servers. In an Atom-based server, the memory subsystem consumes the largest portion of the overall power. The Atom processor itself has a relatively modest power draw, but the memory modules and associated components have to work harder to compensate for the processor's limited memory capabilities, resulting in high memory power consumption[Tur14]. On the other hand, in a Xeon-based server, the CPUs are the main power consumers. Xeon processors are designed for high-performance server workloads and have significantly higher power requirements compared to Atom. The CPU cores, cache hierarchy, and advanced features all contribute to the Xeon's greater power draw. While the memory subsystem also consumes power, it is not as dominant a factor as in the Atom-based system, as Xeon processors have more memory channels and higher memory bandwidth[Smi23].
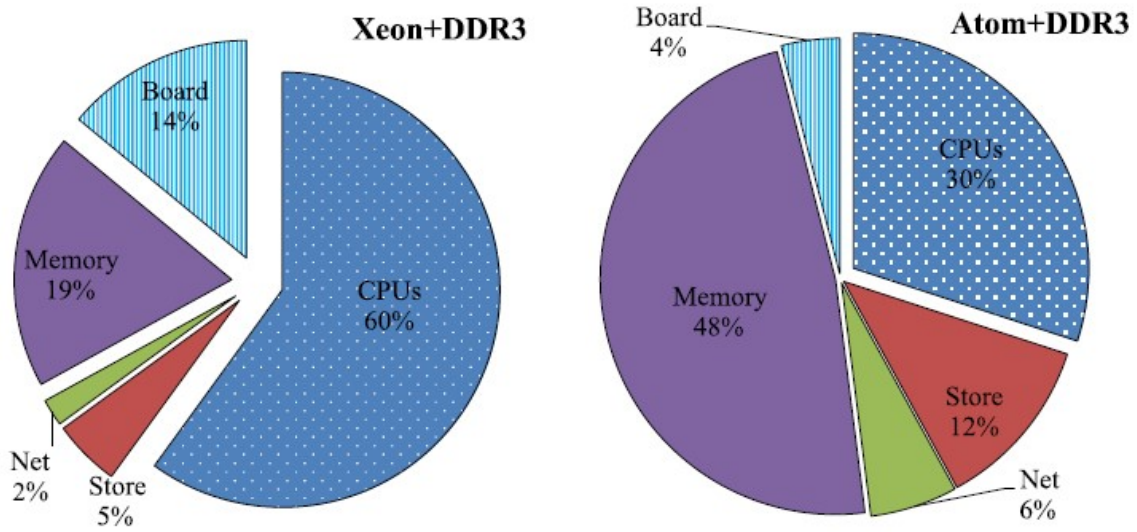
Figure 4.2: Power breakdown across the components of two servers[DWF15]

4.1.1 Server States

In data centers, the servers are not always active, as servers can be idle. Then, the power consumption of the counterparts can be divided into two parts.

Baseline power P_{base}, which is the power consumption when the machine is idle, includes the power consumption of the fans, CPU, memory, I/O and other motherboard components in their idle state and is often considered as a fixed value. Idle servers are troublesome because they are not efficient and expensive[Cie19]. In 2015, it was estimated that servers were wasting 30% of energy in idle state, but the situation has improved a lot since then[Doi22][BND12]. Methods like PowerNap have been proposed[MGW09] that eliminate idle power in servers by quickly transitioning in and out of an ultra-low power state. This method reduced in average power relative up to 70% for Web 2.0 servers.

Active power P_{active}, which is the power consumption due to the workload, depends on the workload of the machine and the way it utilizes CPU, memory and I/O components. Hence, the power model can be expressed as the sum of baseline power and active power[JBY+20].

4.1.2 Backup Generators

Backup generators play a crucial role in ensuring the operational reliability of data centers. These generators, powered by diesel fuel, are responsible for generating electricity during power outages or routine testing. However, it is important to note that when these generators are activated, they produce direct emissions that can have an impact on the environment. While their operational hours may be limited compared to primary equipment, the combustion of fuel leads to a higher release of greenhouse gases (GHGs)[JYC15].

Figure 4.3: Cooling System with Raised Floor Configuration (hot aisle/cold aisle layout)[Bha15]

4.2 Energy used for Thermal Management

Historically, data centers have heavily relied on traditional HVAC (Heating, Ventilation, and Air Conditioning) systems to maintain desired temperatures. However, these systems are known for their high energy c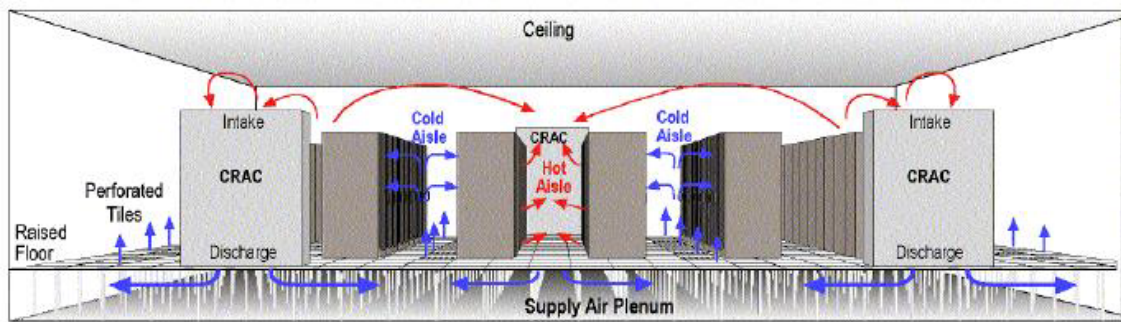onsumption. The main reason for this is their use of mechanical cooling, which involves compressors and refrigerants that consume significant amounts of energy, sometimes even matching the energy consumption of the servers themselves[Bha15].

In addition to the energy required to power the servers, a substantial amount of energy is dedicated to cooling them and maintaining optimal operating temperatures[ZMH+21]. This is necessary because the processors within the servers generate a significant amount of heat during operation. Consequently, server rooms tend to become hot due to the heat produced. To address this challenge, numerous measures have been implemented to effectively manage heat distribution and ensure efficient cooling within data centers[ZMH+21]. Figure 4.3 is a design configuration of underfloor air distribution system uses a raised floor plenum to supply conditioned air into a space. The air conditioning equipment, such as CRAC units, is located around the room's perimeter. The conditioned air is delivered upwards through vents or diffusers in the raised floor.

Operating computing systems for extended periods of time at high temperatures greatly reduces reliability, longevity of components and will likely decrease QoS. ASHRAE has in fact now recommended an acceptable operating temperature range of 18° to 27°C (64° to 81°F) to be optimal for system reliability. For environments with low levels of both copper and silver corrosion, the recommended temperature range is between 18° and 21°C (64 to 69.8 °F). However server manufacturer Dell states that the temperature "sweet spot" for their servers is 26.7°C (80°F)[22]. Expensive IT equipment should not be operated in computer rooms or data centers where the ambient room temperature exceeds 85°F (30°C)[42U16].

It is worth noting that the excessive energy consumption associated with traditional HVAC systems has prompted the exploration and adoption of more sustainable and energy-efficient cooling solutions in modern data centers[NLL18]. These innovative approaches aim to reduce both the environmental impact and operational costs of data center cooling. By employing advanced cooling techniques, such as liquid cooling, airflow optimization, and heat recycling, data centers can achieve greater energy efficiency and minimize their carbon footprint.

According to [ZZG+23b] approximately 15–27% of the energy consumed by DC can be reduced via research and development of advanced cooling technologies, including natural cooling and liquid cooling to achieve sustainability.

Below are some strategies and layout designs that improve air circulation in the server rooms:

Enhancing Natural Ventilation and Thermal Efficiency Designs that prioritize natural ventilation, use thermally conductive materials, and optimize server layout can reduce the need for artificial cooling. By enabling efficient airflow, these designs improve temperature regulation in data centers. Materials with high thermal conductivity also help dissipate heat more effectively, keeping servers at optimal operating temperatures. This combination of natural ventilation and thermally conductive materials creates a more energy-efficient data center environment.[ZNZS21][SPHA23].

Utilizing Energy-Efficient Architectural Features Implementing certain architectural designs can further enhance the energy efficiency of a data center[MTP+19]. For instance, roofs painted with reflective coatings help to reduce heat absorption from the sun, minimizing the need for additional cooling[Akb03]. Green roofs, which incorporate vegetation, provide natural insulation and cooling effects, reducing the overall energy demand[SGD11]. Additionally, incorporating thermal buffers such as double-wall constructions can act as a barrier against external temperature fluctuations, maintaining a more stable internal environment. By integrating these features, a data center can inherently become more energy-efficient[ENO+23].

Innovative Layout Strategies Hot/cold aisle containment is a cooling strategy for data centers. It involves arranging server racks so that the hot air exhausts are directed one way, and the cold air intakes are directed the other way. This separation of hot and cold airflows helps prevent hot air from being recirculated back into the cold aisle. This improves the overall cooling efficiency and reduces energy consumption[JBNS+20][JBY19].

Another layout strategy being explored is vertical server stacking. This configuration takes advantage of the natural physics of heat rising, as hot air naturally moves upward. By stacking servers vertically and strategically placing vents, the vertical arrangement can facilitate better heat dissipation and improve cooling efficiency[JBNS+20][JBY19].

By implementing these design principles and layout strategies, data centers can significantly reduce their energy consumption, enhance cooling efficiency, and contribute to a more sustainable and environmentally friendly operation.

The strategies for achieving energy-efficient and carbon-emission reduction (ECER) in different districts (DCs) can vary based on factors like geographical location, natural resources, and economic foundations. A single energy-saving approach may not be sufficient to meet the goal of zero-carbon emission across all DCs.

4.2.1 Free Cooling

There are several types of temperature management methods employed in servers and data centers, with air cooling being the most commonly utilized. Air cooling involves the use of fans that generate airflow to cool down the servers and distribute cold air to the hot components. Another air cooling technology worth mentioning is free cooling[DAT21], which represents a more recent development in this field.

In the case of free cooling, data centers located in extremely cold regions leverage the ambient temperature to maintain a consistent temperature within the server rooms[DAT21]. By harnessing the naturally low temperatures of their surroundings, these data centers are able to reduce their reliance on traditional cooling mechanisms. Data centers have several options for free cooling approaches. One is airside free cooling, which uses outside air to directly cool the data center without mechanical refrigeration. Another is waterside free cooling, which relies on a water-based heat exchange system to leverage natural cold water sources. The third main approach is heat pipe free cooling, which utilizes a network of heat pipes to transfer heat from the data center to the outside. The choice of free cooling method depends on factors like the local climate, water availability, and the facility's specific cooling requirements. Data centers that are situated in warmer climates or regions lacking a sufficiently cold environment may not be able to fully utilize this method. In such cases, many data centers end up using a blend of these free cooling techniques to enhance energy efficiency and to ensure optimal temperature management and prevent overheating of the servers and related equipment[ZSX+14].

Free cooling approach not only results in lower energy consumption compared to conventional air cooling, but it also minimizes the environmental impact associated with cooling operations[Ree21].

Examples of data centers that use free cooling are:

- Google has built its data centers in Hanima, where they use seawater from the Bay of Finland for the cooling system[dat09]

- Microsoft has drowned 864 servers 22 km from the Scottish coast and uses local cooling to reduce energy consumption[Rat18]

4.2.2 Liquid Cooling

Liquid cooling systems use fluids to dissipate heat more effectively than air cooling. The cooling capacity of liquid systems is typically 1000-3000 times greater than air cooling. This improved heat transfer can enable slightly lower energy consumption in some applications that utilize liquid cooling.[ZZG+23b].

Liquid cooling is an advanced temperature management technique that surpasses the efficiency of air cooling. While the majority of current IT equipment is designed for air cooling, liquid cooling offers several notable advantages[XZW23].

1. Indirect liquid cooling is a method of heat removal where the heat source and liquid coolant do not directly interact. To implement this approach, the traditional air-cooled heat sink must be replaced with a liquid-cooled alternative, such as an evaporator. This change allows for more
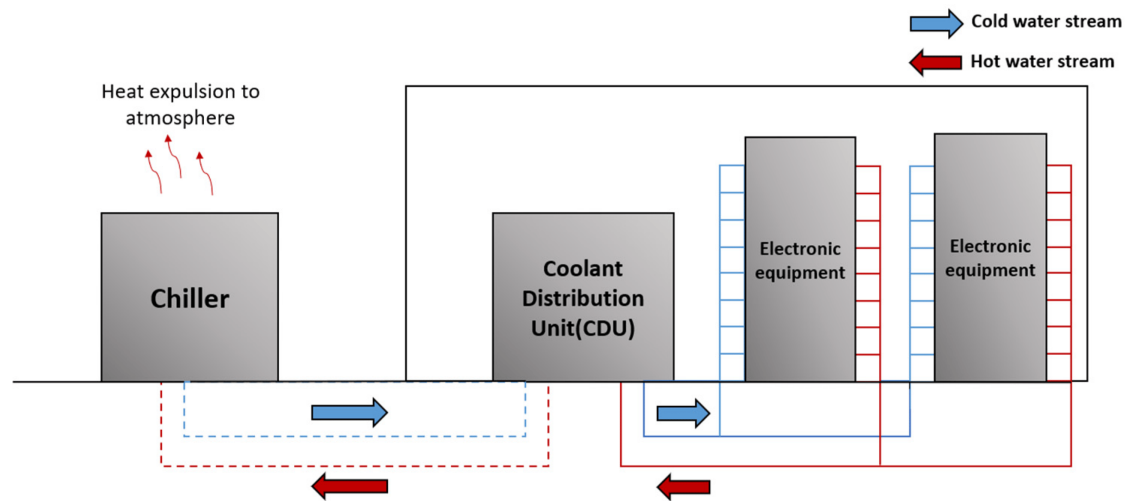
Figure 4.4: The schematic diagram of indirect water cooling system; Source: [KH17]

efficient heat transfer from the source to the coolant, and can result in smaller component sizes and greater heat dissipation capabilities compared to air cooling[KH17]. Figure 4.4 shows a schematic diagram of this kind of cooling technology.

2. In direct liquid cooling, the coolant flows directly over the surfaces of electronic components, enabling highly efficient heat transfer by eliminating the additional thermal interface present in indirect liquid cooling systems. The coolants used are typically dielectric fluids - electrically insulating liquids that can safely make direct contact with active electronics, providing both effective cooling and electrical isolation, in contrast to the separated coolant loop of indirect liquid cooling approaches[KH17][TI24].

It's important to acknowledge that maintaining a liquid cooling system presents certain challenges[AAC24]. In the case of dielectric cooling, the management of the liquid becomes more complex[TI24]. To implement dielectric cooling effectively, substantial containers capable of accommodating all the components must be created. Such large-scale implementation is currently limited, with testing primarily conducted on smaller servers.

Immersion cooling 1,400 times better thermal conductor than air[TI24] which translates to being way more energy efficient. However the transition from air cooling to liquid cooling requires careful consideration and adaptation of IT equipment. As technological advancements continue, it is expected that liquid cooling will become more prevalent and feasible for a wider range of applications.

5 Hardware Footprint and E-waste

It is estimated that manufacturing storage devices has resulted in 20 million metric tonnes of CO_2 emissions in 2021 alone[Pat23]. Data centers are comprised of a vast amount of hardware which are categorized into two distinct types of equipment: data center infrastructure and computing components. The data center infrastructure consists of a wide range of mechanical and electrical components, such as transformers, generators, air conditioners, racks, and cables. These components work together to support the functioning of the data center. On the other hand, the computing components refer to the servers that handle the processing, storage, and retrieval of data. To ensure optimal performance, the equipment in this category is periodically replaced. Typically, infrastructure components are replaced every 10 to 15 years, taking into account advances in technology, energy efficiency, and the evolving demands of the data center environment[SLSG24]. In contrast, computing components are more frequently changed. This process generates a significant amount of metallic waste, contributing to a substantial environmental footprint. Fortunately, advancements in technology have led to the development of smaller and more efficient hardware solutions.

One notable advancement is the improvement in server design[Hoo16]. Modern servers not only offer better performance but also prioritize energy efficiency. They are designed to provide more computational power per watt, reducing overall energy consumption. Additionally, the adoption of solid-state drives (SSDs) instead of traditional hard drives and the utilization of energy-efficient processors have further optimized energy usage within data centers. A 1 terabyte (TB) hard disk drive (HDD) is estimated to consume around 184 kilowatt-hours (kWh) of electrical energy over a 5-year period. In comparison, a 1TB solid-state drive (SSD) would only consume approximately 57 kWh over the same timeframe[Pat23].

Implementing intelligent operations and maintenance management for the cooling system, IT equipment, and lighting in a data center in Langfang resulted in a 1.2% reduction in the PUE value. This implementation also led to an annual electricity saving of 33.36 million kWh[LSW+23].

Furthermore, innovative techniques such as virtualization have played a crucial role in reducing redundant hardware operations[hiv23]. Virtualization allows a single physical server to operate as multiple virtual servers, thereby reducing the need for numerous physical servers and minimizing energy consumption. Additionally, technologies like data deduplication, which identifies and stores redundant data only once, have optimized storage capacity and further reduced energy requirements.

While recycling is necessary to manage the waste generated by data centers, it is important to acknowledge that it also has its own environmental impact, illustration figure 5.1. The transportation of waste to recycling facilities contributes to energy consumption and emissions[NHA19]. To address this, data center operators are exploring ways to improve recycling processes, such as implementing local recycling facilities or utilizing more energy-efficient transportation methods.
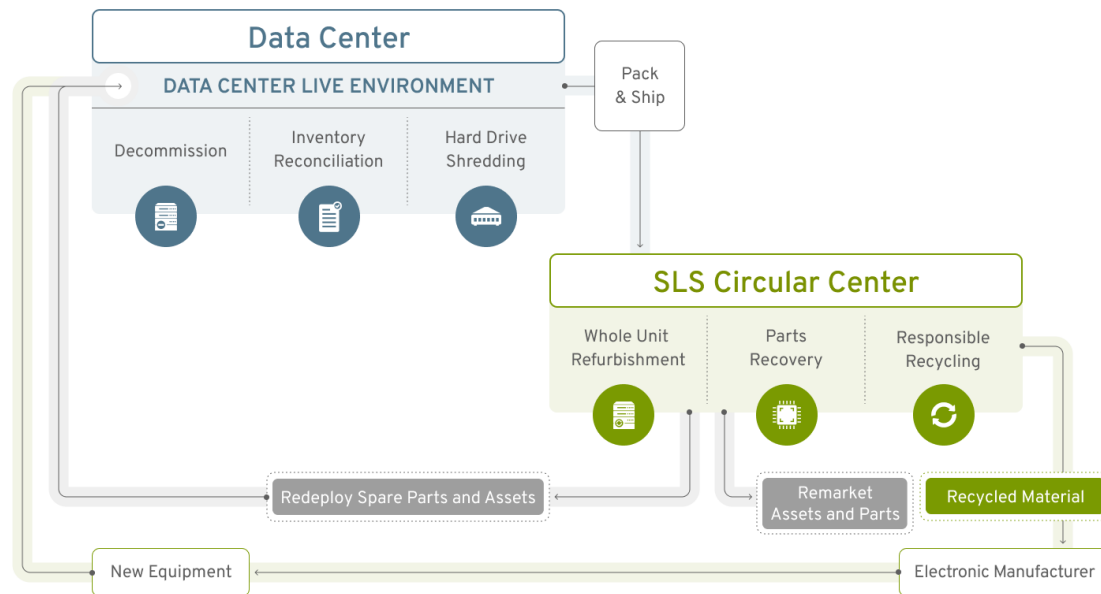
Figure 5.1: IT Equipment Recycling Process; Source: Sims Lifecycle Services[Ser24]

Furthermore, the concept of circular economy is gaining traction in the data center industry. This approach emphasizes the reuse and repurposing of hardware components whenever possible, reducing the need for constant replacement and minimizing waste generation. By adopting circular economy principles, data centers can significantly reduce their environmental footprint[Wal22].

Technological advancements in server design, the reduction of redundant hardware operations through virtualization, and the adoption of sustainable practices such as recycling and the circular economy are key factors in mitigating the environmental impact of data centers. By continuously striving for energy efficiency, waste reduction, and responsible resource management, the data center industry can contribute to a more sustainable and eco-friendly future.

6 Clouds and Virtualization

In the early days, industries relied on physical, role-based servers. These servers posed several challenges. Firstly, scaling them according to the workload they received was difficult. As the demand on the servers increased, it was hard to expand the infrastructure to accommodate the growing load. Secondly, managing the infrastructure of these servers was a complex task. The maintenance, configuration, and overall upkeep required significant time and resources. Additionally, if one of these physical servers failed, it would directly impact the corresponding service, resulting in downtime and disrupted operations. Due to these challenges, companies started considering alternative approaches to tackle them, which eventually gave rise to the concept of outsourcing the infrastructure and maintenance of servers. This led to the development of cloud computing, where organizations could ship these responsibilities and concentrate on their core operations, benefiting from remote server management. As of today, Cloud computing is the fastest growing internet technology[ACA21]. Berkley RAD lab defines "Cloud Computing refers to both the applications delivered as services over the Internet and the hardware and systems software in the datacenters that provide those services. The services themselves have long been referred to as Software as a Service (SaaS), so we use that term. The datacenter hardware and software is what we will call a Cloud"[FGJ+09] Clouds perform better in terms of CPU utilization, latency, scalability which in the long run transfer to less energy use [KR13].

Virtualization is a key technology in cloud computing that brings numerous advantages. It offers increased flexibility, dynamic resource allocation, and improved resource utilization. By consolidating applications onto fewer physical servers, virtualization helps reduce power consumption and the need for cooling systems. Data center operators can optimize energy usage and pricing of cloud computing platforms by employing suitable VM power models. Results from [LDR13] show that a data center using the proposed task-scheduling scheme consumes on average over 70 times less on server energy than a data center using a random-based task-scheduling scheme. Clouds use various approaches and strategies to optimize cloud performance[ASZ+20].

The adoption of cloud computing has resulted in a significant annual reduction of 20% in the energy intensity of data centers since 2010. The benefits of energy-optimized and cost-efficient cloud data centers are not limited to a select few companies' employees; individuals worldwide can now access and utilize these resources through services provided by Alibaba Cloud, Amazon Web Services, Google Cloud Platform, and Microsoft Azure. This widespread availability empowers people from diverse backgrounds to conveniently rent computing resources from these platforms, enabling them to leverage the advantages of efficient and sustainable cloud infrastructure[PGL+21].

There have been meaningful discussions regarding the impact of cloud computing on the low-carbon economy[TSNR22]. Cloud computing technology has been recognized for its contribution to the evolution of the industrial structure towards low energy consumption and the facilitation of a low-carbon economy. By consolidating computing resources and implementing energy-efficient technologies, cloud computing significantly reduces energy consumption compared to traditional

on-premises infrastructure[SWDZ22]. On the other side, there are those who believe that the said technological innovation has led to the creation of large-scale data centers and extensive information infrastructures.

Cloud evaluation is difficult compared to systems as many factors have to be taken into consideration like configurations, connectivity and liveliness. But in terms of cloud data centers as a whole, big companies like Google, Amazon, Microsoft have done many research to be efficient more than any other local system provider[Höl20].

7 Energy saved from Data Centers/Clouds

Reducing the carbon footprint on your project should not increase the carbon footprint elsewhere.

The increasing adoption of information and communication technology (ICT) across various sectors of the economy has resulted in a significant rise in energy consumption from data centers and clouds. This upward trend can be characterized as exponential, reflecting the growing reliance on ICT for enhanced productivity and efficiency.

Research focusing on emerging economies has uncovered a noteworthy relationship between Internet usage and electricity consumption. Specifically, a 1% increase in Internet users has been found to correspond to an increase in per capita electricity consumption of up to 0.36%[RR17a]. This indicates that as more individuals gain access to the Internet and engage in online activities, the demand for energy to power the necessary ICT infrastructure also escalates.

Conversely, studies conducted in OECD countries have revealed an intriguing finding. They suggest that a 1% increase in ICT capital can lead to a reduction in energy demand by 0.235%[LPS20]. However, it is important to note that this reduction is primarily attributed to a decrease in the consumption of non-electric energy sources rather than electricity consumption itself. This implies that the implementation of ICT technologies in these sectors has resulted in energy efficiency gains in non-electric energy usage.

In a study, researchers discovered energy implications of various technological shifts. The study found that transitioning from conventional newspapers to online newspapers had the potential to yield energy savings of up to 60%[LPS20]. These findings align with previous research that demonstrated similar energy savings when comparing music downloads to physical CD delivery. Additionally, the adoption of e-readers was identified as another avenue for achieving substantial energy savings.

The study also uncovered contrasting results in different areas. For instance, it was discovered that Internet game downloads resulted in higher greenhouse gas (GHG) emissions compared to physical Blu-ray discs[LPS20]. Similarly, when examining the energy savings in e-commerce, the findings were mixed. A study focusing on the Japanese book sector revealed that e-commerce was as energy-intensive as conventional retailing in rural areas, but more energy-intensive in urban areas.

The researchers identified several key factors that influence energy consumption in e-commerce, including population density, freight mode, product return rate, trip allocation, and packaging type[ZDB+19]. They also compared the energy impact of paper book sales in traditional and online bookshops [LPS20] and concluded that online bookshops were marginally more beneficial. The study emphasized that the perspective of the buyer, including their means of transport and combination with other activities, plays a significant role in determining the overall outcome.

Interestingly, despite the availability of video conferencing systems[LPS20], the number of international scientific conferences has been on the rise. Similarly, the demand for printed books has remained steady, while e-books and online reading materials have experienced increased popularity. Although video streaming can offer energy savings compared to physical DVD purchases or rentals, the growing hours of streaming and data traffic associated with video streaming are expected to offset these potential savings.

Shifting focus to processors, the study found that the energy intensities of processing units (CPUs) decrease by approximately half every 1.5 years[LPS20]. However, Moore's Law[Sch97] suggests that processing capacities also double within the same timeframe. Consequently, the potential energy savings resulting from increases in energy efficiency are counterbalanced by the escalating demand for processing services. The extent to which the growth in scientific conferences, books, data traffic, and processing capacities can be attributed to increased energy efficiency or other factors remains unclear. Nonetheless, it is evident that increases in output often offset gains in energy efficiency, highlighting the need for further examination of the role of economic growth in this context.

Additionally, approximately 97% of the energy consumed by DCs can be converted into heat and reused[WBBG14].

7.1 Carbon-Free Energy Data Centers

To have carbon free energy, electricity should be produced from renewable resources. The availability of solar and wind energy is influenced by both investment and weather conditions. But wind doesn't always blow, sun doesn't always shine. Thats when utility-scale batteries come to power that can actually support the grid with continuous energy.

According to an official statement from Google, they have announced their commitment to achieving carbon-free energy across all their data centers and campuses worldwide. This ambitious goal ensures that their facilities consistently rely on clean energy sources, without any carbon emissions, to power the essential products and services that users like yourself depend on daily. As a result, whether you're sending an email via Gmail, making inquiries through Google Search, watching YouTube videos, or navigating with Google Maps, rest assured that each of these activities will be supported by renewable energy around the clock[Pic20].

8 Results

1. How much GHG do data centers currently produce, and what can be an estimate of the GHG production for the upcoming years?

   1st question is answered throughout the whole thesis. In each section we have something related to how much GHG is produced. And we also have an estimation of 720 million tones of CO2 emission in 2030.

2. Study of the emission causes in data centers, focusing on factors like electricity, cooling and physical hardware fragments.

   2nd question is answered in chapters 4, 5

3. Introduction to carbon footprint and study of the (existing) measures for the reduction of carbon footprint.

   3rd question is answered in chapter 7

4. How can outsourcing to cloud computing reduce the environmental impact?

   4th question is answered in chapter 6

5. Study of the DCIM Software for carbon footprint measuring and evaluation of the software's accuracy via experiments.

9 Heading on Level 0 (chapter)

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match the language. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

9.1 Heading on Level 1 (section)

Hello, here is some text without a meaning. $d\Omega = \sin\vartheta d\vartheta d\varphi$. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sin^2(\alpha) + \cos^2(\beta) = 1$. This text should contain all letters of the alphabet and it should be written in of the original language $E = mc^2$. There is no need for special content, but the length of words should match the language. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$.

9.1.1 Heading on Level 2 (subsection)

Hello, here is some text without a meaning. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. This text should show what a printed text will look like at this place. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$. If you read this text, you will get no information. $d\Omega = \sin\vartheta d\vartheta d\varphi$. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. $\sin^2(\alpha) + \cos^2(\beta) = 1$.

Heading on Level 3 (subsubsection)

Hello, here is some text without a meaning $E = mc^2$. This text should show what a printed text will look like at this place. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. If you read this text, you will get no information. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information

about the selected font, how the letters are written and an impression of the look. $a \sqrt[n]{b} = \sqrt[n]{a^n b}$. This text should contain all letters of the alphabet and it should be written in of the original language. $d\Omega = \sin \vartheta d\vartheta d\varphi$. There is no need for special content, but the length of words should match the language.

Heading on Level 4 (paragraph)   Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. $\sin^2(\alpha) + \cos^2(\beta) = 1$. If you read this text, you will get no information $E = mc^2$. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$. This text should contain all letters of the alphabet and it should be written in of the original language. $\frac{\sqrt[n]{a}}{\sqrt[n]{b}} = \sqrt[n]{\frac{a}{b}}$. There is no need for special content, but the length of words should match the language. $a \sqrt[n]{b} = \sqrt[n]{a^n b}$.

9.2 Lists

9.2.1 Example for list (itemize)

- First item in a list
- Second item in a list
- Third item in a list
- Fourth item in a list
- Fifth item in a list

Example for list (4*itemize)

- First item in a list
  - First item in a list
    * First item in a list
      · First item in a list
      · Second item in a list
    * Second item in a list
  - Second item in a list
- Second item in a list

9.2.2 Example for list (enumerate)

1. First item in a list

2. Second item in a list

3. Third item in a list

4. Fourth item in a list

5. Fifth item in a list

Example for list (4*enumerate)

1. First item in a list

   a) First item in a list

      i. First item in a list

         A. First item in a list

         B. Second item in a list

      ii. Second item in a list

   b) Second item in a list

2. Second item in a list

9.2.3 Example for list (description)

First item in a list

Second item in a list

Third item in a list

Fourth item in a list

Fifth item in a list

Example for list (4*description)

First item in a list

    First item in a list

        First item in a list

            First item in a list

            Second item in a list

        Second item in a list

    Second item in a list

Second item in a list

10 Related Work

Describe relevant scientific literature related to your work.

11 Conclusion and Outlook

The demand for data storage and processing will continue increasing. The need for electricity therefore will be increasing too. But with the newest advancements in technology, the hardware efficiency has actually increased and the power consumption has decreased for the same processing of data. Also electricity production does not produce as much carbon as it used to due to usage of renewable resources.

Outlook

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All links were last followed on March 17, 2018.

A LaTeX Hints

One sentence per line. This rule is important for the usage of version control systems. A new line is generated with a blank line. As you would do in Word: New paragraphs are generated by pressing enter. In LaTeX, this does not lead to a new paragraph as LaTeX joins subsequent lines. In case you want a new paragraph, just press enter twice (!). This leads to an empty line. In word, there is the functionality to press shift and enter. This leads to a hard line break. The text starts at the beginning of a new line. In LaTeX, you can do that by using two backslashes (\\). This is rarely used.

Please do *not* use two backslashes for new paragraphs. For instance, this sentence belongs to the same paragraph, whereas the last one started a new one. A long motivation for that is provided at http://loopspace.mathforge.org/HowDidIDoThat/TeX/VCS/#section.3.

One can write *emphasized text (rendered in italics)* and **bold text**.

A.1 File Encoding and Support of Umlauts

The template offers foll UTF-8 support. All recent editors should not have issues with that.

A.2 Citations

References are set by means of \cite[key].

Code: Result:

```
Example: \cite{WSPA} or by author input: \
citet{WSPA}.
```

Example: [WCL+05] or by author input: Weer-
awarana et al. [WCL+05].

The following sentence demonstrates 1. the capitalization of author names at the beginning of the sentence, 2. the correct citation using author names and the reference, 3. that the author names are a hyperlink to the bibliography and that 4. the bibliography contains the name prefix "van der" of "Wil M. P. van der Aalst".

Code:

```
\Citet{RVvdA2016} present a study on the
effectiveness of workflow management systems.
```

Result:

Reijers et al. [RVA16] present a study on the effectiveness of workflow management systems.

The following sentence demonstrates that you can overwrite the text part of the generated label using `label` in a bibliopgrahie-entry, but the year and the uniqueness are still generated by biber.

Code:

```
The workflow engine Apache ODE \cite{
ApacheODE} executes \BPEL processes reliably.
```

Result:

The workflow engine Apache ODE [ASF16] executes BPEL processes reliably.

Code:

```
Words are best enclosed using \texttt{\
textbackslash qq\{..\}}, then the correct
quotes are used.
```

Result:

Words are best enclosed using \qq{..}, then the correct quotes are used.

When creating the Bibtex file it is recommended to make sure that the DOI is listed.

A.3 Formulas and Equations

Code:

```
Equations $f(x)=x$ inside the text can be
provided.
```

Result:

Equations $f(x) = x$ inside the text can be provided.

A list with all available mathematical symbols is provided at http://texdoc.net/pkg/symbols-a4.

Code:

```
As an example, the set of natural numbers is
given by $\mathbb{N}$.
```

Result:

As an example, the set of natural numbers is given by $\mathbb{N}$.

Listing A.1 The code is separated by two horizontal lines in the listings environment.

```
<listing name="second sample">
  <content>not interesting</content>
</listing>
```

For the documentation of editing mathematical formulas read the package documentation of amsmath[1].

Equation A.1 is numbered and can be referenced in the text:

Code: Result:

```
\begin{align}
  \label{eq:test}
  x = y
\end{align}
```

$$(A.1)$$
$$x = y$$

The following equation is not numbered because of using \align* as environment.

Code: Result:

```
\begin{align*}
  x = y
\end{align*}
```

$$x = y$$

The template offers \abs to enable the bars to scale well at the absolute value:

Code: Result:

```
$\abs{X}$.
```

$|X|$.

The documentation available at http://www.ctan.org/tex-archive/help/Catalogue/entries/voss-mathmode.html provides more details about mathematical environments.

A.4 Sourcecode

Listing A.1 shows how to embed source code. With \lstinputlisting the source code can be loaded directly from files.

---

[1] http://texdoc.net/pkg/amsmath

Algorithm A.1 Sample algorithm

---

procedure SAMPLE(a,v_e)

    parentHandled $\leftarrow$ (a = process) $\vee$ visited(a'), $(a', c, a) \in$ HR

                                     // $(a', c'a) \in$ HR denotes that a' is the parent of a

    if parentHandled $\wedge$ ($\mathcal{L}_{in}(a) = \emptyset$ $\vee$ $\forall l \in \mathcal{L}_{in}(a)$: visited(l)) **then**

        visited(a) $\leftarrow$ true

$$\text{writes}_\circ(a, v_e) \leftarrow \begin{cases} \text{joinLinks}(a, v_e) & |\mathcal{L}_{in}(a)| > 0 \\ \text{writes}_\circ(p, v_e) & \exists p : (p, c, a) \in \text{HR} \\ (\emptyset, \emptyset, \emptyset, false) & \text{otherwise} \end{cases}$$

        if $a \in \mathcal{A}_{basic}$ **then**

            HANDLEBASICACTIVITY(a,v_e)

        else if $a \in \mathcal{A}_{flow}$ **then**

            HANDLEFLOW(a,v_e)

        else if a = process **then**   // Directly handle the contained activity

            HANDLEACTIVITY(a',v_e), $(a, \perp, a') \in$ HR

            writes$_\bullet$(a) $\leftarrow$ writes$_\bullet$(a')

        end if

        for all $l \in \mathcal{L}_{out}(a)$ **do**

            HANDLELINK(l,v_e)

        end for

    end if

end procedure

Code:

```
Source code is also available in the text \
lstinline|<listing />|.
```

Result:

Source code is also available in the text `<listing />`.

A.5 Pseudocode

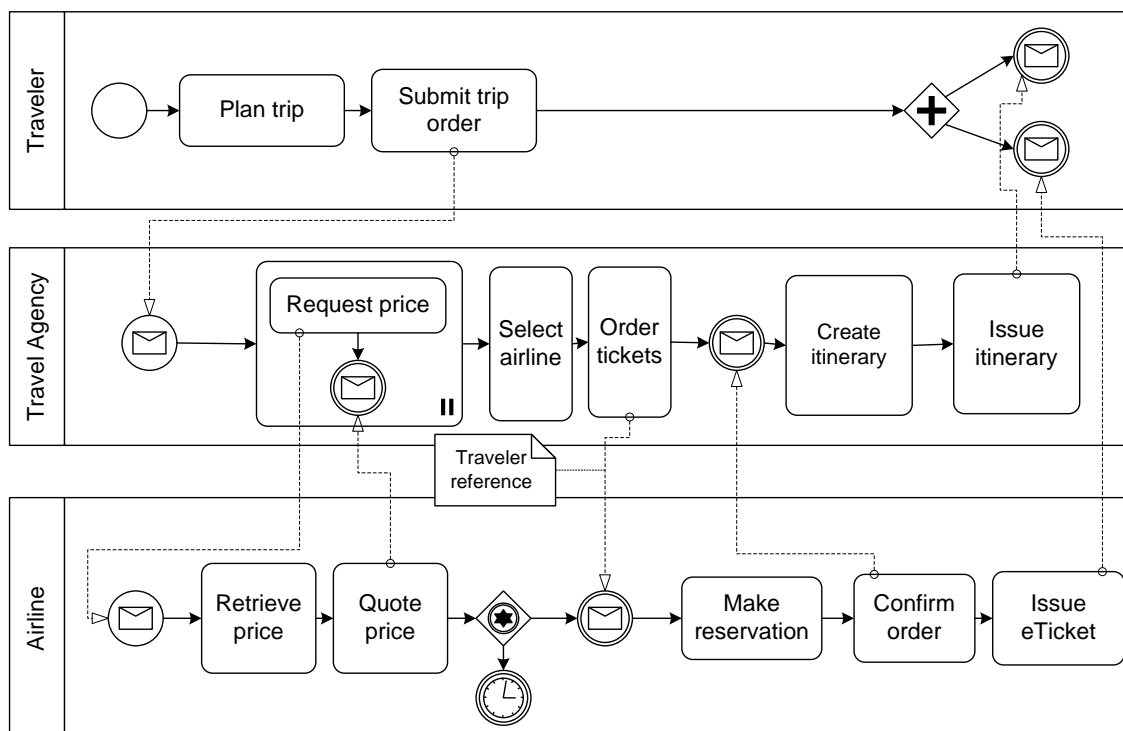Algorithm A.1 shows a sample algorithm.

Figure A.1: Example Choreography

And if you want to write an algorithm that goes over several pages, you can only do this with the following **dirty** hack:

Algorithmus A.2 Description
---
code goes here
test2

A.6 Figures

The Figure A.1 and A.2 are important to understand this document. In the appendix Figure A.4 on page 67 shows again the complete choreography.

Figure A.3 shows the usage of the package subcaption. It is indeed possible to reference to sub figures: Figure A.3a.

It is possible to convert SVGs to PDF directly during compilation. This is described in the source code of latex-tipps.tex, but commented out.

A.7 More Illustrations

Figures A.4 and A.5 show two choreographies, which should further explain the facts. The second figure is rotated 90 degrees to demonstrate the pdflscape package.

Figure A.2: The example choreography. Now slightly smaller to demonstrate `\textwidth`. And also the use of alternative captions for the list of images. However, the latter is only conditionally recommended, because who reads so much text under a picture? Or is it just a matter of style?

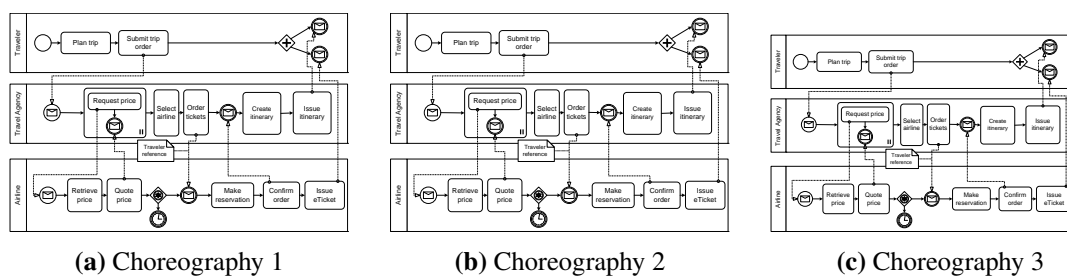**(a)** Choreography 1   **(b)** Choreography 2   **(c)** Choreography 3

Figure A.3: Example to place 3 illustrations next to each other. Further, it is possible to reference each separately.

Figure A.4: Example Choreography I
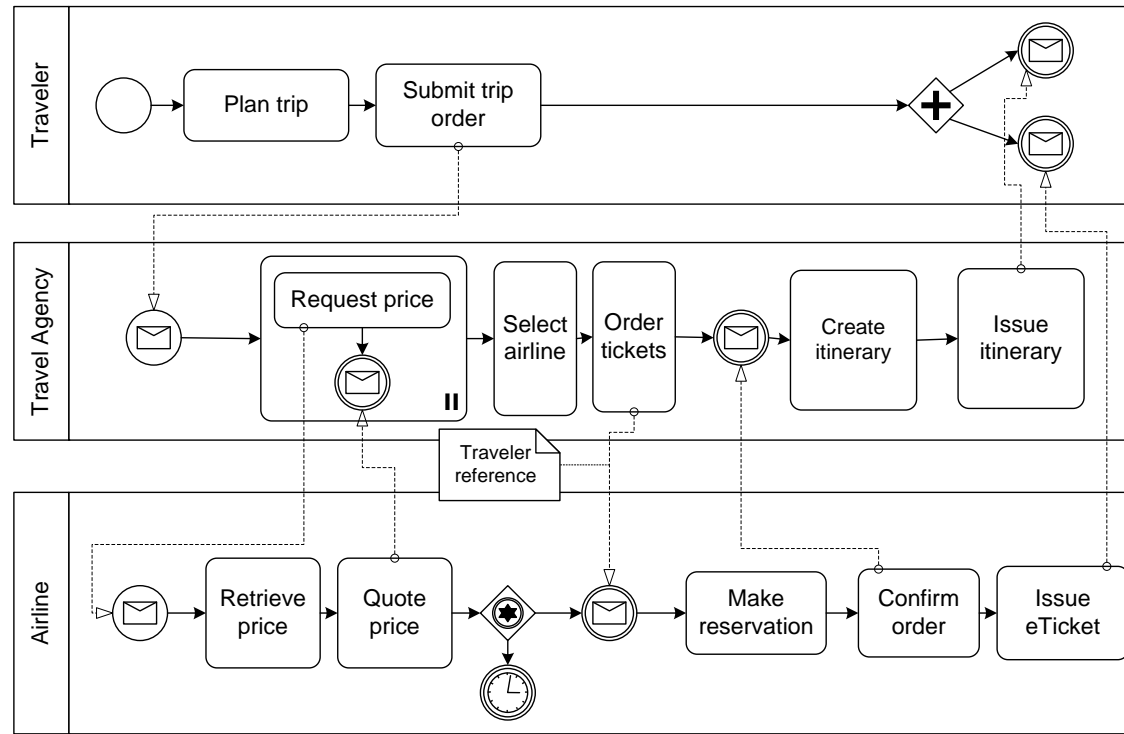
Figure A.5: Example Choreography II

A.8 Plots with pgfplots

The package pdfplots provides plotting of functions directly in LATEX like with matlab or gnuplot. Some visual examples are available here[2].

Figure A.6: Plot of $\sin(x)$ direclty inside the figure environment with pgfplots.
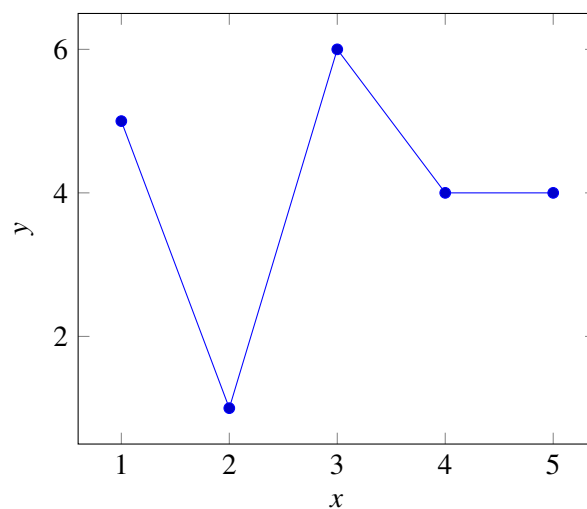
Figure A.7: Coordinates x and y read from csv file and plotted pgfplots.

A.9 Figures with tikz

The tikz is a package for creating graphics programmatically. With this package grids or other regular strucutres can be easliy generated.

---

[2]http://texdoc.net/pkg/visualtikz
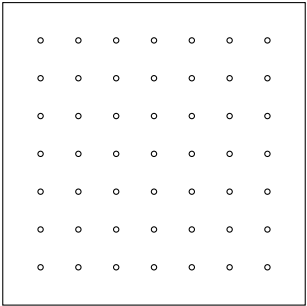
Figure A.8: A regular grid generated easily with two for loops.

A.10 UML diagrams using tikz-uml

Figure A.9 presents a class diagram typeset using tikz-uml.
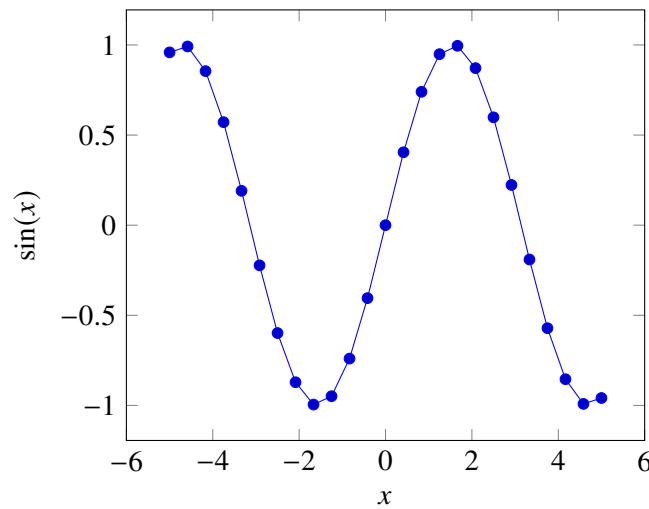
A.11 UML diagrams using PlantUML

In case LuaLaTeX is used and PlantUML is installed, UML diagrams can be defined using PlantUML.

A.12 Linguistic Forests

Code:

```
\begin{forest}
  [VP
    [DP]
    [V
      [V]
      [DP]
    ]
  ]
\end{forest}
```

Result:

A.13 Tables

Table A.1 shows results and Table A.2 shows how numerical data can be represented in a table.

A.13.1 Tables with pgfplots

With the pgfplotstable package tables can be directly generated from a csv file.
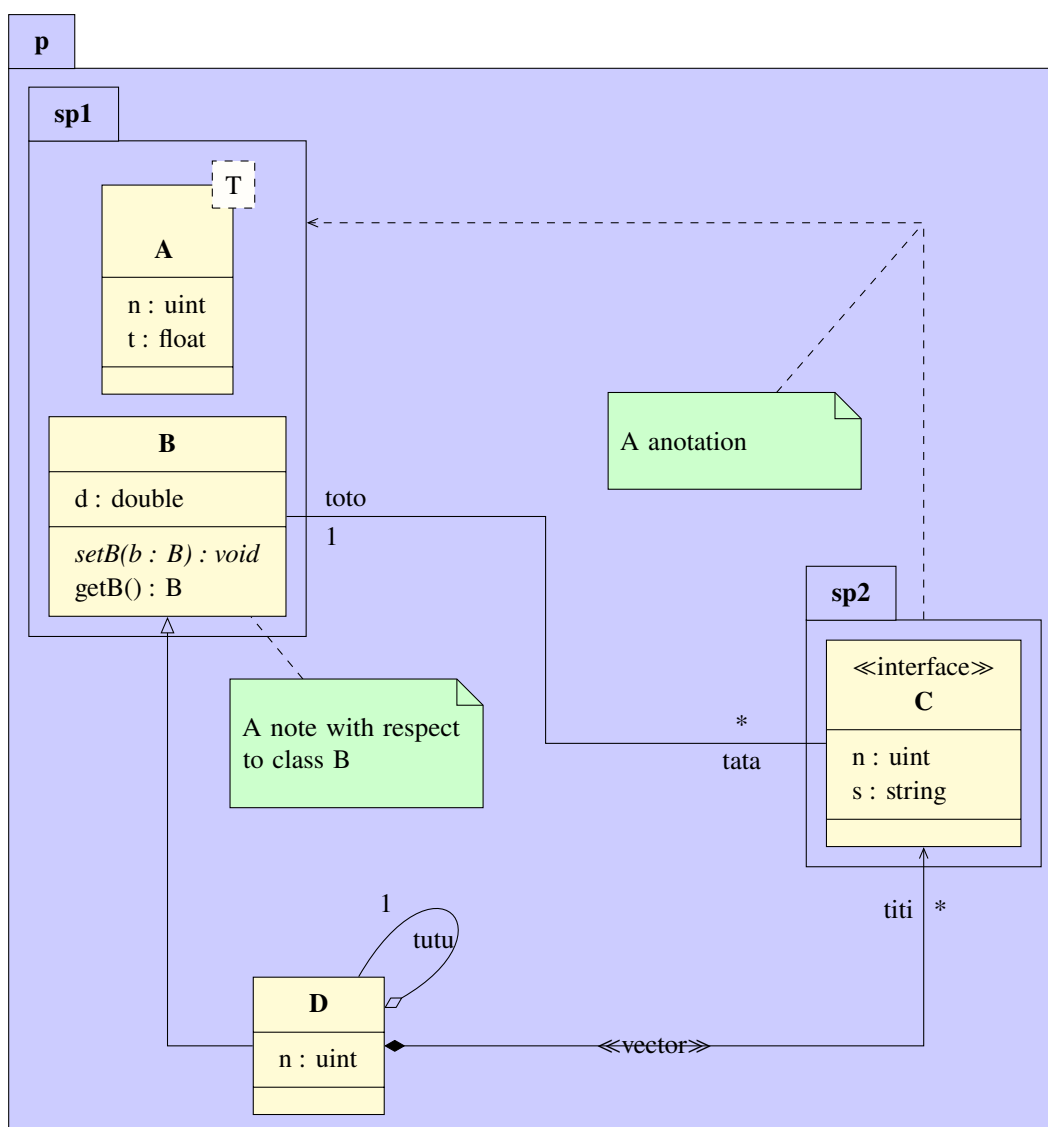
Figure A.9: Class diagram generated with tikz-uml. Example adapted from Nicolas Kielbasiewicz.

	summed	Title
Table	as	in
`tabsatz.pdf`	recommended	gesetzt
Example	a nice example for using "multirow"	

Table A.1: Exampe Table – see `http://www.ctan.org/tex-archive/info/german/tabsatz/`

Bedingungen	Parameter 1		Parameter 2		Parameter 3		Parameter 4	
	M	SD	M	SD	M	SD	M	SD
W	1.1	5.55	6.66	.01				
X	22.22	0.0	77.5	.1				
Y	333.3	.1	11.11	.05				
Z	4444.44	77.77	14.06	.3				

Table A.2: Example table for 4 constraints (W-Z), each having 4 parameters with (M und SD). Note: use always the same number of decimal places.

	b	c	d
1	4	5	1
2	3	1	5
3	5	6	1
4	1	4	9
5	3	4	7

Table A.3: Table directly generated from the values of a csf file.

A.14 Tables spanning multiple pages

Table A.4: A sample long table.

First column	Second column	Third column
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
Continued on next page		

Table A.4 – continued from previous page

First column	Second column	Third column
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
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A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
Continued on next page		

Table A.4 – continued from previous page

First column	Second column	Third column
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D
A	BC	D

A.15 Abbreviations

At the first pass, the Fehlerrate (FR) was 5. At the second pass was FR 3. The plural form can be seen here: error rates (ERs). To demonstrate what the list of abbreviations looks like for longer description texts, Relational Database Management Systems (RDBMS) must be mentioned here.

With \gls{...} you can enter abbreviations, the first time you call it, the long form is used. When reusing \gls{..} the short form is automatically displayed. The abbreviation is also automatically inserted in the abbreviation list. With \glspl{...} the plural form is used. If you want the short form to appear directly at the first use, you can use \glsunset{..} to mark an abbreviation as already used. The opposite is achieved with \glsreset{..}.

Abbreviations are defined in \content\ausarbeitung.tex by means of \newacronym{...}{...}{...}.

More information at: http://tug.ctan.org/macros/latex/contrib/glossaries/glossariesbegin.pdf

A.16 References

For distant sections "varioref" is recommended: "See Appendix A.3 on page 62". The command \vref works similarly to \cref the difference being that a reference to the page is additionally added. vref: "Appendix A.1 on page 61", cref: "Appendix A.1", ref: "A.1".

If "varioref" causes difficulties, then "cref" can be used instead. This also creates the word "section" automatically: Appendix A.3. This is also possible for illustrations etc. In English please use \Cref{...} (with large "C" at the beginning).

A.17 Definitions

Definition A.17.1 (Title)
Definition Text

Definition A.17.1 shows . . .

A.18 Footnotes

Footnotes are provided by the command \footnote{...}[3]. Citing footnotes is possible by providing a label\footnote{\label{...}...} and cite the footnote with \cref{...} in the text[3].

A.19 Various Things

Code:

```
\begin{compactenum}[I.]
  \item You can also keep the numbering
compact thanks to paralist
  \item and switch to a different numbering
\end{compactenum}
```

Result:

I. You can also keep the numbering compact thanks to paralist
II. and switch to a different numbering

---

[3]Example footnote.

The words "workflow" and "dwarflike" can be copied from the PDF and pasted to a text file.

Code:

```
In case \LuaLaTeX{} is used as the compiler,
there is no ligature at \qq{f\/l} in the word
 \qq{dwarflike} (in contrast to \qq{fl} at \
qq{workflow}).
In other words: \qq{dwarflike} and \qq{dwarf
\/like} look the same in the PDF.
In case they do not, there is an issue with
Lua\LaTeX{} and the selnolig package.
```

Result:

> In case LuaLATEX is used as the compiler, there is no ligature at "fl" in the word "dwarflike" (in contrast to "fl" at "workflow"). In other words: "dwarflike" and "dwarflike" look the same in the PDF. In case they do not, there is an issue with LuaLATEX and the selnolig package.

A.20 Closing remarks

Please feel free to provide enhancements for this template and create a new ticket on GitHub (https://github.com/latextemplates/uni-stuttgart-computer-science-template/issues).

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.

_____

place, date, signature