Institute of Architecture of Application Systems

University of Stuttgart
Universitätsstraße 38
D–70569 Stuttgart

Masterarbeit

Energy and CO2 footprint of cloud/backend processing

Erisa Hoxha

Course of Study:	Computer Science
Examiner:	Prof. Dr. Marco Aiello
Supervisor:	Prof. Dr. Marco Aiello
Commenced:	November 22, 2023
Completed:	May 22, 2024

Abstract

<Short summary of the thesis>

Contents

List of Figures

List of Tables

List of Listings

List of Algorithms

Acronyms

ER error rate. 52

FR Fehlerrate. 52

RDBMS Relational Database Management System. 52

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. 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

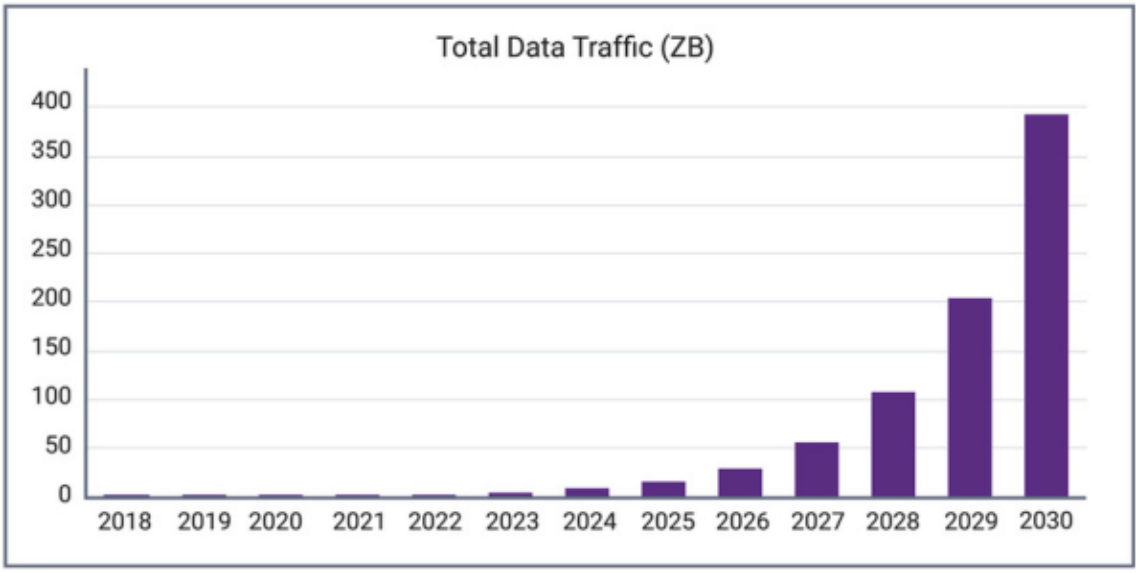


Figure 1.1: Total Data Traffic Forecast through 2030. Source: “Impact of AI on Electronics and Semiconductor Industries”, IBS, April 2020

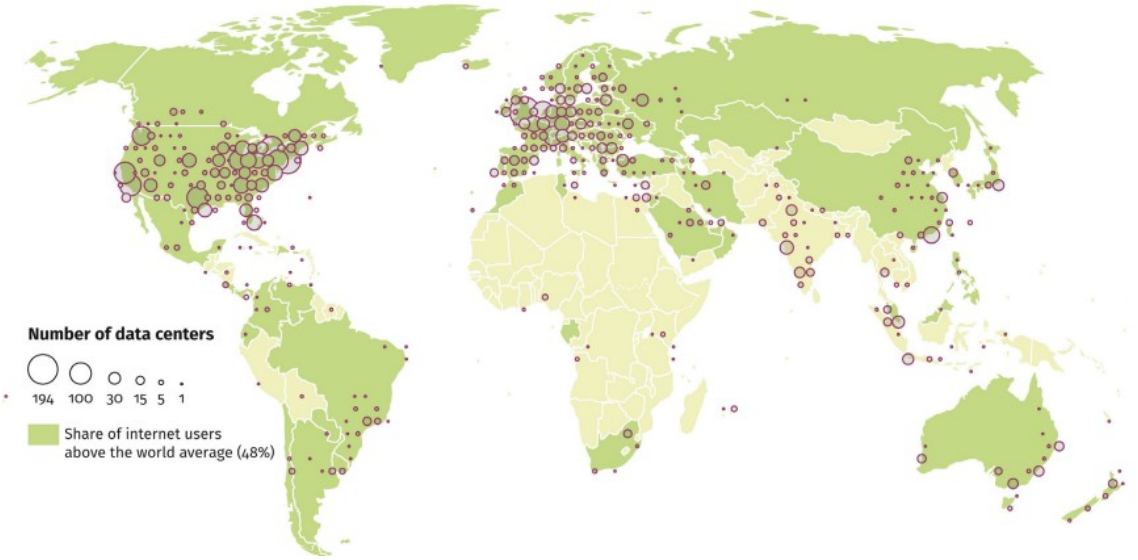


Figure 1.2: Data Center distribution worldwide

effect while the 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

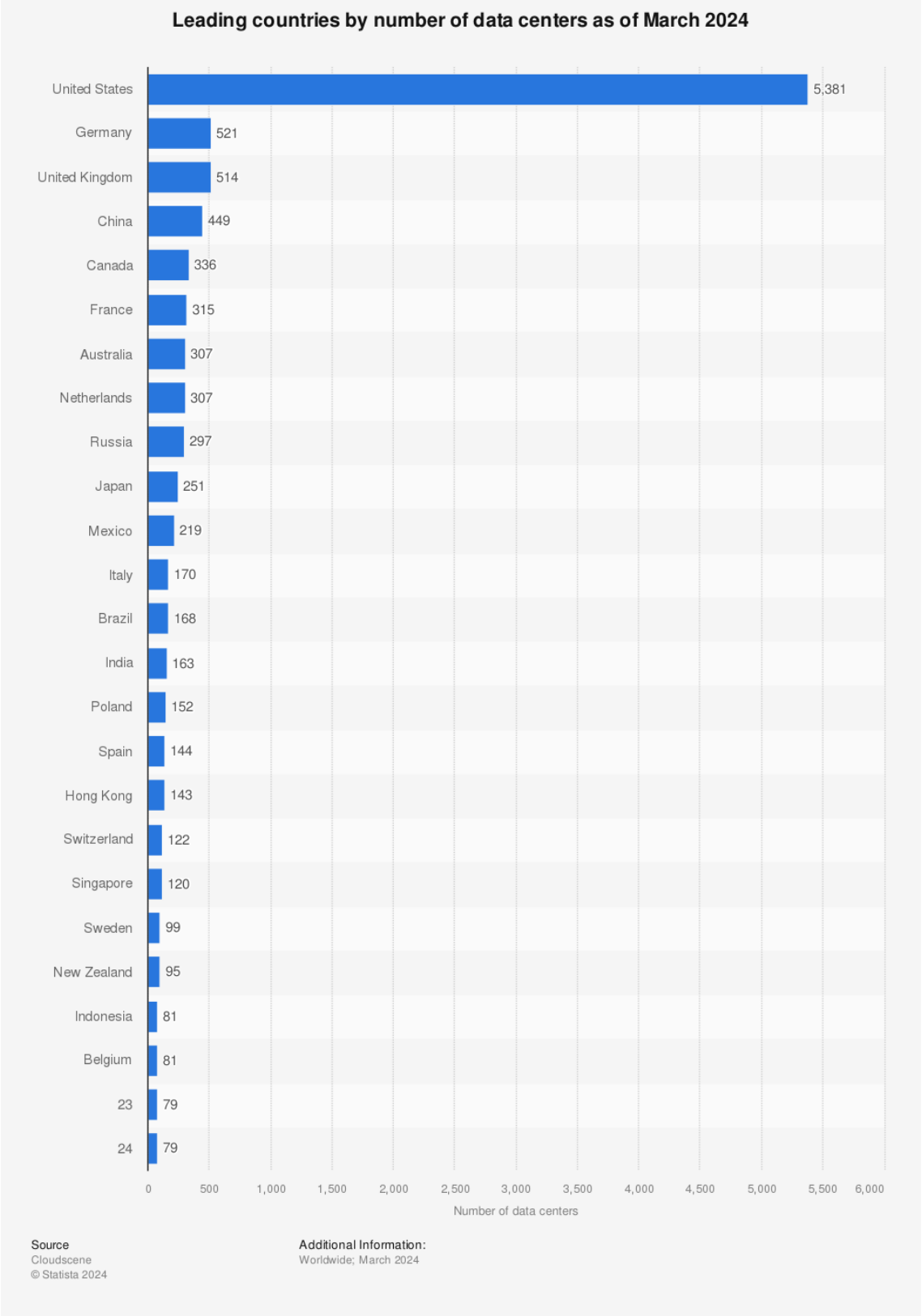


Figure 1.3: Source Statista[24b]

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[RR17].

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].

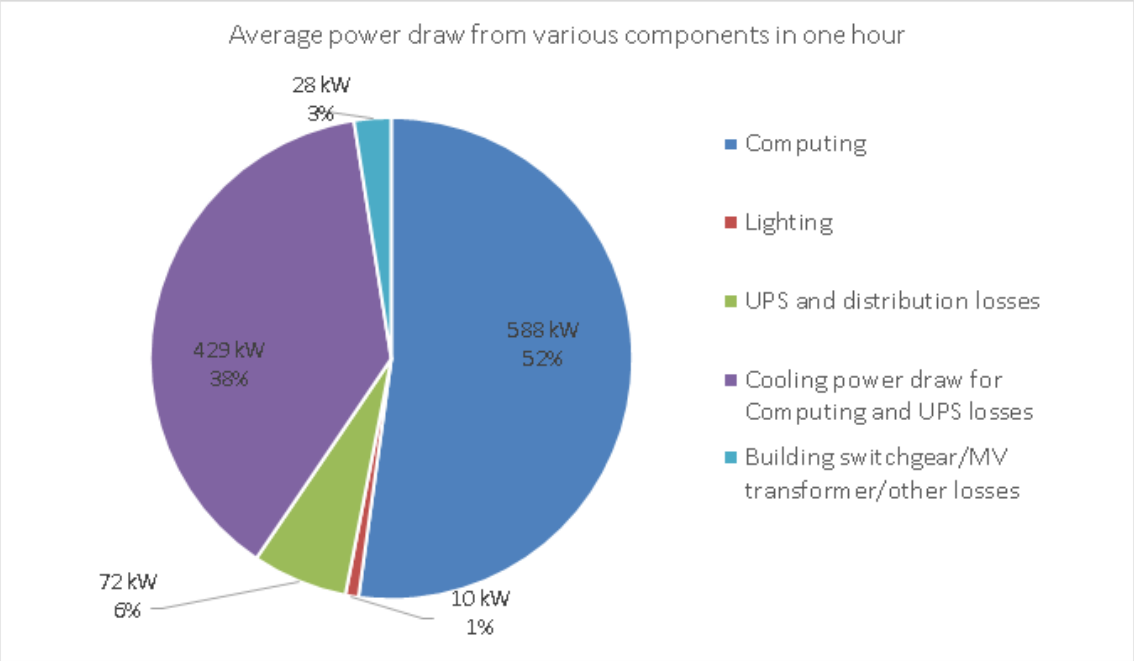


Figure 2.1: Analysis of a typical 465 m2 data center, Source Emerson Network power[Eme15]

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].

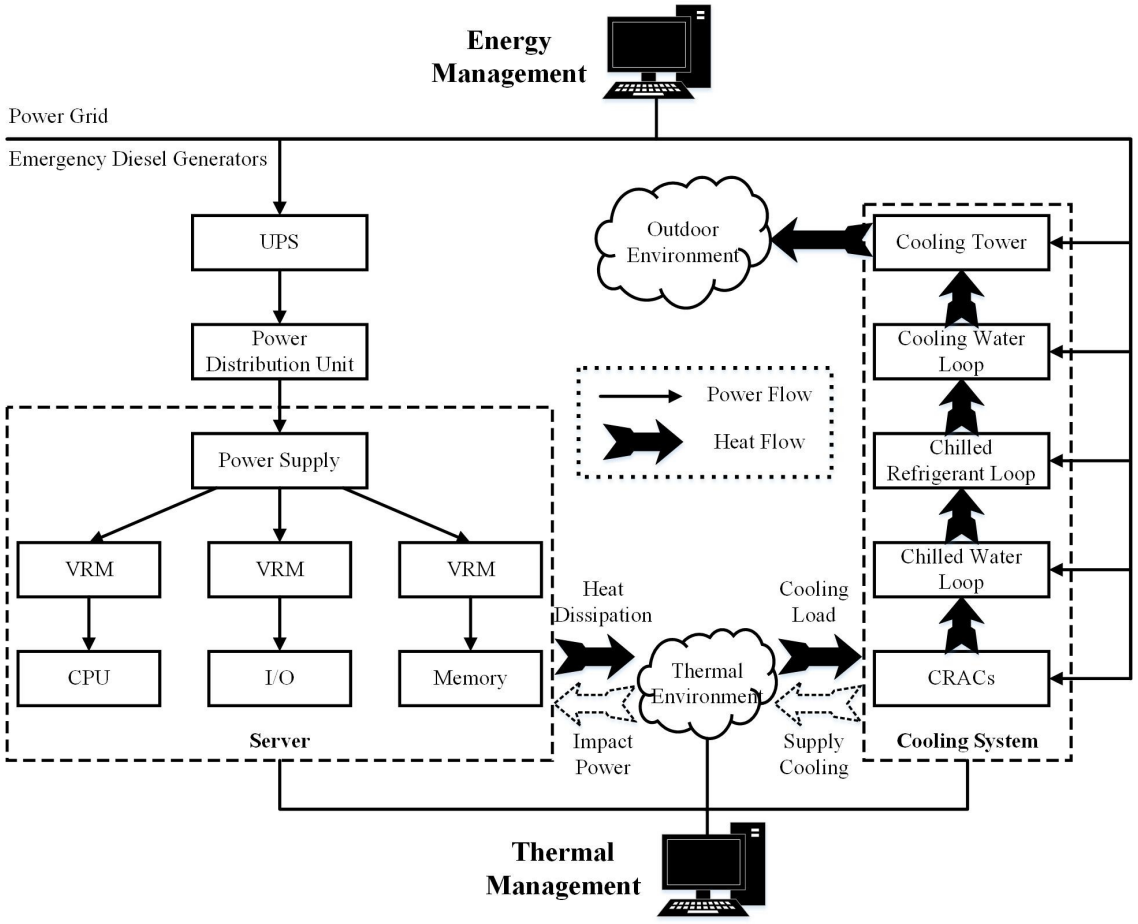


Figure 2.2: The power flow and heat flow in general data centers [JBY+20]

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 CO2) 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

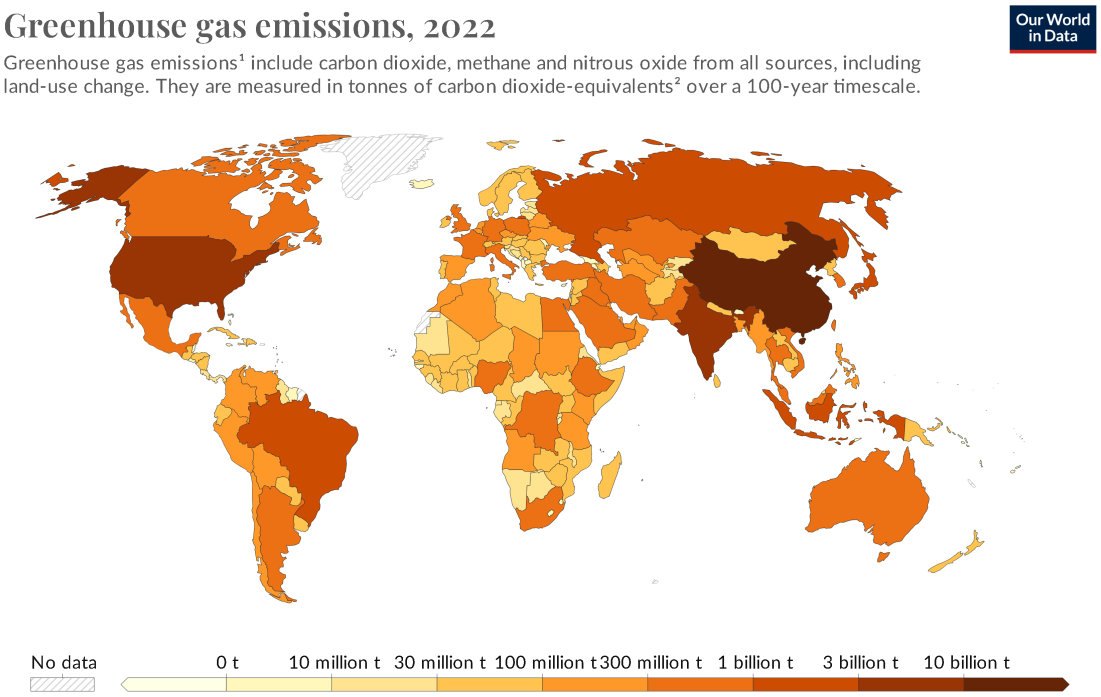


Figure 2.3: Greenhouse gas emissions, 2022 [RRR23a]

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]. [ABA21] 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 CO2 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].

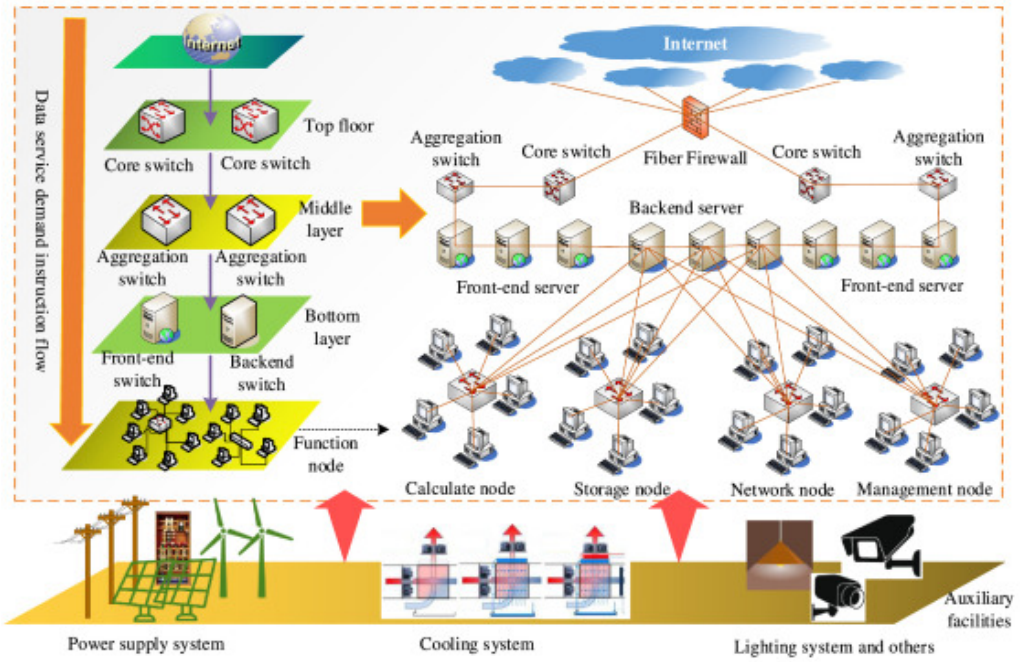


Figure 2.4: Diagrammatic representation of the DC's overall structure[ZZG+23b]

3 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. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

3.1 Heading on Level 1 (section)

Hello, here is some text without a meaning. $\mathrm{d}\Omega = \sin\vartheta \mathrm{d}\vartheta \mathrm{d}\varphi$. 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. $\sqrt[n]{a} \cdot \sqrt[n]{b} = \sqrt[n]{ab}$.

3.1.1 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. $\mathrm{d}\Omega = \sin\vartheta \mathrm{d}\vartheta \mathrm{d}\varphi$. 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. $\mathrm{d}\Omega = \sin\vartheta \mathrm{d}\vartheta \mathrm{d}\varphi$. 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. $a\sqrt[n]{b} = \sqrt[n]{a^n b}$.

3.2 Lists

3.2.1 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

3.2.2 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

3.2.3 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

4 Related Work

Describe relevant scientific literature related to your work.

5 Conclusion and Outlook

Outlook

Bibliography

[23] Dec. 2023. URL: https://eia.gov/tools/faqs/faq.php?id=74%5C&t=11 (cit. on p. 24).

[24a] Apr. 2024. URL: https://www.britannica.com/technology/software (cit. on p. 18).

[24b] *Leading countries by number of data centers as of March 2024*. Apr. 2024. URL: https://www.statista.com/statistics/1228433/data-centers-worldwide-by-country/ (cit. on pp. 19, 20).

[ABA21] K. M. U. Ahmed, M. H. J. Bollen, M. Alvarez. "A Review of Data Centers Energy Consumption and Reliability Modeling". In: *IEEE Access* 9 (2021), pp. 152536–152563. DOI: 10.1109/ACCESS.2021.3125092 (cit. on p. 24).

[AKK15] N. Abas, A. Kalair, N. Khan. "Review of fossil fuels and future energy technologies". In: *Futures* 69 (2015), pp. 31–49 (cit. on p. 22).

[AM21] N. K. Arora, I. Mishra. "COP26: More challenges than achievements". In: *Environmental Sustainability* 4.4 (Dec. 2021), pp. 585–588. DOI: 10.1007/s42398-021-00212-7 (cit. on p. 23).

[ASF16] The Apache Software Foundation. *Apache ODE™ – The Orchestration Director Engine*. 2016. URL: http://ode.apache.org (cit. on p. 40).

[Cos19] M. Cosar. "Carbon footprint in data centre: A case study". In: *Feb. Fresenius Environ. Bull* 600 (2019) (cit. on p. 18).

[Dio17] C. Dioxide. "Overview of greenhouse gases". In: (2017) (cit. on p. 23).

[Eme15] Emerson Network Power. *Energy logic: reducing data center energy consumption by creating savings that cascade across systems*. White Paper. 2015 (cit. on p. 22).

[FFN+20] H. K. Firozjaei, M. K. Firozjaei, O. Nematollahi, M. Kiavarz, S. K. Alavipanah. "On the effect of geographical, topographic and climatic conditions on feed-in tariff optimization for solar photovoltaic electricity generation: A case study in Iran". In: *Renewable energy* 153 (2020), pp. 430–439 (cit. on p. 22).

[Hum06] C. Humby. *Data is the new Oil!, ANA Senior marketer's summit, Kellogg School*. 2006 (cit. on p. 18).

[IBM24] IBM. *What Is a Data Center?* https://www.ibm.com/topics/data-centers. 2024 (cit. on p. 25).

[JBY+20] C. Jin, X. Bai, C. Yang, W. Mao, X. Xu. "A review of power consumption models of servers in data centers". In: *Applied Energy* 265 (2020), p. 114806. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2020.114806. URL: https://www.sciencedirect.com/science/article/pii/S0306261920303184 (cit. on pp. 21, 23).

[KBB+16] J. von Kistowski, H. Block, J. Beckett, C. Spradling, K.-D. Lange, S. Kounev. "Variations in cpu power consumption". In: *Proceedings of the 7th ACM/SPEC on International Conference on Performance Engineering*. 2016, pp. 147–158 (cit. on p. 21).

[KKAH17] N. d. Khan, A. Kalair, N. Abas, A. Haider. "Review of ocean tidal, wave and thermal energy technologies". In: *Renewable and Sustainable Energy Reviews* 72 (2017), pp. 590–604 (cit. on p. 22).

[KOW+19] D. Kryzia, P. Olczak, J. Wrona, M. Kopacz, K. Kryzia, D. Galica. "Dampening variations in wind power generation through geographical diversification". In: *IOP Conference Series: Earth and Environmental Science*. Vol. 214. 1. IOP Publishing. 2019, p. 012038 (cit. on p. 22).

[MSS12] S. Mekhilef, R. Saidur, A. Safari. "Comparative study of different fuel cell technologies". In: *Renewable and Sustainable Energy Reviews* 16.1 (2012), pp. 981–989 (cit. on p. 22).

[NLA19] D. Nevado-Peña, V.-R. López-Ruiz, J.-L. Alfaro-Navarro. "Improving quality of life perception with ICT use and technological capacity in Europe". In: *Technological Forecasting and Social Change* 148 (2019), p. 119734 (cit. on p. 18).

[Pal06] M. Palmer. *Data is the New Oil*. 2006. URL: https://ana.blogs.com/maestros/2006/11/data_is_the_new.html (cit. on p. 19).

[QHR+19] A. Qazi, F. Hussain, N. A. Rahim, G. Hardaker, D. Alghazzawi, K. Shaban, K. Haruna. "Towards sustainable energy: a systematic review of renewable energy sources, technologies, and public opinions". In: *IEEE access* 7 (2019), pp. 63837–63851 (cit. on p. 22).

[RR17] H. Ritchie, P. Rosado. "Fossil fuels". In: *Our World in Data* (2017). https://ourworldindata.org/fossil-fuels (cit. on p. 21).

[RRR20] H. Ritchie, M. Roser, P. Rosado. "Renewable Energy". In: *Our World in Data* (2020). https://ourworldindata.org/renewable-energy (cit. on p. 22).

[RRR23a] H. Ritchie, P. Rosado, M. Roser. "CO2 and Greenhouse Gas Emissions". In: *Our World in Data* (2023). https://ourworldindata.org/co2-and-greenhouse-gas-emissions (cit. on p. 24).

[RRR23b] H. Ritchie, P. Rosado, M. Roser. "Nuclear energy". In: *Our World in Data* (2023) (cit. on p. 21).

[RVA16] H. Reijers, I. Vanderfeesten, W. van der Aalst. "The effectiveness of workflow management systems: A longitudinal study". In: *International Journal of Information Management* 36.1 (Feb. 2016), pp. 126–141. DOI: 10.1016/j.ijinfomgt.2015.08.003 (cit. on p. 40).

[RZX+16] H. Rong, H. Zhang, S. Xiao, C. Li, C. Hu. "Optimizing energy consumption for data centers". In: *Renewable and Sustainable Energy Reviews* 58 (2016), pp. 674–691 (cit. on p. 21).

[SBI+13] R. Sipahutar, S. M. Bernas, M. S. Imanuddin, et al. "Renewable energy and hydropower utilization tendency worldwide". In: *Renewable and Sustainable Energy Reviews* 17 (2013), pp. 213–215 (cit. on p. 22).

[STA24] C. STAMFORD. “Gartner Forecasts Worldwide IT Spending to Grow 8% in 2024”. In: *https://www.gartner.com/en/newsroom/press-releases/2024-04-16-gartner-forecast-worldwide-it-spending-to-grow-8-percent-in-2024* (2024).

[WCL+05] S. Weerawarana, F. Curbera, F. Leymann, T. Storey, D. F. Ferguson. *Web Services Platform Architecture : SOAP, WSDL, WS-Policy, WS-Addressing, WS-BPEL, WS-Reliable Messaging, and More*. Prentice Hall PTR, 2005. ISBN: 0131488740. DOI: 10.1.1/jpb001 (cit. on p. 39).

[WK13] L. Wang, S. U. Khan. “Review of performance metrics for green data centers: a taxonomy study”. In: *The journal of supercomputing* 63 (2013), pp. 639–656 (cit. on p. 24).

[Zho21] D. Zhou. “Role of green data center in human resources development model”. In: *Sustainable Computing: Informatics and Systems* 30 (2021), p. 100492 (cit. on p. 17).

[ZZG+23a] H. Zhu, D. Zhang, H. H. Goh, S. Wang, T. Ahmad, D. Mao, T. Liu, H. Zhao, T. Wu. “Future data center energy-conservation and emission-reduction technologies in the context of smart and low-carbon city construction”. In: *Sustainable Cities and Society* 89 (2023), p. 104322 (cit. on p. 19).

[ZZG+23b] H. Zhu, D. Zhang, H. H. Goh, S. Wang, T. Ahmad, D. Mao, T. Liu, H. Zhao, T. Wu. “Future data center energy-conservation and emission-reduction technologies in the context of smart and low-carbon city construction”. In: *Sustainable Cities and Society* 89 (2023), p. 104322. ISSN: 2210-6707. DOI: https://doi.org/10.1016/j.scs.2022.104322. URL: https://www.sciencedirect.com/science/article/pii/S2210670722006266 (cit. on pp. 25, 26).

All links were last followed on March 17, 2018.

A LaTeX Hints

> We cannot solve our problems with the same level of thinking that created them
>
> *(Albert Einstein)*

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:

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

Result:

Example: [WCL+05] or by author input: Weerawarana 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:

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

Result:

$$x = y \tag{A.1}$$

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

Code:

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

Result:

$$x = y$$

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

Code:

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

Result:

$|X|$.

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 $\leftarrow$ $(a = \text{process}) \vee \text{visited}(a'), (a', c, a) \in \text{HR}$
    // $(a', c'a) \in \text{HR}$ denotes that a' is the parent of a
  if parentHandled $\wedge$ $(\mathcal{L}_{in}(a) = \emptyset \vee \forall l \in \mathcal{L}_{in}(a) : \text{visited}(l))$ **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), $(a, \perp, a') \in \text{HR}$
      $\text{writes}_\bullet(a) \leftarrow \text{writes}_\bullet(a')$
    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.

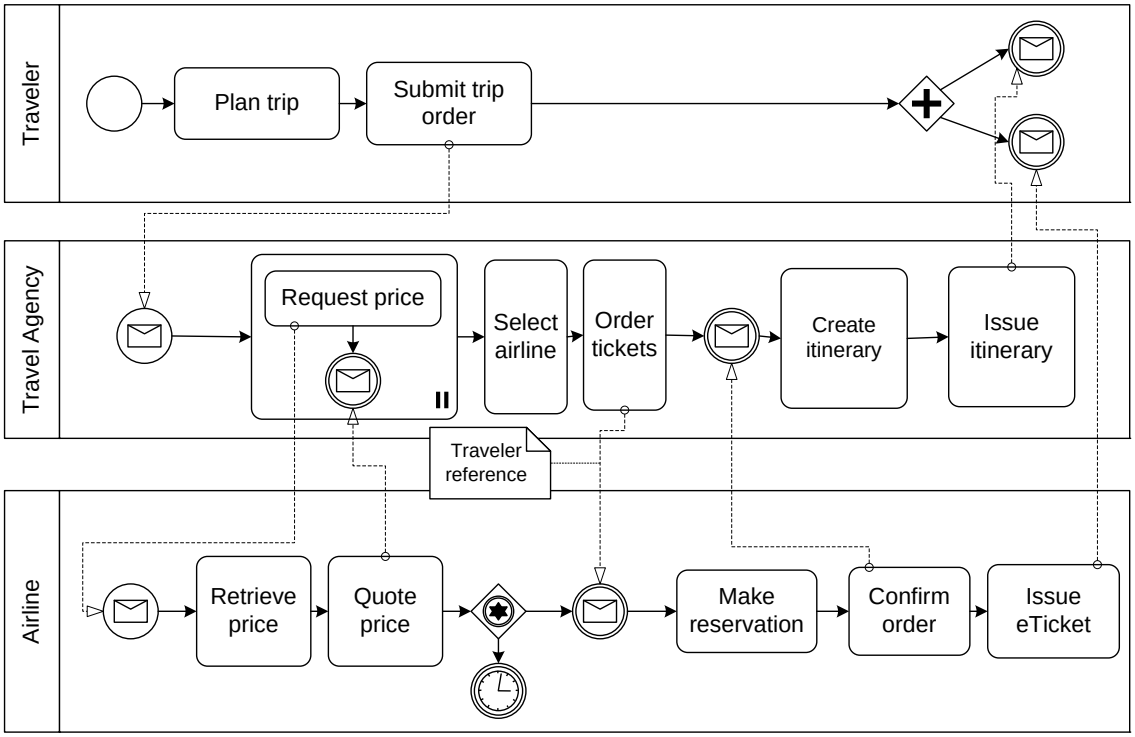


Figure A.1: Example Choreography

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 45 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.

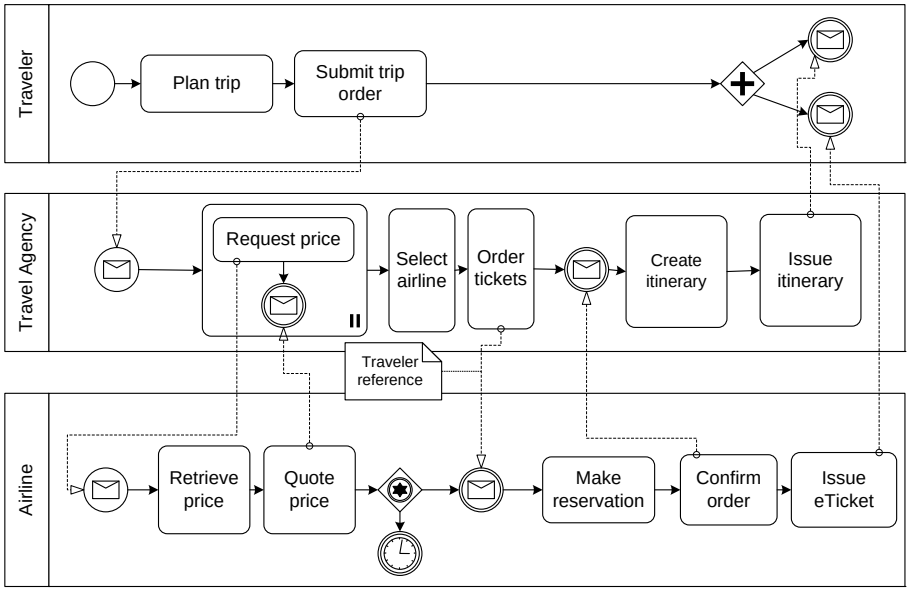
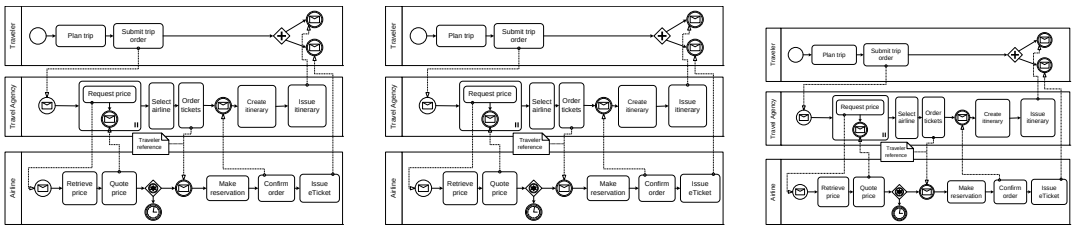


Figure A.2: The example choreography. Now slightly smaller to demonstrate `\textwidth`. And also the use of alternative captions for the list of images. However, the latter is only conditionally recommended, because who reads so much text under a picture? Or is it just a matter of style?



(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.

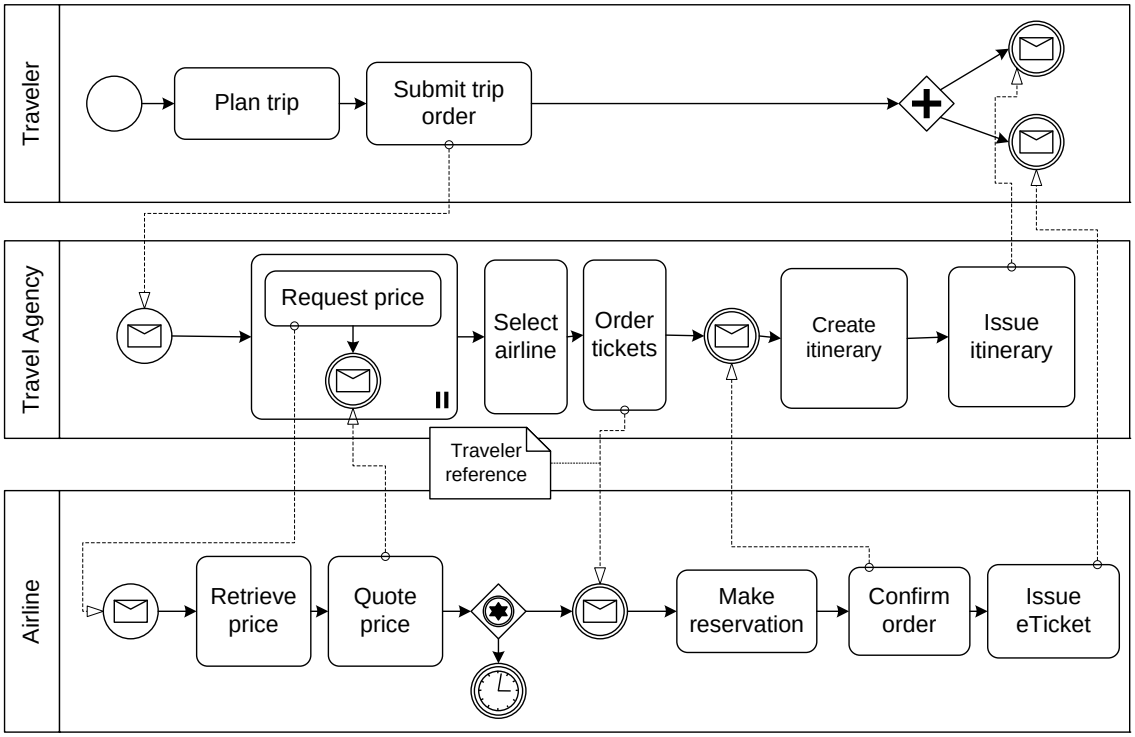


Figure A.4: Example Choreography I

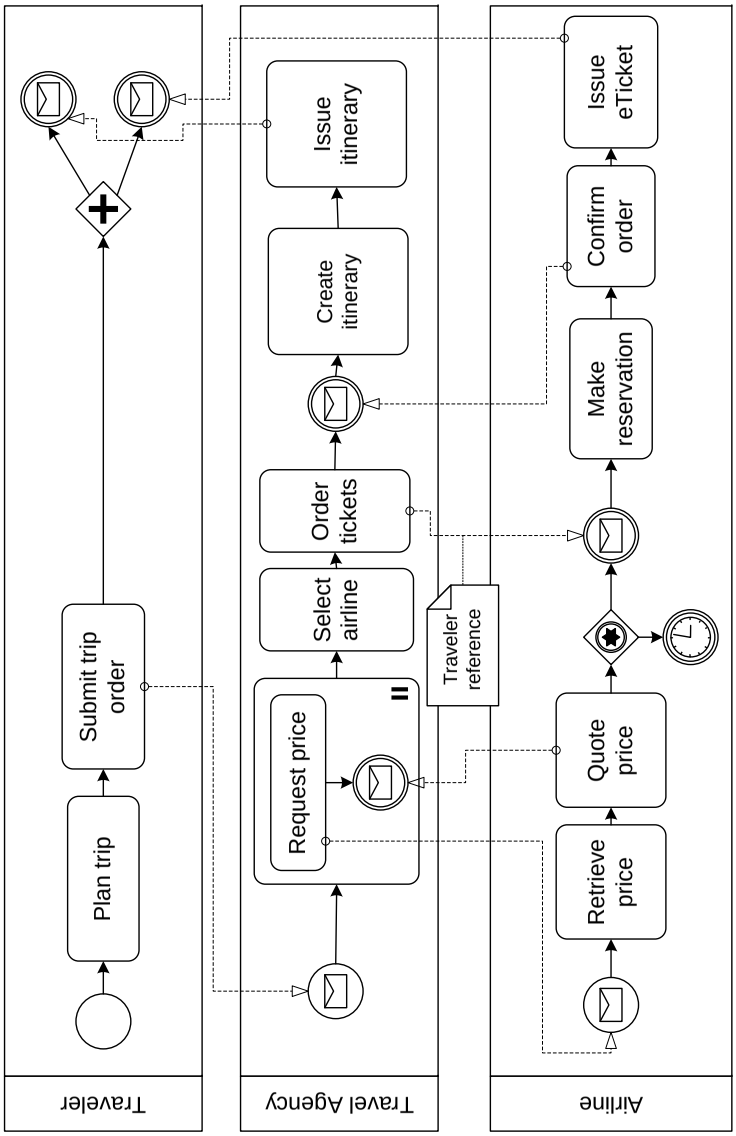


Figure A.5: Example Choreography II

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].

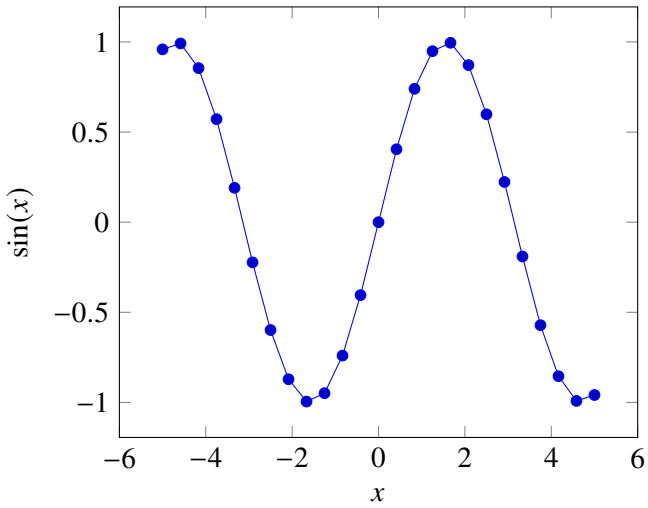


Figure A.6: Plot of $\sin(x)$ direclty inside the figure environment with pgfplots.

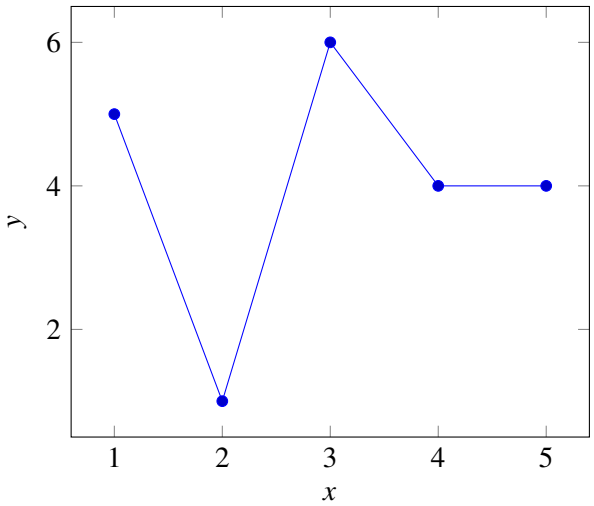


Figure A.7: Coordinates x and y read from csv file and plotted pgfplots.

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

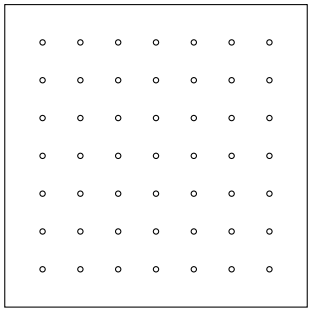


Figure A.8: A regular grid generated easily with two for loops.

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.

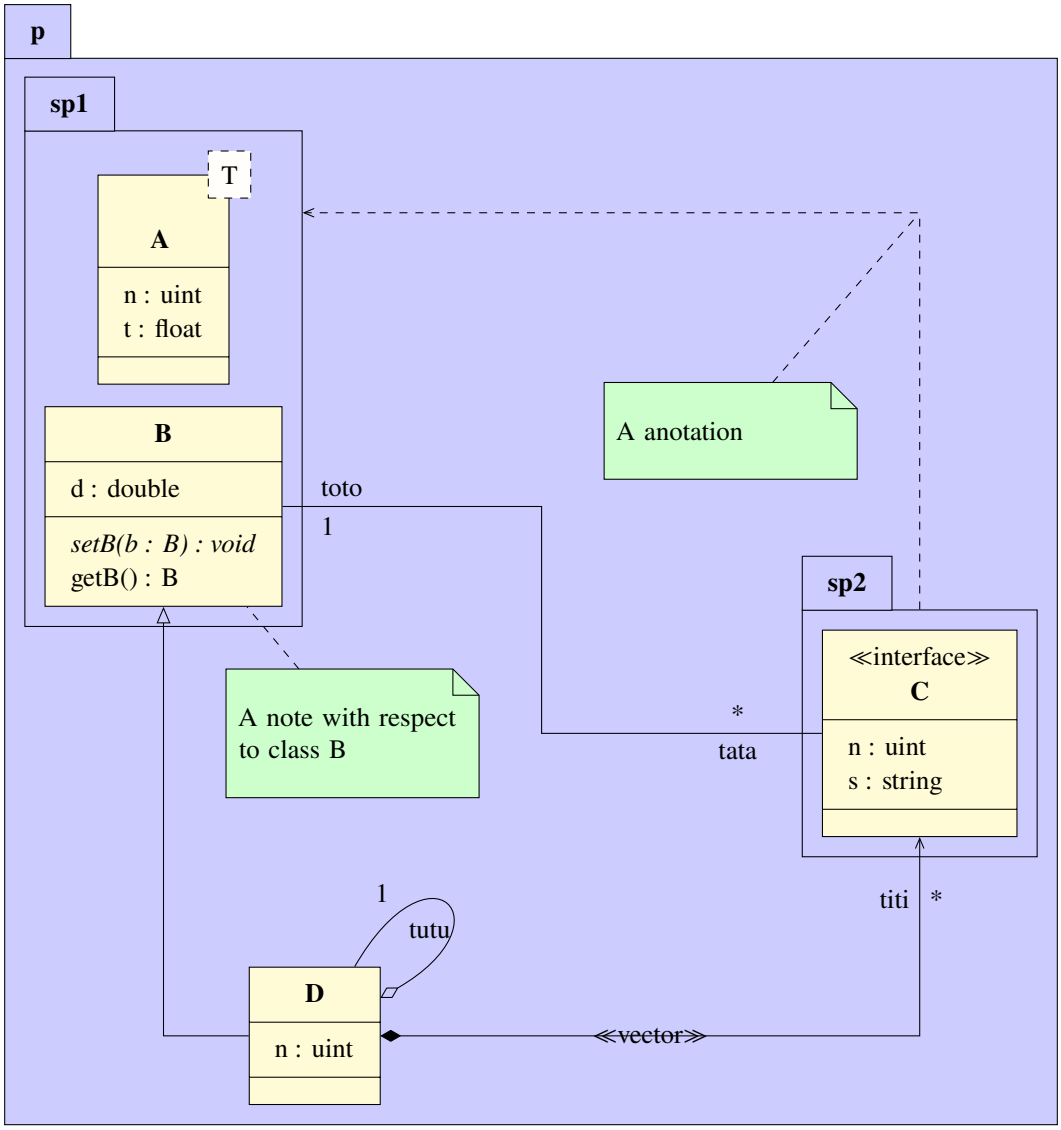


Figure A.9: Class diagram generated with tikz-uml. Example adapted from Nicolas Kielbasiewicz.

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/

	Parameter 1		Parameter 2		Parameter 3		Parameter 4	
Bedingungen	**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
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	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
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 40”. 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 39”, `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 provinding 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