Real-Time Monitoring of the CO$_2$ Footprint of Production for SMEs

Henning Strauß*, Julian Sasse

Abstract: The core of the research work is the development and implementation of a real-time product carbon footprint with a focus on applicability for small and medium-sized enterprises. In addition to the life cycle analysis, a central element is the implementation of a machine carbon footprint for a 5-axis universal machining center that records and visualizes resource consumption in real time. With the help of a wide range of sensors, consumption such as energy, compressed air and cooling lubricants are dynamically measured as well as material consumption. The measurement data is then processed, stored and visualized with the help of open-source low-code platforms. This real-time data forms the basis for the precise determination of the production-specific CO$_2$ footprint. The results of the Product Carbon Footprint show that the greatest savings potential lies in the choice of sustainable raw materials (a reduction of 38%) and the use of renewable energies (a reduction of 19%). The approach offers a high level of transparency and supports companies in optimizing their processes as well as meeting future regulatory requirements.

Keywords: CO$_2$ Footprint; IoT; Machine Data Acquisition; Open Source Software (OSS); Process Data; Production

1 INTRODUCTION

In Germany, the manufacturing industry is responsible for 23% of CO$_2$ equivalent emissions [1]. In recent years, however, increased efforts to reduce emissions have been observed [2]. The background to this development is, for example, the increased efficiency of production processes, especially with regard to the resources used. In addition, policies such as the CSRD Directive and the European Union's Green Deal help to further reduce emissions. Companies are forced to record, store and visualize CO$_2$ data, i.e. document it, in order to identify further potential for saving resources [3].

The aim of this thesis is therefore to show SMEs a way to enable first steps towards sustainable production with limited financial resources, simple technical solutions and with the help of low-code platforms. For this purpose, a real-time digital CO$_2$ twin of a machine is created, which makes it possible to derive the Product Carbon Footprint (PCF) of a product based on the individual production steps.

1.1 Definition and Limitation

"A product carbon footprint balances all greenhouse gas emissions – related to a defined unit of benefit – that occur during the life cycle of a product" [4]. All process steps are taken into account – from the development, manufacture and transport of raw materials to production, use and disposal of the product [5].

Depending on the system boundaries, however, only certain parts of the life cycle of a product can be recorded. In the business customer (B2B) sector, often only the part that includes emissions from production and the precursors required for this is taken into account [6]. This means that emissions are calculated from the procurement of raw materials to the completion of the product, but the use and disposal by the end customer are excluded. This method is called cradle-to-gate (from the origin to the factory gate) [7].

In the field of consumer trade (B2C), on the other hand, the path of the product to the sale to the customer is often also taken into account [6]. In addition to production, the emissions caused by the transport and storage of the product before it ends up in the store or online shop are also recorded. This ends at the so-called point of sale [6].

Another option is the cradle-to-grave approach (from origin to disposal), which looks at the entire life cycle of a product. This includes not only the emissions from production and transport, but also the emissions during use and finally those during the disposal of the product. This method provides a comprehensive view of a product's environmental impact [8].

1.2 Standards and Frameworks

The calculation of a product's carbon footprint is regulated by various international standards. Among the most well-known are PAS 2050, the Greenhouse Gas Protocol and ISO 14067.

The Publicly Available Specification (PAS) 2050 was developed by the British Standards Institution (BSI) in 2008 and revised in 2011. It offers one of the first internationally applicable frameworks for quantifying greenhouse gas emissions along the life cycle of products and services. Its goal is to provide companies with a clear indicator to evaluate and compare the environmental impact of products [9].

The Greenhouse Gas Protocol, published in 2011 by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), builds on PAS 2050 and aims to provide internationally valid guidelines for calculating and reporting product-related CO$_2$ emissions, while at the same time identifying emission reduction potential, especially for companies [9].

ISO 14067, first published in 2013 and updated in 2018, provides standardized rules for calculating and communicating the carbon footprint of products. It is based on several ISO standards such as life cycle analysis (ISO 14040 and ISO 14044). According to the standardised calculation of the PCF, the standard allows it to be communicated in order to enable comparability between similar products [10].

All three standards pursue the goal of systematically recording the greenhouse gas emissions of products and making them comparable in order to enable more sustainable decisions along the value chain.

1.3 Methodology

A Life Cycle Assessment (LCA) is required as a methodological basis for the PCF according to ISO 14067 [11]. Based on the LCA, each section of the product life cycle is subjected to a process step analysis, in which the individual process steps are recorded and the associated data is analyzed. This process is shown as an example for an example aluminium product in Fig. 1. For each life cycle of a product, a detailed process step analysis is required. In this analysis, the entire cycle is divided into individual process steps, with each step backed up with specific data or well-founded estimates of the consumption involved, such as energy or materials.
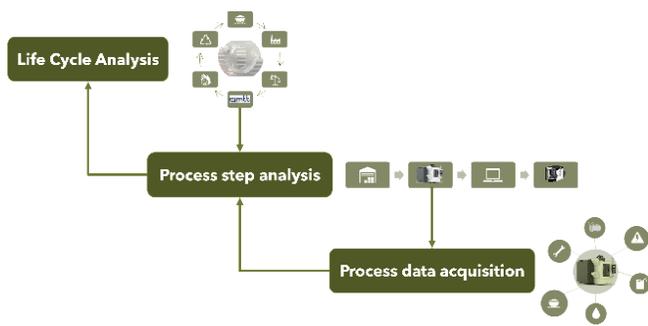

Figure 1 Life cycle analysis of the product [Own figure, CC]

2 LIFE CYCLE ANALYSIS

In this chapter, an initial estimation of an LCA is explained on the basis of an example product in order to systematically derive a PCF from it. The individual steps of the process are described in detail with the help of an LCA and process step analysis and the relevant data sources and calculation methods are shown. The section of an LCA described here does not claim to be complete and serves only as an initial orientation and should be carried out holistically and software-supported in accordance with the applicable regulations.

2.1 The Life Cycle

The calculation of the PCF is based on a comprehensive LCA that covers all phases of the product life cycle. The transport routes and means between the individual cycles are also taken into account. The cradle-to-grave approach is followed for the product. Starting from the extraction of resources, through the manufacture, production and processing of the aluminium, to the disposal or recycling of the product, the entire life cycle is thus considered, which is schematically shown in Fig. 2.

Figure 2 The life cycle of the product

If the composition of the aluminium used is not known, the assumption is followed that it is pure aluminium without recyclate content. This marks the beginning of the life cycle in the extraction of bauxite, which is converted into raw aluminium using energy-intensive chemical processes. The raw aluminium is shipped to Europe for further processing, where it is formed into round bars, heat treated and then made available to customers at dealers. From there, these are delivered to the producers and processed into individual products. The life cycle of the product ends with the use of the dispensers and their subsequent return to the recycling cycle.

2.2 Process Step Analysis

The step of process step analysis is illustrated by the life cycle section of production. Within this cycle, various process steps take place, which can be easily traced, especially in terms of measurement technology. This enables precise recording of the relevant consumption data and a detailed mapping of emissions in the individual phases of the production cycle.

The production process includes the transformation from the aluminium round bar to the finished, individualised product. An overview of these production steps is schematically shown in Figure 3.

Figure 3 Process steps of production for the product

The purchase of the aluminium round bars and their transport to the production hall mark the beginning of the life cycle stage in production. In a first step, the round bars are divided into blanks with a diameter of 50 mm and a thickness of 20 mm on a lathe. Subsequently, students model and individualize the adhesive tape dispensers as part of courses. The necessary CNC programs for machining are also developed. In a further step, the blanks are processed and finished on another machine using these CNC programs. This

process step concludes the considered life cycle section before the product enters the use phase.

2.3 Process Data Acquisition

According to the methodological approach, the individual process steps must be analysed with regard to their resource consumption and the associated emissions. Especially when using machines, comprehensive collection of machine data forms the basis for the assessment of product-related greenhouse gas emissions. Fig. 4 serves as a first guide to identify the basic data for the calculation of the PCF.
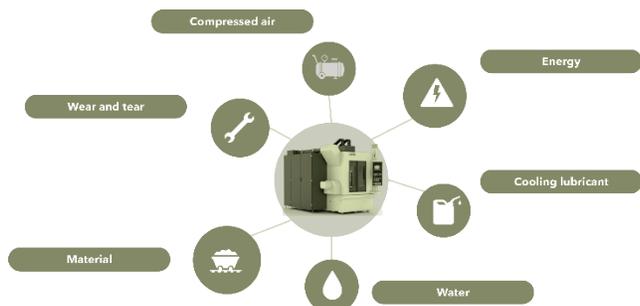
Figure 4 Exemplary data collection to determine an MCF

The recorded machine data includes not only energy consumption in the form of electricity, but also the consumption of operating resources such as materials, water, compressed air and cooling lubricants. In addition, the emissions generated during the manufacture of the machines themselves and from wear and tear, for example of the tools, must be taken into account proportionately. The collection of this data can be done with limited financial and technical resources. If this data is not immediately available, realistic estimates or observations are used first.

2.4 Calculation

The determined consumption data is linked to emission factors to calculate the CO_2 equivalent. These emission factors, which are stored in databases such as those of the Oeko-Institut e.V., the European Environment Agency (EEA) or the ProBas database of the Federal Environment Agency, relate to materials, means of transport and production processes. They include not only CO_2, but also other greenhouse gases such as methane (CH_4), nitrous oxide (N_2O) and fluorinated gases.

The collected emission factors are processed in a spreadsheet program or appropriate software (such as Open LCA), with specific values calculated for each process step identified in the Life Cycle Analysis (LCA). The calculation is made by multiplying the consumption data by the corresponding emission factors to determine the greenhouse gas emissions in CO_2 equivalents. The calculated emissions are then aggregated to determine the product-specific CO_2 footprint.

3 TECHNICAL IMPLEMENTATION

Below, the focus is on the technical process for creating the PCF for the product. The focus here is on the production steps and the real-time recording of machine data in production. From this, a so-called CO_2 twin of the machine is determined in order to derive the product-specific PCF. For this purpose, the machines used are described and the relevant consumption data – such as energy, cooling lubricants, material and compressed air – is recorded with the help of sensors. In addition, estimates of machine wear, tool use and water consumption are made.

The collected data is processed, stored and visualized using open source software (OSS). On this basis, the specific consumption of the product is derived, including both reference runs and estimates. Finally, the consumption data is processed in a calculation tool in order to calculate the product-related greenhouse gas emissions with the help of the emission factors.

3.1 Machine Carbon Footprint

The CO_2 twin of a machine includes all CO_2 equivalents that are generated in connection with the machine. The focus is on dynamic consumables such as energy, coolants and compressed air, while also taking into account static values, such as emissions from the machine's manufacture. To this end, a large amount of data relating to the machine is recorded and supplemented with estimates and assumptions. The recorded data is processed, stored and then visualized so that real-time monitoring is possible.

The consumption data is measured and calculated directly as CO_2 equivalents. This allows an efficient derivation of the PCF by analyzing the machine carbon footprint (MCF), as well as by reference runs. At the same time, the CO_2 consumption of the respective machine is monitored in real time, see Fig. 5 below.
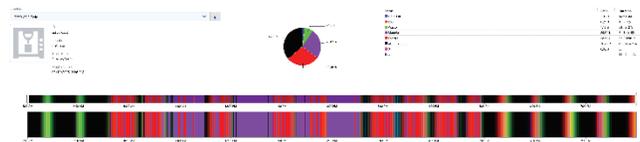
Figure 5 Machine carbon footprint as a CO_2 twin in the cloud.

3.2 Data acquisition and sensor technology

For the real-time monitoring of consumption during the production steps, a machining center from Chiron and Grob is used. Both machines are equipped with various sensors that record electricity, compressed air, cooling lubricant and the material used. The collected data is processed, stored and then visualized on various platforms.

Current measurement is carried out via three-phase current clamps of the Shelly brand. These are mainly used in the home automation sector on photovoltaic systems. The implementation is machine-independent and cost-effective. These sensors record the entire electrical load of the

machines directly at the power supply. All three phases of the machine are recorded and approved.

Flow sensors from Emerson are used for compressed air monitoring. These sensors work on the basis of a hot-wire anemometer, which measures the flow based on the temperature difference of a heated wire.

The coolant consumption is recorded by a specially developed monitoring system, which monitors the level of the coolant tank as well as the temperature and pH value. The measured values are recorded by temperature sensors, an ultrasonic sensor and a pH sensor and merged and forwarded on an ESP32 microcontroller.

The material consumption is recorded on an order-related basis via a smart scale. Here, the blank is weighed before and after machining to determine the exact amount of material consumed. For this purpose, the material used is specified in order to correctly allocate the consumption and determine the amount of chip waste.

Water consumption is not yet measured directly. Instead, an estimate based on the weekly refill quantity is used and calculated down to the measurement period so that the estimated values can be transmitted in accordance with the real consumption data.

The CO$_2$ emissions caused by the production of the machines are treated in a similar way. An assumed, fictitious CO$_2$ value for machine manufacturing is broken down in time on the basis of the depreciation tables (AfA) and taken into account on a pro rata basis. An estimate for tool wear is also made. Here, the average service life of the tools is used as a guideline to determine the approximate material consumption. However, since the tools are only used sporadically in the production process, this component is not further considered in the present analysis.

All sensors, scales and monitors are able to send their collected data to an MQTT broker at an individually definable interval. This structures the information from the various sensors under the respective topics and makes it available for further processing. The machine data as well as current values are sent to the database every second. The flow of compressed air is sent every 100 ms.

3.3 Data Processing

The collected data from the machines is sent in real time to a central MQTT broker via the MQTT protocol. The broker is managed by a Node-Red instance installed on an industrial PC (IPC). Node-Red acts as an interface for data processing. The incoming sensor data is sorted in Node-Red according to its respective MQTT topics and merged into a message object and stored. In this step, the recorded consumption is retrieved every 10 seconds to ensure a uniform and precise database. In addition, the CO$_2$ equivalents for the measured consumption are calculated here by applying the appropriate emission factors to the data and adding them to the news object as further information.

The message object is then sent to an InfluxDB database that is also installed on the IPC. InfluxDB is an open-source database optimized specifically for time series data, which makes it possible to efficiently store and manage large amounts of continuously incoming data. The data is stored in so-called "buckets" (similar to databases) and structured in "measurements" (similar to tables). Within the measurements, the data points are displayed in "Fields" (columns) [12]. In addition, data points are tagged with "properties" so that later filtering and analysis according to certain criteria is possible.

3.4 Data Visualization

For an initial visualization of the collected and processed data, the InfluxDB UI offers an integrated query builder. This makes it possible to perform data queries without in-depth knowledge of the Flux query language, which means that the database can be understood as a low-code solution. In this way, relevant consumption and CO$_2$ data can be clearly displayed and further processed in order to gain deeper insights into machine performance and machine-related CO$_2$ consumption.

Another visualization of the collected machine data is done with the help of the open source software Grafana, which enables a flexible and customizable display. Grafana supports the integration of a wide range of data sources, including InfluxDB, and provides a user-friendly interface to present the stored data in a clear and interactive way. Once the InfluxDB database is linked to Grafana, the data can be visualized in the form of graphs and dashboards.

Visualization is done via Flux queries that access the data stored in the InfluxDB. This allows each graph to be individually designed and adapted to show various consumption parameters and CO$_2$ emissions in real time. In addition, the use of variables within the dashboard allows for flexible adjustment, for example to visualize the consumption data of different machines.

Another feature of Grafana is the ability to integrate thresholds and KPIs (Key Performance Indicators) directly into the visualizations. In this way, critical thresholds or targets can be clearly displayed in the dashboards. This not only enables real-time monitoring of machine data, but also the immediate identification of inefficient processes or exceeded consumption limits to ensure proactive process optimization.

In addition, the consumption data is forwarded to a cloud of the company Grob, so that in addition to the information from the machine, the consumption data of the resources but also the CO$_2$ are visualized.

3.5 Determination of the PCF

To determine the PCF, the recorded consumption values are now retrieved from the database. For this purpose, it is necessary to know the exact time of production and to carry out reference runs for the individual processing steps. For product-related tracking, consecutive product numbers must be carried in addition to consumption, so that a clear assignment is possible. For the entire PCF, the data is divided into two categories: static and dynamic values.

Static values are emission data that cannot be influenced by the production process itself. They refer to all emissions

that occur before and after the actual production, such as through raw material extraction, transport and disposal. In order to enable a precise accounting of these emissions, a detailed research of the corresponding emission factors is required. These factors, such as those stored in databases such as ProBas, must be applied to the real reference masses and transport routes. An example of this is the calculation of the CO_2 equivalent for the aluminum used to manufacture the product. Based on the weight of the product, the specific CO_2 equivalent for aluminium production is determined by converting the weight of the product to the reference value of the emission factors (usually per tonne) and multiplying it by the corresponding factor.

Dynamic values are real-time measurement data collected and can be assigned directly to the respective processing steps. This data is determined either by reference runs or by measuring individual manufacturing processes. Therefore, there are two approaches to incorporate the dynamic data into the PCF of the product: Either the production of a single product takes place in each process step and the corresponding consumption is directly assigned, or a larger number of dispensers is produced from a material batch and the consumption is distributed among the manufactured units.

For the final determination of the CO_2 equivalents, all determined consumption data, estimates and assumptions are collected and offset against the respective emission factors. For an initial assessment of the PCF, it is sufficient to implement it in Excel or another suitable spreadsheet tool. Another possibility of implementation is in the open source software "openLCA". This enables a process-oriented recording and collection of all emissions with the help of stored databases.

Finally, all recorded, estimated and assumed consumption values are summed up to calculate the total PCF of the dispenser. The PCF thus represents a comprehensive representation of the emissions that occur over the entire life cycle of the product.

3.6 Evaluation

The CO_2 footprint of the product over the entire life cycle is about 4.5 kg CO_2. This is roughly equivalent to the volume of 2,400 milk cartons filled with CO_2 [13]. From this initial estimate, the main sources of emissions are the extraction and production of the aluminium used, which accounts for 51% of the total, and the production of the dispenser itself, which accounts for about 27% of emissions. The remaining 22% is divided between transport, use and recycling of the product. When looking at production, it can be seen that electricity consumption accounts for 55% and compressed air for 44% of the carbon footprint. The calculation results are summarized in Fig. 6.

The example of the product shows that the greatest savings potential lies primarily in the choice of raw materials and production. In production, the shares make it clear that optimizing energy use is a key lever for reducing the CO_2 footprint. By using sustainably generated electricity, 19% of emissions are saved, as this electricity usually has an

emission factor of zero. However, the much greater influence on the CO_2 footprint is the choice of raw material. The use of recycled aluminium significantly reduces the footprint, as recycled aluminium requires only about 5% of the energy required compared to primary production [14]. This, in turn, leads to a reduction in the overall footprint of up to 38%.
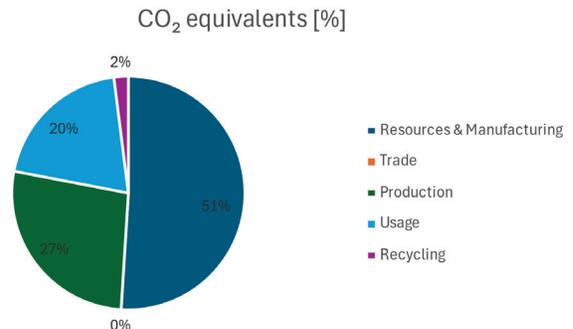

Figure 6 Percentage distribution of emissions by life cycle

These results show that a shift to greener materials and energy sources can have a significant impact on reducing the carbon footprint and provides a basis for strategic decisions to reduce greenhouse gas emissions.

4 CONCLUSION

In the context of this paper, a Product Carbon Footprint was created for an example product. First, the regulatory requirements and framework conditions were examined and a methodology for the systematic preparation of the PCF was developed. This was followed by an initial life cycle analysis, in which all phases of the product life cycle were analysed and supplemented by a process step analysis. Both process data and well-founded estimates were included in the evaluation. A central aspect was the implementation of a CO_2 twin of the machine. With the help of sensors, consumption such as electricity, compressed air, cooling lubricants and materials were monitored in real time in order to record, store and visualize the CO_2 consumption of the machines in detail. This data forms the basis for the precise determination of the production-specific CO_2 footprint of the product.

The aim of this work and the machine carbon footprint was to show how the PCF can be integrated into existing production environments in a cost-effective way. This data can be used to identify optimization potential in order to take targeted measures to reduce the CO_2 footprint.

In addition to improving resource efficiency, the PCF supports companies in preparing for future regulatory requirements at an early stage, so that the data contributes to the long-term optimization of the company's environmental balance. Another advantage of the determined production data is the increased transparency within production. They serve as a basic building block for estimating the possible CO_2 emissions even before production begins. Companies are thus able to choose production processes with regard to lower CO_2 emissions or to design them in such a way that resources are used more efficiently and that they implement targeted measures to reduce emissions and reduce costs. In

this context, it is necessary to examine the influence of a reduction, e.g. of the KSS on product quality as well as the PCF. This work thus promotes continuous improvement of production processes and contributes to more sustainable production.

5 REFERENCES

[1] "Greenhouse gas emissions by sector in Germany 2023", Statista. Accessed: December 18, 2024. Available at: https://de.statista.com/statistik/daten/studie/1241046/umfrage/treibhausgasemissionen-in-deutschland-nach-sektor/ (in German)

[2] Wilke, S. (2024). *Indicator: Greenhouse Gas Emissions from Industry*. Federal Environment Agency. Accessed: December 18, 2024. Available at: https://www.umweltbundesamt.de/daten/umweltindikatoren/indikator-treibhausgas-emissionen-der-industrie (in German)

[3] Schroedter, F. (2023). *The Impact of CSRD on Companies: A Comprehensive Overview*. Engel & Zimmermann. Accessed: August 23, 2024. Available at: https://engel-zimmermann.de/blog/die-auswirkungen-der-csrd-auf-unternehmen/ (in German)

[4] *Carbon Footprint - IZU*. Accessed: October 1, 2024. Available at: https://www.umweltpakt.bayern.de/energie_klima/fachwissen/279/carbon-footprint (in German)

[5] Gacs, J. (2024). *What is a PCF? | How companies use the Product Carbon Footprint*. Green Vision Solutions GmbH. Accessed: February 4, 2025. Available at: https://greenvisionsolutions.de/blog-product-carbon-footprint/ (in German)

[6] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), ed. (2010). *Product-related climate protection strategies Product Carbon Footprint verstehen und nutzen*. Available at: https://bdi.eu/media/presse/publikationen/PCF-Leitfaden_100810_Online.pdf (in German)

[7] *Greenhouse gas protocol: product life cycle accounting and reporting standard*. Washington, DC, Geneva, Switzerland: World Resources Institute; World Business Council for Sustainable Development, 2011.

[8] *"life cycle assessment"*. European Environment Agency. Accessed: October 2, 2024. Available at: https://www.eea.europa.eu/help/glossary/eea-glossary/life-cycle-assessment

[9] ghgprotocol.org, ed. (2011). *QUANTIFYING THE GREENHOUSE GAS EMISSIONS OF PRODUCTS PAS 2050 & the GHG Protocol Product Standard*. Available at: https://ghgprotocol.org/sites/default/files/ghgp/standards_supporting/GHG%20Protocol%20PAS%202050%20Factsheet.pdf

[10] Ullrich, A. & Gronau, N. (2021). Norms for the Calculation of the CO₂ Footprint. *Ind. 40 Manag., 2021*(4), 17-20. https://doi.org/10.30844/I40M_21-4_S17-20

[11] Pandey, D., Agrawal, M. & Pandey, J. S. (2011). Carbon footprint: current methods of estimation", *Environ. Monit. Assess., 178*(1-4), 135-160. https://doi.org/10.1007/s10661-010-1678-y

[12] *InfluxDB key concepts | InfluxDB OSS v1 Documentation*. (2015). Accessed: February 4, 2025. Available at: https://docs.influxdata.com/influxdb/v1/concepts/key_concepts/

[13] *What kind of volume does CO₂ actually have?* Accessed: October 16, 2024. Available at: https://www.gasag.de/magazin/nachhaltigkeit/CO₂-volume/

[14] Frischenschlager, H. et al. (2010). *Klimarelevanz Ausgewählter Recycling-Prozesse in Österreich*. umweltbundesamt. https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0303.pdf (in German)

Authors' contacts:

Henning Strauß, Prof. Dr.-Ing.
(Corresponding author)
Kiel University of Applied Sciences,
CIMTT Kiel University of Applied Sciences,
Schwentinestraße 13, 24149 Kiel, Germany
henning.strauss@fh-kiel.de

Julian Sasse, M. Eng.
EDIH-SH, CIMTT FH Kiel
Schwentinestraße 24, 24149 Kiel, Germany
julian.sasse@fh-kiel.de