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Energy-efficient Supply Chain Design: Data Aggregation and Processing

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Purpose: Due to changing customer requirements and political regulations more and more companies strive to optimize their energy efficiency in regards to products and processes. The optimization of processes within supply chain design (SCD) is one lever in this regard. Since required data is often not available, this paper elaborates how data can be generated on a suitable level of aggregation.

Methodology: In order to highlight the research gap, established energy measurement procedures as well as existing energy databases for procurement, production and transportation are analyzed and compared with data requirements for SCD tasks. Based on these findings, necessary methods and procedures for data preparation are presented.

Findings: Firstly, it is shown that addressing energy efficiency within SCD leads to new challenges in regards to data availability and preparation. Secondly, this paper elaborates the requirements for necessary data usable in the context of SCD. The findings are the basis for a comprehensive approach combining collection, aggregation and clustering of energy and product related data.

Originality: This paper works out the gap between usually available energy related information and the requirements of SCD. Since key conditions for optimizing energy efficiency are defined in strategic planning, the findings create a necessary prerequisite for realizing energy-optimized supply chains on a large scale in the future.

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1 Introduction

Energy and raw materials form the basis for the producing economy as well as for a consuming society. The competitiveness of manufacturing companies is therefore always closely linked to the availability of and demand for energy and raw materials. Decreasing reserves of fossil fuels, a globally increasing energy demand and a likewise strongly growing global demand for fossil and renewable raw materials are therefore leading to many challenges for companies. In recent years, companies have begun to rethink their way of business and ecological goals are increasingly being anchored in corporate strategies (Bidgoli 2010). Companies are not only concerned with the energy efficiency of the goods to be produced, but also with the energy efficiency potential of their value-adding activities in production and logistics. The relevance for including the energy aspect in this regard is illustrated by the following number: The production and transport sectors together account for 58% of final energy consumption in Germany (BMWi 2018). Potentials for energy savings are seen primarily in industrial processes that require process heat and mechanical energy, and in the area of freight transport.

Since the essential conditions for the later operation of a production and logistics network are defined within strategic planning, the so-called supply chain design (SCD), the greatest levers for reducing the required energy demand can be expected in these activities. The tasks of SCD include the determination of the production and logistics strategy, the choice of locations, volume allocation as well as the selection of modes of transport (Parlings et al. 2013). The quality of the specifications made in this regard mainly determines energy demand and costs for the products to be produced and transported in the supply chain. Thus, the possibility of being able to evaluate the energy effects of planning decisions in this area is a central prerequisite for being able to influence the overall energy footprint of a product at all.

Right now, companies normally use methods and tools based on Life Cycle Assessment (LCA), which is regulated in the ISO standard 14040 (Principles and Framework) and 14044 (Requirements and Guidelines), to describe the environmental impacts of the entire life cycle of production systems and services in detail (ISO 14040; ISO 14044). LCA studies are valuable but often not practicable as a regular data source for SCD due to their complexity. Over the past decade, initial research and development work has already taken place in the field of ecological assessment of production and logistics processes (see Cirullies et al. 2011; Bretzke 2014a; Lochmahr and Boppert 2014). However, the results achieved in this field are only being used to a limited extent in practice. The reasons for this are manifold and range from the lack of availability of relevant energy data to the lack of manageable models, methods and tools for the energetic evaluation of production and logistics networks. The aim of this paper is to present a solution approach to the challenge of energy-related data availability in strategic planning.

The availability of directly usable energy-related data is a crucial research aspect, as cost and energy do not have a 1:1 relation in their measurand. However, the availability of usable energy data is mandatory, as the implementation of an energy-efficient SCD aims to point out the positive and negative correlations of energy efficiency and cost minimization in the form of corresponding trade-off solutions (Bretzke 2014b). To begin with, the following chapter will show data requirements from a SCD perspective. In Chapter 3, these findings are compared with existing methods of energy measurement and with information from commercial or publicly accessible energy databases. On this basis, an approach for bridging the identified gap between energy-related data requirements and data availability in SCD is shown in Chapter 4. The paper concludes with an outlook on the existing challenges and further steps to finalize the approach.

2 Suitable Level of Aggregation for Supply Chain Design

This chapter aims to point out the necessary data requirements and data granularities for methodologically approaching SCD tasks. SCD consists of several individual design tasks, which influence each other mutually. Experiences from practice and literature show, that there is only a rudimentary consideration of these interactions, since individual planning approaches for the design tasks are integrated isolated from one another (Parlings et al. 2015). For each application area, different analytical and simulative approaches have been considered already, which can be applied as logistics assistance systems for the individual design tasks. If these methods are applied with the aim of improving energy efficiency, special energy measurement procedures are required to gather input data for the underlying target system. However, as the measurement methods do not gather energy related data which can be processed subsequently, further intermediate approaches have to be developed. The first challenge in designing an energy-efficient supply chain is thus to address the individual design tasks in combination and simultaneously detect the resulting dynamic interdependencies in production and logistics processes. The second challenge derives from the requirement to be able to use gathered energy data within the methodological approaches. Considering different measurement procedures with unsuitable data structures as an outcome create special demands on the integration capability of a planning methodology for energy efficient supply chains.

In previous research approaches it was outlined that a combination of analytical optimization methods and event-discrete simulation promises a

high quality of results. A feasible way of solving this problem is the modularization of related SCD tasks, which generate partial solutions for individual task modules independently of each other using various analytical models. The SCD tasks can be divided into the areas of procurement, production and distribution. In a sequential feedback-based procedure, these partial solutions are evaluated by an event-discrete simulation, considering the interdependencies of the generated parameter configurations (Schreiber 2019).
In the course of the conception of the models, it was observed that the input parameters in classical SCD require specific forms of data aggregation in order to configure the models appropriately and to generate useful solutions. Since the integrated target values in the models in the literature are mostly cost-driven, a data analogy on the same level of aggregation is required to accomplish a transfer towards an energy-efficient SCD. For this purpose, an analysis of the cost-related input data used in the literature is provided to identify the required aggregation levels of the energy indicators to be included.

2.1 Procurement

In the area of procurement, the design tasks of partner selection and the sourcing process design are to be addressed particularly. Typical approaches often originate from the descriptive decision theory (Analytic Hierarchy Process, Promethee) or combine them with linear optimization.
Hruška et al. (2014) propose an approach based on the Analytical Hierarchy Process (AHP), Jain et al. (2018) add an Fuzzy component to the AHP and combine it with the Technique for Order Preference by Similarity to Ideal

Solution (TOPSIS). Furthermore the so called PROMETHEE method is used commonly (see Abdullah et al. 2019). Torğul and Paksoy (2019) combine approaches from the descriptive decision theory with linear optimization. From the given literature sources, as well as from operational experience, it appears that the following cost-related data granularity must be available for the appropriate use of these models. A differentiation is necessary to identify the current processing stage of the part to be procured. In the case of raw materials, the price per kilogram is usually decisive, whereas the price per piece is usually relevant for semi-finished products. The following common cost-related data granularities can be listed as follows:

- Order cost for one kilogram of raw material *p* from supplier *s* ($\left[\frac{€}{kg}\right]_p^s$)
- Order cost for one piece of a semi-finished product *p* from supplier *s* ($\left[\frac{€}{pc.}\right]_p^s$)

2.2 Production

The production branch in SCD is primarily relevant for the allocation of available capacities. The production and storage capacities of the production network must be used cost-optimally. Due to different machine parks and location conditions, the resulting operating costs can vary depending on the allocation within the network. The common problem-solving tools from the respective literature are linear optimization models. In mathematical modelling, the decision variables represent the production quantities of individual products, semi-finished products and raw materials at the different function areas at nodes of the network with respective destinations. Thus, the allocation of goods to the locations in the network is determined (see Tsao et al. 2018; Serdar and Al-Ashhab 2017; Sabri and Beamon 2000).

The identified models tend to integrate the transport costs in addition to the production costs. These are examined separately in the following section. The required cost-related data granularities of the production side in SCD are as follows:

-Variable production costs at function area f at production site i for product p $\left(\left[\frac{€}{pc.}\right]_{f,p}^{i}\right)$

- Fixed production costs at function area f of production site i per period $\left([\frac{€}{period}]_{f}^{i}\right)$

2.3 Transportation and Warehousing

The last relevant module to be considered is transport and warehousing. As already mentioned in the previous section, this area includes generic SCD optimization models which, in addition to transportation and warehousing, also address other relevant fields of SCD (see Lee et al. 2018; Zokaee et al. 2017; Paksoy et al. 2019). In addition, there are specific models which relate mainly to the improvement of transport and storage costs. In this context, the different types of vehicle routing problems or models focusing on the optimization of cross-docks or warehouses should be mentioned (see Lashine et al. 2006, Goodarzi and Zegordi 2016, Perboli et al. 2011). On the one hand, the relevant components of the input data are distance-related data and information on the transport type. Depending on the properties of the product (e. g. base unit) and the selected transport mechanism (e. g. container), a distinction is necessary, as the costs vary in this regard. On the other hand, similar to production, the operation of warehouses and the individual storage of products will lead to costs. The required input data granularities are as follows:

- Variable costs per ton kilometer per mode of transport m and product p ($\left[\frac{€}{tkm}\right]_p^m$)
- Variable costs per container per product *p* and mode of transport *m* ($\left[\frac{€}{TEU\ km}\right]_p^m$)
- Variable warehousing costs at function area f of product p at warehousing site *i* ($[\frac{€}{pc.}]_{f,p}^i$)
- Fixed warehousing costs at function area f of warehousing site i per period ($[\frac{€}{period}]_f^i$)

As the necessary cost-related input data for SCD models with their respective data granularities have been identified for the relevant areas of procurement, production, transportation and warehousing, the following Table 1 sums up the results of this chapter. The results will be revisited to derive the desired energy-related data analogy and the outcome is compared to the given energy data structures which will be shown in chapter 3.

Table 1: Cost-related data granularities for SCD approaches

Task	Description	Unit
Procurement	Order cost for one kilogram of raw material p from supplier s	$[\frac{€}{kg}]_p^s$
	Order cost for one piece of semi-finished product p from supplier s	$[\frac{€}{pc.}]_p^s$
Production	Variable production costs at function area f at production site i for product p	$[\frac{€}{pc.}]_{f,p}^i$
	Fixed production costs at function area f of production site i per period	$[\frac{€}{period}]_f^i$
Transportation and Warehousing	Variable costs per ton kilometer per product p and mode of transport m	$[\frac{€}{tkm}]_p^m$
	Variable costs per container per product p and mode of transport m	$[\frac{€}{TEU\ km}]_p^m$
	Variable warehousing costs at function area f of product p at warehousing site i	$[\frac{€}{pc.}]_{f,p}^i$
	Fixed warehousing costs at function area f of warehousing site i per period	$[\frac{€}{period}]_f^i$

3 Existing Energy Measurement Procedures and Energy Databases

After describing suitable level of aggregation for cost-related SCD, this chapter describes existing energy measurement procedures with linkage to specific data sources. A common way to visualize the energy consumption of products and services over their life cycle is the 'Cumulative Energy Demand' (CED) (VDI-Richtlinie 4600). The CED is considered to be the total of all energy inputs concerning the consumption of primary energy and results shall be expressed in joule (*J*) or multiples thereof, e. g. megajoules (*MJ*) or gigajoules (*GJ*). The score can be used instead of or in addition to detailed LCA approaches, which often take a wide range of impact or damage categories into consideration (see Kaltschmitt and Schebek 2015; Huijbregts et al. 2016; VDI-Richtlinie 4600).

In practice, the CED is subdivided into three phases: production, use and disposal.

$$CED = CED_P + CED_U + CED_D$$

As the phases use and disposal are normally not within the scope of SCD, this paper focusses on the production phase of CED with the mentioned transformation and distribution processes: procurement, production and transportation. In general, calculating the CED is a combination of different approaches covering primary or measured data, generic datasets or scientific estimations. Hence, there are always trade-offs between suitability of data concerning data accuracy and significance for energy-related SCD and data gathering expenditure necessary.

3.1 Procurement

As companies are not only concerned with the energy efficiency of the goods to be produced, but also with the overall sustainability of their products and actions, especially when sourcing input materials globally, the ISO standard 20400 'Sustainable Procurement' assists organizations in meeting their sustainability responsibilities (ISO 20400). The standard highlights the importance of taking energy consumption and energy efficiency as one dimension of sustainability into consideration when communicating to external stakeholders during procurement decisions.

Therefore, ISO 20400 is a valuable overarching framework for integrating the idea of energy efficiency in supply chains. But it is more a selective performance measurement of actions than a consistent energetic evaluation of procurement relationships. It also does not solve the lack of primary data.

For this, additional research and data gathering out of external data sources is necessary, e. g. Life Cycle Inventory (LCI) databases, statistical databases and literature values. In this context LCI databases serve as key data sources, because many LCI databases contain datasets about raw materials, which are sourced externally by the companies. A common LCI database for example is 'ecoinvent' (Wernet et al. 2016).

From this LCI datasets it is possible to calculate the CED, which was introduced at the beginning of this chapter. The primary energy used up to this point, e. g. for the mining, smelting and refining of a metal, can be derived. Some LCI databases also include datasets to identify the CED country- or region-specification for raw materials. This geographical coverage of different datasets for raw materials are of high interest for procurement decisions e. g. comparing a great number of suppliers in various regions for various raw materials. Hence, it is possible to calculate the region-specific (r) energy consumption for raw materials $[\frac{J}{kg}]_p^r$ or semi-finished products $[\frac{J}{pc.}]_p$. The challenge is that the origin and the suppliers of raw materials or the composition of (semi-finished) products are often not known or very vague.

Summing up, due to a lack of primary data in procurement, generic datasets are useful to describe transformation processes from an energetic perspective. Nevertheless, the connection between material related or region-specific energy information and logistics information for strategic network design to calculate the specific energy efficiency potential of procurement decisions is still missing.

3.2 Production

When considering energetic efforts of production sites in SCD, LCI databases also provide average datasets for branch-specific production processes. But these datasets are normally highly aggregated. Deriving the CED gives a first indication of the process energy consumption, but it is not suitable for deriving company specific energetic network decisions on that basis.

For this, it is necessary to gather more detailed information of the companies' network and production characteristics. While the European Energy Efficiency Directive requires the reporting of annual energy consumptions and the definition of energy saving measures (EED 2012/27/EU), the data collected in this way is not directly suitable for SCD. For example, smart metering systems are often obligatory when reaching higher annual electricity consumptions, e. g. >6.000 kWh in Germany (MsbG). But the challenge is, that usually only the global (g) consumption of the production site is measured and known $[\frac{J}{period}]_g^i$. Sometimes this is completed with energy consumption information or energy efficiency measures of single equipment in production facilities. Nevertheless, reliable data for production sites with their related function areas are missing to allocate the energy consumption to the following categories:

- Output independent base load (e. g. lighting)
- Output dependent load (e. g. sawing)
- Output independent additional load (e. g. pre-heating)

Summing up, due to a lack of primary data and data connection, product related energy indicators such as energy consumption per product $[\frac{J}{pc.}]_p^i$ and energy consumption per function area $[\frac{J}{period}]_f^i$ are missing for methodological approaches towards an energy-efficient SCD.

3.3 Transportation and Warehousing

After considering energy-related data gathering for procurement and production, the phase of transportation and warehousing is described from an energy-related perspective. Companies are able to derive primary data out of their transport management or warehouse management systems. For further processing, the Global Logistics Emission Council (GLEC) provides a globally harmonized framework with emission resp. energy consumption calculation methodologies for the transport modes air, inland waterways, rail, road and sea plus logistics sites (Smart Fright Centre 2019). For the transport mode 'road', GLEC refers to the European standard DIN EN 16258, which provides a methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers) (DIN EN 16258). For 'logistics site' it refers to the „Guide for Greenhouse Gas Emissions Accounting for Logistics Sites“, which gives additional information for the calculation of energy consumption and emissions at logistics sites (Dobers et al. 2019).

When primary data is not available, default values from public sources or other databases can be looked up. For example, the 'Handbook Emission Factors for Road Transport (HBEFA)' provides emission factors as well as fuel / energy consumption for all prominent vehicle categories, considering also different traffic situations (Notter et al. 2019).

Summing up, the energetic evaluation of transport is challenging, but by knowing a handful of characteristics it is possible to methodologically integrate respective data with variable energy consumption for transportation of general freight $[\frac{J}{tkm}]_p^m$ or container freight $[\frac{J}{TEU\ km}]_p^m$, while the allocation of the known global energy consumption of logistics sites $[\frac{J}{period}]_g^i$ can be more sophisticated.

Table 2 summarizes the given energy-related data granularities for SCD for the tasks procurement, production as well as transportation and warehousing.

Table 2: Given energy-related data granularities for SCD

Task	Description	Unit
Procurement	Energy consumption for one kilogram of raw material p from region r	$[\frac{J}{kg}]_p^r$
	Energy consumption for one average piece of semi-finished product p	$[\frac{J}{pc.}]_p$
Production	Global g energy consumption at production site i per period	$[\frac{J}{period}]_g^i$
Transportation and Warehousing	Variable energy consumption for transportation per ton kilometer	$[\frac{J}{tkm}]_p^m$
	Variable energy consumption for container transportation	$[\frac{J}{TEU\ km}]_p^m$
	Global g energy consumption at logistics site i per period	$[\frac{J}{period}]_g^i$

4 Data Gaps and approaches for bridging the gap

After describing the data granularity in cost-related SCD and the availability of energy-related data, Chapter 4 discusses the gaps between these two perspectives and suggests approaches for bridging the gaps in the phases of procurement, production and transportation and warehousing.

For the procurement of raw materials generic LCI datasets are useful to describe transformation processes from an energetic perspective. The datasets are available for different materials and processing stages for geographic regions and can be matched with the location of (potential) suppliers and additional information resulting from a structured 'supplier survey'. Then, the connection between material related and region specific energy information and logistics information (distribution processes) to derive the suppliers' CED is done with the help of a 'resource model' (Jarmer et al. 2020), considering global raw material flows.

When procuring semi-finished products, the composition is often not known, but crucial to determine the CED. On the one hand parts list could help to derive material compositions, on the other hand special material characterization, e. g. X-ray fluorescence (XRF) spectroscopy for metals, could help before using the mentioned 'resource model' for calculating the CED for semi-finished products and accordingly create an energy-related data analogy to the cost-related input data structures.

The steps for the transition from cost-related SCD-parameters to energy-related SCD-parameters for procurement are summarized in Figure 1.

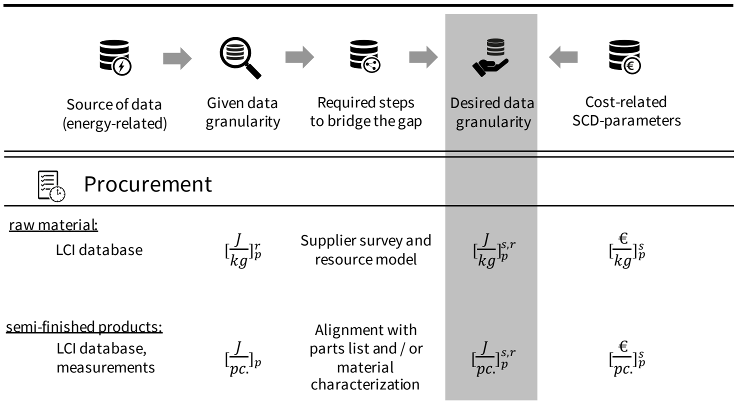

Figure 1: Bridging the data gap for procurement

To overcome the lack of primary data and data connection in the area of production to derive product related energy indicators such as energy consumption per product $[\frac{J}{pc.}]_p^i$ and energy consumption per function area $[\frac{J}{period}]_f^i$, a breakdown by function areas and equipment plus an alignment with the companies' individual production program is suggested. Keeping in mind that for a given production site i the global energy consumption is the sum of the defined function areas:

$$[\frac{J}{period}]_g^i = \sum_f^n [\frac{J}{period}]_f^i \; with \; f = 1, \dots, n$$

Analyzing the correlations and dependencies between energy consumption and the underlying production program (and possibly more parameters), serves to characterize the function areas and to integrate energy-related production data into SCD-approaches. Then, it is possible to prognosticate energy consumptions and plan the re-allocation of products to other facilities with different function areas / technologies from an energetic perspective. The steps for the transition from cost-related SCD-parameters to energy-related SCD-parameters for production are summarized in Figure 2.

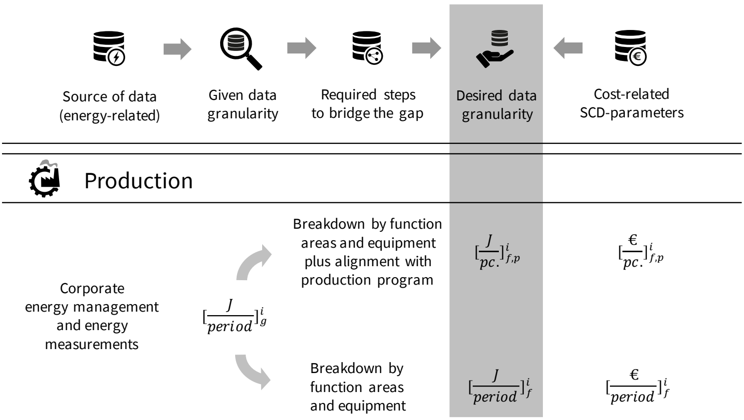

Figure 2: Bridging the data gap for production

Company specific data to characterize transport activities like distances of (potential) transport relations, (potential) tonnage or container as well as fuel consumptions are often available in the companies' transport management or corporate energy management department. On that basis, the energetic evaluation of transport is possible to derive the variable energy consumption for transportation of general freight $[\frac{J}{tkm}]_p^m$ or container freight

$[\frac{J}{TEU\ km}]_p^m$ for SCD-approaches. In order to define appropriate energetic parameters for warehousing activities, it is important to analyze the material flows within the function areas of the logistics sites (e. g. ambient or cooled areas), similar as described for production sites. When distinct data is missing, the default values of different databases, mentioned in chapter 3, are helpful. For further processing, the GLEC Framework is suggested as a guidance for the calculation and allocation of energy consumptions in transport and warehousing (Smart Fright Centre 2019).

The steps for the transition from cost-related SCD-parameters to energy-related SCD-parameters for transportation and warehousing are summarized in Figure 3.

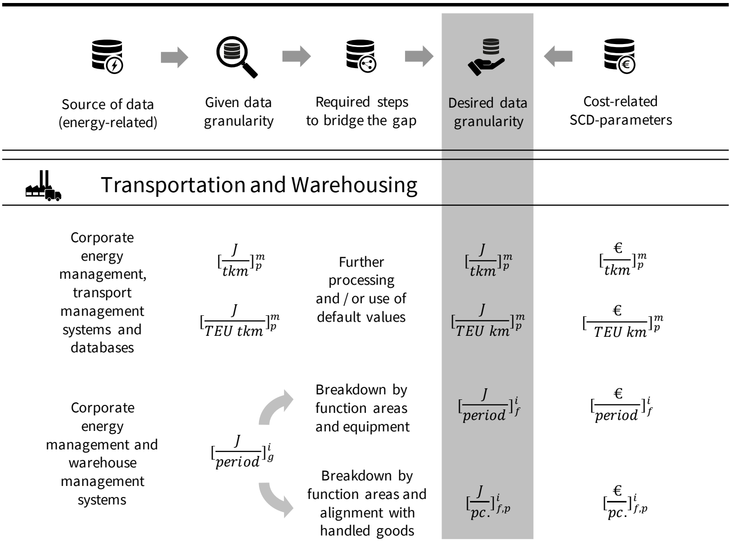

Figure 3: Bridging the data gap for transportation and warehousing

Considering the described steps, the original tasks of SCD including the determination of the production and logistics strategy, the choice of locations, volume allocation as well as the selection of modes of transport can be done from an energetic perspective.

5 Conclusion and Outlook

This paper revealed that the use of common SCD-approaches requires a considerable effort for the measurement, analysis and aggregation of energy data to enable the inclusion of energy-related target values. The creation of an energy-related data analogy to the cost-side data is essential to realize a holistic approach and to consider the component of energy efficiency in all areas of SCD.

In the area of procurement, it was found that the energy data for raw materials is available mostly region-specific. The problem is primarily due to the lack of transparency with regard to the exact origin of all components of the semi-finished product or raw material to be procured. To close the data gap, a material characterization (e. g. XRF) is proposed in order to identify the composition of the products and thus to identify the current energetic footprint already at the procurement stage. In the production area, energy data has to be gathered from the corporate energy management or measurements have to be conducted to collect raw energy data. The main problem with the non-suitability of the data is the lack of breakdown towards functional areas and individual products. Accordingly, a specific alignment analysis of measurement data and the production program must be performed in order to obtain the necessary data granularity. The area of transport is already well equipped with databases and frameworks, so that a data analogy can be created relatively easy. Similar to the area of production, warehouse energy-related data is difficult to break down into functional areas and onto specific products, which can be managed by comparing energy and stocking data.

The findings are the basis for a comprehensive approach combining collection, aggregation and clustering of energy and product-related data. The proposed data processing steps and methods will be tested and validated in further research on different use cases.

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