Environmental impact of warehousing: A scenario analysis for the United States

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Abstract: In recent years, there has been observed a continued growth of global carbon dioxide emissions, which are considered as a crucial factor for the greenhouse effect and associated with substantial environmental damages. Amongst others, logistic activities in global supply chains have become a major cause of industrial emissions and the progressing environmental pollution. Although a significant amount of logistic-related carbon dioxide emissions is caused by storage and material handling processes in warehouses, prior research mostly focused on the transport elements. The environmental impact of warehousing has received only little attention by research so far. Operating large and highly technological warehouses, however, causes a significant amount of energy consumption due to lighting, heating, cooling and air condition as well as fixed and mobile material handling equipment which induces considerable carbon dioxide emissions.
The aim of this paper is to summarize preliminary studies of warehouse-related emissions and to discuss an integrated classification scheme enabling researchers and practitioners to systematically assess the carbon footprint of the considered warehouse operations. Based on the systematic assessment approach containing emissions determinants and aggregates, overall warehouse emissions as well as several strategies for reducing the carbon footprint will be studied at the country level using empirical data of the United States. In addition, a factorial analysis of the warehouse-related carbon dioxide emissions in the United States enables the estimation of future developments and facilitates valuable insights for identifying effective mitigation strategies.

Keywords: Warehouse management; CO2 emissions; carbon footprint; environmental sustainability; scenario analysis

Introduction

Over the past twenty years, the emission of greenhouse gases (GHG) which are assumed to induce substantial environmental damages and to be a major cause of the climate change, has increased significantly due to continuously rising carbon dioxide (CO_2) production (cf. Peters et al., 2012 and Boden et al., 2013). Even though emerging countries, in particular, show a recent rise in CO_2 emissions, the major part of environmental pollution is still caused by few industrialized countries (see Figure 1). In this context, especially logistic activities such as transportation and storage of materials and finished goods which are, however, necessary to maintain economic prosperity, are considered to be an important cause of emissions and the largest single sources of environmental pollution in global supply chains (Piecyk and McKinnon, 2010). Altogether, it is estimated that between 5.5% and 13% of the global GHG emissions are caused by logistic activities in supply chains (IPCC, 2007; WEF, 2009). Out of this, the transport sector accounts for over 23% of all CO_2 emissions globally (OECD, 2010). Among them, emissions from road transport play a dominant role, with road freight accounting for up to 40% of road sector CO_2 emissions (WEF, 2009; OECD, 2010). In the United States, for example, transportation represents 27% of overall GHG emissions, with the share of CO_2 on total GHG emissions accounting about 96% (EPA, 2013). Within the transportation sector, the share of GHG emissions caused by light, medium and heavy duty road transport trucks is

40% (EPA, 2013). In a recent report, the U.S. Department of State exposed that the transport sector alone caused GHG emissions of about 1,931 Mt CO_2 equivalents (CO_2e) in 2005 and 1,765 Mt CO_2e in 2011 (note that CO_2e is used to summarize the global warming potential of a greenhouse gas and represents the equivalent amount pure of CO_2 emissions which leads to a comparable greenhouse effect, cf. Carbon Trust, 2013). Even considering possible measures to reduce emissions, this report forecasted road transport emissions of about 1,702 Mt CO_2e in 2020, and of 1,672 Mt CO_2e in 2030 (U.S. Department of State, 2014). In the European Union, in contrast, road transport causes more than two-thirds of EU transport-related GHG emissions and over one-fifth of total emissions of CO_2 (EC, 2014).

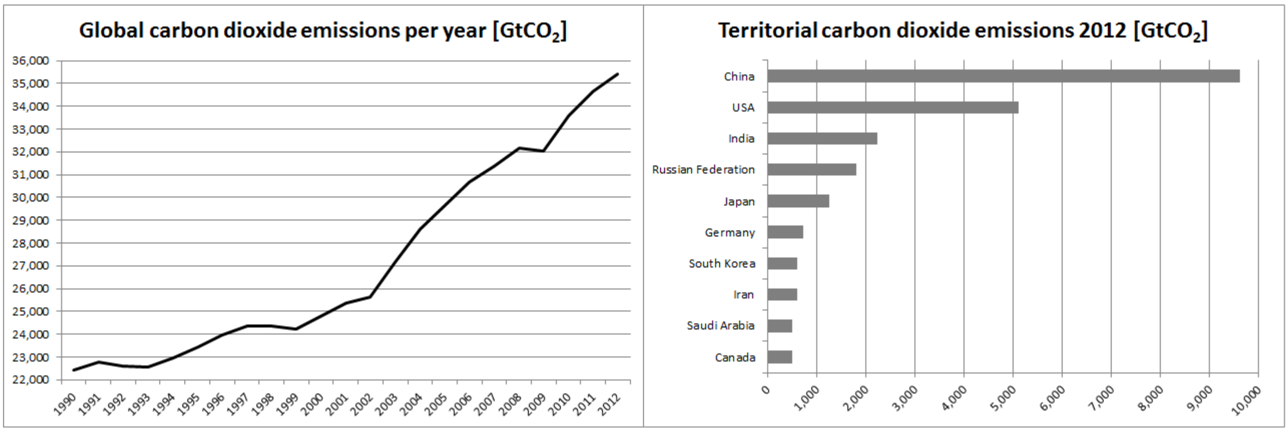

Figure 1: Development of CO_2 emissions from fossil fuels and cement production

Accordingly, a vast amount of research on the environmental impact of logistics has focussed on carbon emissions associated with transport activities (e.g., Piecyk and McKinnon, 2010; Ubeda et al, 2011). Although it was mentioned that the most promising way for companies to reduce carbon footprint of products and services is depleting emissions within their entire supply chain (EPA, 2010; Schaltegger and Burritt, 2014), other sources of logistic-related carbon dioxide emissions have mostly been ignored in previous analyses (Plambeck, 2012).

One of the most significant categories of supply chain emissions, besides transport, is warehousing including material handling in logistics buildings. The environmental impact of warehouses due to heating, cooling, lighting and material handling, however, has largely been overlooked in the literature, with only few notable exceptions (e.g., Dhooma and Baker, 2012; Fichtinger et al., 2015). Nevertheless, carbon emissions caused by material handling activities in logistics buildings, comprising warehouses and sortation facilities, are significant and account for 13% of overall supply chain emissions (WEF, 2009). In the UK, for example, it is estimated that warehouses are responsible for approximately 10.2 million tonnes of CO_2e (UKWA, 2010), while 1.5 million tonnes could easily be saved just by making simple changes (Richards, 2014; UKWA, 2010). As warehouses are an essential element in global supply chains, it is inevitable to take account of the carbon intensity of storage and handling operations for assessing full life cycle emissions of products and services (cf. Dekker et al., 2012), and for finding effective measures to decarbonise overall logistic activities to achieve a long term sustainable business practice.

The intention of this article is twofold. Firstly, a systematic literature review is conducted to assess the current state of research on environmental sustainability of warehousing and its impact on logistic-related CO_2 emissions. Secondly, based on the results of the literature review, the paper discusses a classification scheme for the systematic assessment of the environmental impact of material handling activities in warehouses. Based on the systematic assessment approach and important emission determinants such as warehouse space, inventory turns, warehouse technology, building characteristics (e.g. lighting equipment and insulation) as well as emission intensity, the article provides an outlook of the future development of warehouse emissions exemplified with empirical

data of the United States. The provided factorial analysis facilitates valuable insights for identifying effective strategies for reducing CO_2 emissions caused by warehousing activities and assists managers and researchers in measuring the footprint of warehouses and developing holistic approaches for reducing emissions from a supply chain point of view.
The remainder of this article is structured as follows: Section 2 provides a systematic overview of the literature on environmentally sustainable (green) warehouse management, whereas Section 3 discusses a classification scheme for the assessment of the environmental impact of warehousing. Section 4 provides a description of the methodology for the factorial analysis as well as relevant empirical data and parameters for the estimation of the impact of storage and material handling activities in warehouses. Section 5 presents the results of the factorial analysis and insights of several future scenarios for the United States which illustrate the magnitude of changes in warehouse-related emissions by 2025. Finally, Section 6 concludes the article and suggests promising directions for future research and managerial insights.

Literature on green warehousing

Research on sustainability in logistics and supply chain management has increased constantly in recent years (see, for example, Halldórsson and Kovács, 2010; Hassini et al., 2012; Seuring 2013; Schaltegger and Burritt, 2014). However, knowledge about the environmental impact of warehousing is limited. Thus, to analyse the consideration of warehouse activities in green supply chain management as well as the role of environmental sustainability in warehousing research, a systematic literature review is conducted in this section. The methodology is based on a systematic literature evaluation as described by Cooper (2010) and applied, e.g., by Glock and Grosse (2015) including the following steps:

(i) *Problem definition*: The search aimed at works that study the environmental impact of warehousing activities from a managerial point of view.

(ii) *Selection of keywords*: Keywords are defined in two groups that A) describe the logistics facility (i.e. warehouse, warehousing, storehouse, storing facility, storage building, logistics building, automated warehouses, storage and retrieval systems) or B) are related to the environmental performance dimension (i.e. green, environmental, sustainable, emission, carbon dioxide, greenhouse gas, energy efficiency).

(iii) *Literature search*: Two scientific databases, namely Business Source Premier and Scopus are used to search for relevant articles using the keywords defined above. At least one keyword from group A has to be combined with one keyword from group B in either title, abstract or list of keywords. The document type is set to peer-reviewed journal articles in the subject area of business management and the language is limited to English for any year of publication.

(iv) *Inclusion criteria*: Works are considered as relevant if they focus on energy usage and/or related emissions caused by warehousing and material handling activities in warehouses.

(v) *Critical screening and evaluation*: Our search led to 663 initial hits in Scopus and 423 initial hits in Business Source Premier. After a first check for relevance by title and abstract as well as deleting all duplicates, the initial sample contained 27 works. The papers contained in the initial sample were completely read by all authors to consider their relevance. In this step, 10 papers were excluded from further analysis, which led to 17 relevant papers. Finally, in a backward search, the reference lists of the papers contained in the initial sample were checked to find additional works that could be relevant to the topic of sustainable warehousing. This approach led to 2 additional papers and a final sample of 19 works.

(vi) *Descriptive analysis*: The systematic search of the literature revealed that managerial research on warehouse-related emissions and especially on the operational drivers of emissions is scarce. However, as can be seen in Figure 2, research on environmental issues in warehousing has started to grow distinctly in recent years, with 9 out of 19 publications being from in 2015. Journals that published the most articles are the *International Journal of Production*

Economics (3), the *International Journal of Production Research* (2), the *International Journal of Logistics Research and Applications* (2) and *Production Planning & Control* (2).

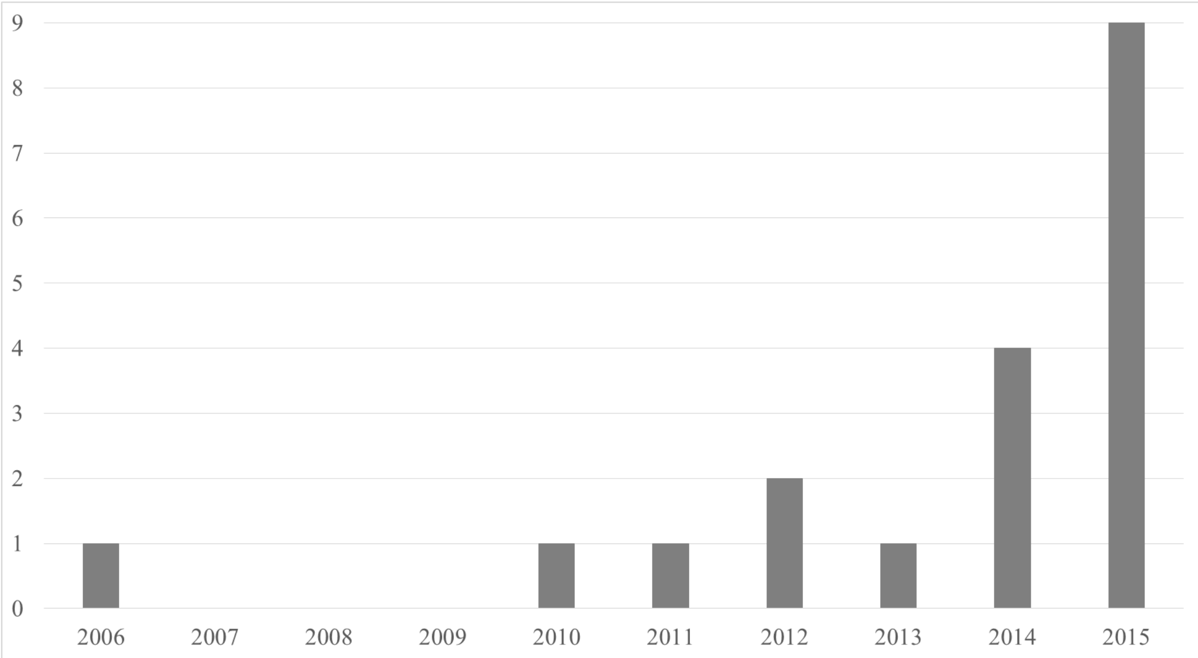

Figure 2: Number of papers published per year dealing with environmental issues in warehousing

In addition to the descriptive evaluation of the relevant literature, a content-related analysis reveals that all relevant works either focus on green supply chain management or deal with the energy/emissions impact of automated storage systems and merely neglect general warehouse-related emissions. For closing this gap in assessing overall carbon dioxide emissions in supply chains, research on the environmental impact (CO_2 footprint) of warehousing and the operational drivers of emissions caused by warehouse activities is essential. The focus and the content of the articles found in the systematic literature review is summarized as in Table 1.

Authors	Focus	Content
Ala-Arja and Helo (2014)	Green SCM in food industry	Presents a case study on emissions of order-picking, transportation, warehousing and distribution processes in three food industry companies. Possible supply chain decisions and their impact on operational efficiency and related emissions are discussed.
Carrano et al. (2015)	Emissions impact of pallet management	Studies an environmental analysis of wood pallets` lifecycle used for storing and shipping goods within a supply chain by comparing three different pallet management strategies. An appropriate pallet management is proposed as a managerial tool to reduce the carbon footprint of distribution operations.
Dadhich et al. (2015)	Green SCM in construction industry	Evaluates potential strategies to reduce emissions in supply chains exemplified for the UK construction industry employing a case study. Emissions caused by transport of goods inside warehouses and warehouse utilities are included in the analysis. Implementing cross-docking principles is proposed as an opportunity to reduce warehousing emissions.
Dekker et al. (2012)	Green logistics in OR literature	Reviews works related to logistics and SCM that deal with environmental sustainability issues in OR. In this review, warehouses are included as major components of supply chains.

		Reducing warehouse-related emissions is highlighted as an important opportunity to decarbonize supply chains.
Dhooma and Baker (2012)	Energy usage in warehouses	Presents a case study on the energy usage by warehousing end-use consumption types (i.e. lighting, equipment, heating, plug loads) in four different warehouses. It is concluded that most energy could be saved in warehouses in the categories lighting and heating/ventilation.
Fahimnia et al. (2015)	Green SCM	Presents a mathematical model for green supply chain management considering warehouse energy usage and related emissions based on case study data. Electricity is regarded as the sole energy source in the warehouse.
Fekete et al. (2014)	Energy usage in material handling	Proposes an approach for energy monitoring in material handling processes considering technological, organisational and economic perspectives that can be sued for the collection of energy data in warehouses.
Fichtinger et al. (2015)	Integrated green inventory and warehouse management	Presents a framework for the assessment of warehouse emissions in an integrated model for warehouse and inventory planning. Using simulation, warehouse emissions by end-use category for three different warehouse types and sourcing scenarios are derived.
Lerher et al. (2014)	Sustainable automated warehousing	Proposes and discusses an energy efficiency model for mini-load AS/RS. The model considers throughput capacity, required engine power, energy consumption and related CO_2 emissions. It is concluded that energy consumption and CO_2 emissions increase with increasing velocity of the AS/RS.
Makris et al. (2006)	Energy-efficient order picking	Studies the trade-off between travel time and energy consumption in an order picking routing model. It is concluded that energy savings can be obtained by changing the sequence of item retrieval.
Meneghetti et al. (2015a)	Sustainable automated warehousing	Develops a decision support model for the design of automated storage and retrieval systems (AS/RS) considering the energy consumption and related emissions of crane movements.
Meneghetti et al. (2015b)	Sustainable automated warehousing	Develops an optimisation model to find the best storage assignment in AS/RS taking into account both retrieval time and energy requirement simultaneously. The model is used to evaluate the energy savings connected with different rack shapes considering energy recovery.
Meneghetti and Monti (2015)	Sustainable automated warehousing	Develops an optimisation model for the design of AS/RS in cold-storage taking into account investment and operating costs, energy usage and emissions. Relevant energy data is taken from a reference case.
Meneghetti and Monti (2014)	Sustainable automated warehousing	Analyses dedicated, class-based, and random storage policies in automated warehouses with regard to energy usage of unit load movements considering different demand patterns and rack shapes. A dynamic storage policy is proposed that outperforms other policies in terms of energy consumption and time performance.
Meneghetti and Monti (2013)	Sustainable automated warehousing	Proposes a model to evaluate the energy usage related to crane movements in AS/RS. Different storage assignments are evaluated with regard to energy consumptions.
Rai et al. (2011)	Emissions impact of	Studies the emissions of warehouses related to installed materials and characteristics of warehouse buildings. Possibilities for energy

	warehouse buildings	savings due to design changes, e.g. roof lights, wall cladding and insulation are highlighted.
Tan et al. (2010)	Sustainable warehouse management	Proposes a sustainable warehouse management model for a reference case. It is assumed that warehouse-related emissions are solely caused by the transportation fleet and can be reduced by purchasing carbon credits and planting trees.
Tappia et al. (2015)	Sustainable automated warehousing	Investigates the trade-off between the environmental and economic perspectives of automated warehousing systems (AS/RS and autonomous vehicle storage and retrieval systems, AVS/RS) using real data.
Zuchowski (2015)	Green warehouse management	Presents emission factors within warehousing (e.g., heating, lighting) and surveys certification methodologies that can be used to evaluate the sustainability of warehouse buildings.

Table 1: Focus and findings of works dealing with environmental sustainability issues in warehousing

To facilitate the systematic assessment of the sources of CO_2 emissions in warehousing operations and thus contributing in reducing its environmental impact, a systematic methodology for assessing emissions based on warehouse operations and characteristics is discussed in the next section. The proposed approach enables the deduction of benchmark figures and is used to forecast the development of warehouse-related emissions in the United States by 2025.

Systematic assessment of warehouse emissions

Emission assessment scheme

The following section presents a structured approach adapted from Fichtinger et al. (2015) for the systematic assessment of warehouse-related emissions. Whilst Fichtinger et al. (2015) use a customer-oriented approach for analysing emissions based on a green-field scenario, i.e. their analysis is built upon a given customer demand that determines the ideal warehouse size, the present work is based on brown-filed scenario with the actual warehouse size. In addition, instead of considering a single warehouse, subsequent analysis will focus on linking macro-economic indicators (e.g. inventory turns) with global statistical aggregates, such as national warehouse floor space to estimate current and prospective impact of energy usage for lighting, heating and cooling as well as fixed and mobile material handling equipment on CO_2 emissions. Accordingly, the impact of warehouse sizes and inventory turns on emissions are not only modelled in a static way (e.g. through regression models), but built into a dynamic warehouse management model which, additionally, allows for sensitivity analysis on all technical or operational parameters as well as external emission determinants. The warehouse model, however, focuses on primary storage and throughput handling activities in the warehouse only and does not explicitly model other value added or non-value added services.

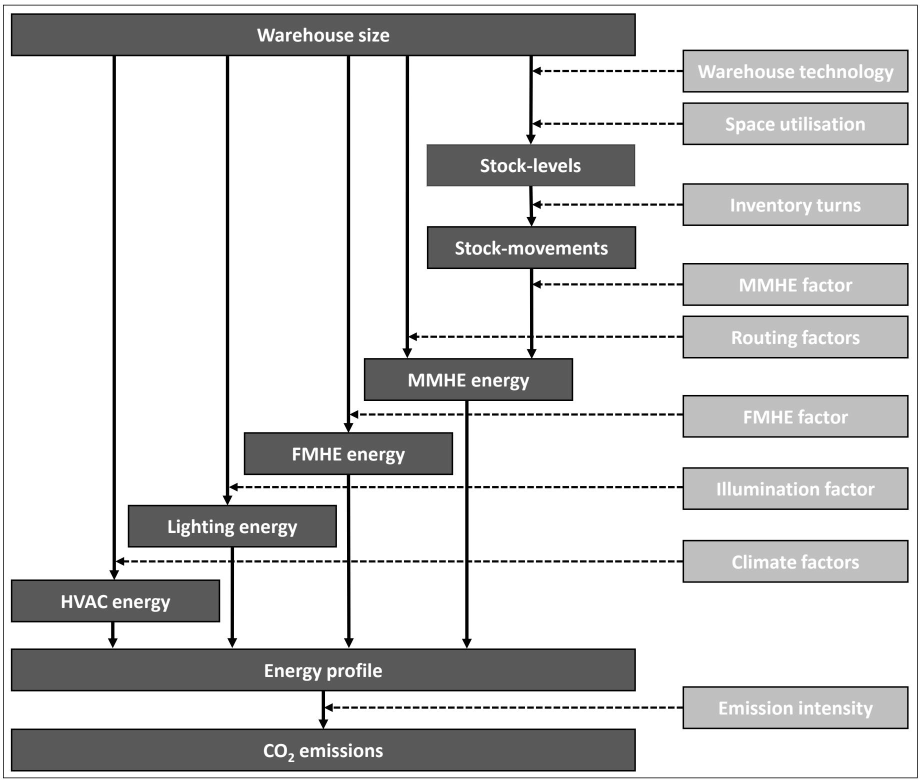

Figure 3: Methodology to assess the environmental impact of warehousing

The systematic assessment of CO_2 emissions caused by warehousing activities is based on a set of parameters and aggregates, (see Figure 3 and Fichtinger et al. 2015) determining overall energy consumption that is translated into carbon dioxide emissions. The presented methodology thus takes (forecasted) overall warehouse floor space as input that directly affects area-related energy consumption for heating, ventilation and air conditioning (HVAC), lighting and fixed material handling equipment (FMHE) such as steady conveyors. In addition, for given warehouse areas, estimated stock-levels and -movements for storage and retrieval processes determine the activity level and energy consumption of all mobile material handling equipment (MMHE). Finally, the warehouse energy profile is used to derive overall CO_2 emissions (or likewise into CO_2e emissions) by considering emission intensity of the different energy sources. All aggregates are estimated on an annual basis assuming an operating time of fifty hours a week (cf. Baker and Perotti, 2008; EIA, 2015). Relevant parameters of the proposed assessment approach (see Figure 3) are explained in the following section whereas the specific values and empirical data for warehouses located in the United States will be discussed in Section 4.

Parameter discussion

Warehouse technology considers the general warehouse characteristics (e.g. type and orientation of aisles) as well as the storage and stock handling system used (palletized, non-palletized, racking types, AS/RS, etc.). All these factors determine the expected efficiency of storage space usage and thus the amount of storage spaces available (e.g. number of pallet spaces, etc.) for a given warehouse area. Depending on the storage characteristics, a different number of pallet spaces per square metre storage space can be achieved (cf. Table 2 as well as Gudehus and Kotzab, 2012 and Rushton et al., 2014). Moreover, some storage systems can work at higher location occupancy levels than others. Depending on the storage system only a certain percentage of all pallet places may be occupied at any certain point in time to maintain operability (note that this factor is sometimes referred to as storage utilisation factor). To ensure that operations maintain effective, a block storage, for example, might require up to one-third of all pallet spaces to be empty which corresponds to a maximum of around 70% storage utilization. Other systems such as AS/RS, for example, might still work effectively until 95% of all storage locations are utilized (cf. Rushton et al., 2014).

Storage system	Block place	Wide aisle	Narrow aisle	AS/RS
Storage density [Pal./m^2]	1	2	4	10
Storage utilization [%]	70%	95%	95%	95%
Non-storage overhead [%]	15%	30%	50%	70%
Space utilization [%]	60%	67%	48%	29%
Building height [m]	8	10	15	25
Required illumination [lx]	200	300	300	100
Air changes [units/hour]	0.6	0.4	0.3	0.2
FMHE utilisation [%]	0%	5%	5%	10%

Table 2: Characteristics of different warehouse types

Apart from storing goods, warehouses provide a number of additional space-occupying activities. These non-storage areas in a warehouse include goods in/out and marshalling areas, order picking and packing, added value services among others. For example, based on a large sample of UK warehouses, Baker and Perotti (2008) show that on average this factor is typically about 50%, which means that only around half of the overall warehouse floor area is used for storage. Consequently, space utilisation reflects the fraction of the total warehouse floor space actually used for the (reserve) storage area also taking into account the storage utilization of the given storage system which has to be considered while assessing the respective inventory based on estimated pallet spaces in use.

Inventory turns or inventory turnover is an important indicator for the efficiency of inventory management and warehouse operations (e.g. high inventory turns allow to serve a certain level of customer demand with lower average stock levels), which is commonly defined as the ratio of annual sales or usage over average inventory, measured in monetary units (Silver et al., 1998). The amount of stock-movements from storage and retrieval processes is closely related to the customer demand, assuming that demand is fulfilled within the planning horizon. Consequently, the average number of stock movements in a warehouse can be estimated given the amount of stock available and average stock turn figures.

Those movements are commonly conducted by mobile material handling equipment (MMHE) including unsteady conveyors such as forklifts, low-level order picking trucks, or AS/RS whose energy consumption merely depends on the distance and amount of stock movements as well as the particular equipment specifications and respective energy efficiencies. Therefore, the routing factor estimates the average distance travelled per customer order and is influenced by the shape of the storage area and the storage and retrieval processes (cf. Hall, 1993).

In addition, many warehouses use fixed material handling equipment (FMHE) such as conveyors, which are used for continuous storage, retrieval and transporting processes (see Napolitano, 2012). The FMHE factor considers the amount and energy consumption of fixed material handling equipment used within the warehouses. Note that the energy consumption of fixed material handling equipment is more related to the size of the facility and its operating hours rather than to throughput

or utilisation and may thus be estimated by the fraction of the warehouse covered and the respective equipment characteristics.
Whilst lighting is often considered as a main driver for energy consumption in warehouses, there is no consistent estimate in the literature (c.f. Fichtinger et al., 2015). The illumination factor therefore determines lighting energy per square metre of warehouse size depending on the required level of illumination within the warehouse based on recommended lux levels, the technical characteristics of the building, and used luminaires. Appropriate estimates can be derived by the help of standard approaches in civil engineering such as the commonly applied lumen method (cf. Szokolay, 2014).
Similarly, the climate factor determines the energy required per square metre of storage space area for heating, ventilation and air conditioning (HVAC). The appropriate energy requirements for cooling, heating and ventilation merely depend on the geographical location of a warehouse as well as its building characteristics and may be quantified by the help of the degree day (DD) method that estimates energy requirements due to thermal losses of a building caused by transmission and ventilation against a given base temperature of 65 degree Fahrenheit (Christenson et al., 2006).
Finally, the warehouse energy consumption can be converted into CO_2 emissions (or likewise into CO_2e emissions) by means of the emission intensity factor after deriving the overall warehouse energy profile while considering all influencing parameters discussed above. Emission intensity considers the emission of greenhouse gases of the used energy sources also taking into account the present energy mix of electricity.

Analysis of warehouse emissions in the United States

This section contains a description of the methodology of our experimental design and a summary of empirical data used to derive the impact on warehouse-related emissions in the US.

Experimental design and factorial analysis

Factorial experiments are applicable to many diverse topics and have been used in a wide range of different application areas to explore the individual effect of changes in input parameters and potential interactions (cf. Dean et al., 2015). Such an experiment typically consists of several controllable input variables called factors determining the output variable whereas each factor may enter two or more possible levels. Factorial experiments where each treatment combination (e.g. each combination of the levels of all considered factors) is applied at least to one experimental unit are usually referred to as full factorial. However, as the number of treatment combinations can become quite extensive in the present case due to the continuous nature of factors, complete factorials are not affordable and will approximated by a fraction of the totality of all possible treatment combinations covering base and extreme scenarios. Those, in practical settings commonly used, fractional factorials allow, under appropriate assumptions, valid inference about factorial effects even without testing every treatment combination (cf. Ledolter and Swersey, 2007).
In general, factorial experiments exhibit the following structure. Consider the setup of a factorial experiment involving $n \geq 2$ factors $F_1, \ldots, F_n$, such that the ith factor F_i apperas at m_i distinct levels, where $m_i \geq 2$, for $i = 1, \ldots, n$. For $1 \leq i \leq n$, let the levels of F_i be coded as $0, 1, \ldots, m_i - 1$. A typical treatment combination can then be represented by an n-tuple $j_1 \ldots j_n$, and the effect due to that treatment combination can be denoted as $\tau(j_1 \ldots j_n)(0 \leq j_i \leq m_i - 1, 1 \leq i \leq n)$ whereas al $v = \prod_{i=1}^{n} m_i$ treatment combinations are assumed to be lexicographically ordered. After a description of the relevant parameter levels in the following subsection, Section 5 presents the results of the factorial analysis of estimated warehouse-related emissions in the United States by 2025.

Aggregated inventories and warehouse capacities

Although it has frequently been proposed to cut inventories at the company level aimed at reducing working capital and cost, inventories in the United States tend to increase continuously within the past years (see Figure 4 for seasonally and inflation adjusted total business inventories in the United States and compare for US Census Bureau, 2015). This trend can be observed at the manufacturing as well as at the wholesale and retail level. Increasing inventories, however, induce a growing demand for overall warehouse space required for storing and handling activities as warehouses have become important elements of modern supply chains involved in various stages of the sourcing, production and distribution of goods (cf. Rushton et al., 2014) and are necessary for receiving, storing and dispatching a larger amount of goods.

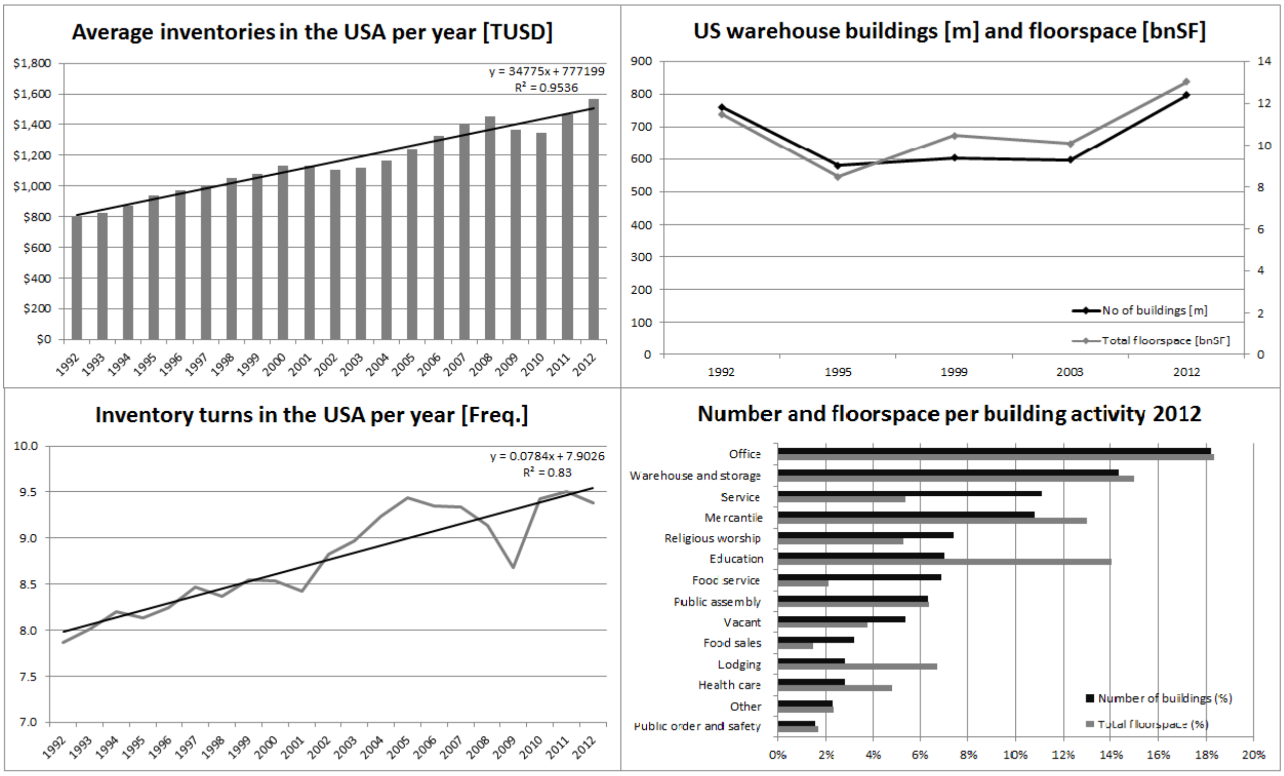

Figure 4: Inventory and warehouse building characteristics in the United States

Comparing current numbers, warehouses and storage buildings account for almost 15% of the total commercial buildings as well as total commercial floor space and thus already represent the second largest building type apart from office buildings (see Figure 4 and cf. EIA, 2015b). The increasing capacity demand is not only reflected in increasing inventories but also in the current stock of warehouse buildings. Between 2003 and 2012, the number of warehouse buildings in the United States increased by one third whereas at the same time the rise in overall commercial building stock was only about 14.37% (EIA, 2015). These developments also lead to a significant increase of total warehouse floor space by 39.31% between 2003 and 2012 (EIA, 2015b) compared to an increase of 21.47% of the overall commercial building floor space at the same time. Warehouse space thus seems to be required for dealing with continuously increasing inventories. Due to required energy consumption for lighting or heating, cooling, ventilation and air conditioning, this directly induces a rise in warehouse-related emissions. According to the lack of more detailed data, three different levels for the development of overall warehouse space until 2025 have been assumed in the following. First, a reduction by 20% as compared to 2012, a stable level as in 2012 and a growth by 20% compared to 2012.

Besides growing aggregated inventories, inventory turns in the United States equally exhibit a positive trend (Figure 4) and increased between 2003 and 2012 by 4.57% (US Census Bureau, 2015). The rise in inventory turns also has immediate influences on warehouse operations and emissions. Due to an increasing number of in- and outbound movements that need to be operated by FMHE and MMHE, energy consumption tends to increase which induces additional CO_2 emissions. Using linear regression, inventory turns in the United States are expected to increase from 9.377 in 2012 to 10.568 in 2025.

Building characteristics and technology
Warehouses may generally be operated by the help of different technologies taking into account building characteristics as well as the storage and handling equipment employed that determine storage and space utilization (cf. Section 3). The following analysis was based on the four most common types of warehouse technology, i.e. a) block-pallet storage, b) wide-aisle racking (WA), c) narrow-aisle racking (NA), and d) automated storage and retrieval systems (AS/RS) with its distinct operational characteristics summarized in Table 2. Considering benchmark figures from the United States, it becomes obvious that most material handling systems in receiving, storage, order picking and replenishment rely on conventional or conveyor-based operations, automated systems are only used in 5%-9% of all systems (cf. Napolitano, 2012). Thus, despite potential process improvements, a future possibility for improving the warehouse performance might also be given by increasing investments in mechanization and automation that might on the one hand improve throughput while reducing operational expenses but on the other hand influence CO_2 emissions of the warehouse by affecting the overall energy consumption.
In conventional warehouses, usually a large proportion of MMHE is related to forklift trucks, which are indoors typically operated by electricity (battery), and outdoors also by Diesel or liquefied petroleum gas (LPG). To take account of the energy characteristics of the different MMHE types, the MMHE factor determines the weighted energy consumption of all equipment employed, which is assumed as 10 W/m (note that the energy parameter was estimated by taking averages from product brochures of storage equipment providers, e.g. Toyota or Still where the energy consumption is given for one VDI 2198 cycle). Together with the routing factor (note that warehouses of rectangular shape with a ratio of depth to width of 2:1 were assumed), the MMHE factor determines the aggregated MMHE energy used for operating a given amount of in- and outbound movements within the warehouse. The aggregated FMHE energy consumption per square metre warehouse size is determined by the fraction of the warehouse covered (note that it was estimated to have 5% in wide and narrow aisle warehouses and 10% in ASRS warehouses, cf. Dhooma and Baker, 2012) and an energy consumption rate per square meter, which is assumed to be 10 W/m^2 (again, the energy parameter per square meter was estimated by taking averages from product brochures of storage equipment companies).

Apart from operating technology, energy consumption in warehouses is merely influenced by the general building characteristics that determine energy consumption for lighting or heating, ventilation and air conditioning. The illuminance required is usually dependent on the visual tasks that have to be performed. For example, AS/RS do not need the same lighting as a picker-to-part order picking warehouse with small items. Therefore, it was assumed a recommended level of 200lx for the block place store, of 300lx for the wide-aisle as well as the narrow-aisle store and of 100lx for the AS/RS (see also Marchant and Baker 2010). Moreover, the maintenance factor that takes account of the deterioration of lamp, luminaire and room surfaces was in the absence of more accurate data assumed as 0.8 whereas the utilization factor that measures the relevant luminous efficiency was assumed as 0.5 on average (cf. Szokolay, 2014). Besides, lighting efficiency is determined by the technical characteristics of the illuminants including the specific luminous flux and the energy consumption (see Table 4 for samples figures of industrial lamps used in US warehouses).

Lighting equipment	**Number of warehouses [thousand]**	**Total floor space warehouses [million m^2]**	**Lighting [lm]**	**Energy [W]**
Incandescent	136	284	1160	100
Fluorescent	670	1415	2660	40
HID	76	273	24000	400

Halogen	66	225	22000	1000
LED	23	93	12000	100

Table 4: Lighting equipment used in US warehouses

Considering the current lighting infrastructure, most warehouses in the United States are equipped with fluorescent bulbs followed by incandescent bulbs whereas very few use efficient LED technology (EIA, 2015b). Multiplying the illumination factor with the warehouse size determines the aggregated lighting energy required (note that all calculations are based on the lumen method, cf. Szokolay, 2014).

The annual heating demand may be derived as the product of heating degree days and thermal losses due to transmission and ventilation less internal heat gains. Heating degree days, defined as the sum of daily temperature difference within a year, for warehouses based in the United States varies from a low of 2000K to a high of more than 8000K a year depending on the respective climate zone (cf. Table 4 and EIA, 2015b). Besides, transmission heat losses are determined by the transmission coefficient (U-value) of the building envelope and its total surface. Conventional warehouses that mainly have low insulated brick, concrete or metal panel walls and metal or synthetic roofs feature an average U-value between 0.25 and 0.30 that might be reduced to less than 0.1 by improving the insulation. Heat losses due to ventilation are determined by the number of air changes per hour that was assumed as 0.6 for the block-place store, 0.4 for the wide-aisle store, 0.3 for the narrow aisle store and 0.2 for the AS/RS, the volume of the room and a constant capturing air density and specific heat capacity (note that density of the air was assumed as 1.2 kg/m^3 at 65 degree Fahrenheit whereas specific heat capacity was assumed as 1000 J/kg K). Beside health and safety regulations which govern the required temperature or the number of air changes, the warehouse climate in many applications has to be controlled for specific products such as fresh, chilled or frozen goods. Thus, the climate factor is influenced by the energy efficiency of the heating and cooling system, by building characteristics such as wall and roof insulation, the state and quantity of windows and doors, the outdoor temperature and product requirements (Rai et al., 2011). Multiplying this factor with the warehouse size determines the aggregated HVAC energy.

Climate zones	Number of warehouses (thousand)	Total floorspace warehouses [million sqft]	Total floorspace warehouses [million sm]	CDD	HDD
Very cold/Cold	273	4,121	382.85	<2000	>7000
Mixed-humid	228	3,740	347.46	<2000	5500-7000
Mixed-dry/Hot-dry	177	2,932	272.39	<2000	4000-5500
Hot-humid	94	2,021	187.76	<2000	2000-4000
Marine	na	na	na	2000	<4000

Table 4: Climate zones of warehouses in the US and related degree days

Considering warehouse buildings in the United States constructed before 2008, which is about 92.72% of the total warehouse building stock, only 23.95% of the warehouses have recently been renovated with regard to energy-saving measures (see Table 3 and EIA, 2015b). In such cases, HVAC equipment upgrades, roof replacements and insulation upgrades have been introduced which have a significant impact on future energy consumption. In few cases lighting upgrades have been introduced in addition and although LED lighting is not very common yet, due to the technical advantages, the use of LED lighting may increase in the future (Marchant and Baker, 2010).

Consequently, given the current equipment characteristics of warehouse buildings in the United States, we considered two different scenarios for 2025. In the first scenario, it was assumed that building characteristics will only be improved slightly by having a larger amount of warehouses being equipped with fluorescent lamps and keeping insulation at the same level whereas the second scenario assumed a higher level of building improvements by equipping warehouses with LED lamps and improving lowering U-values to 0.15 by improved insulation (see Section 3 and Rai et al., 2011)

Energy mix and conversion factors

Finally, the effective carbon dioxide emissions caused by a given energy profile of the warehouse can be deduced by the help of corresponding conversion factors for each source of energy. In the United States, primary energy sources for warehouses are electricity and natural gas (see Table 5 as well as EIA, 2015b). Whereas natural gas emits 0.553 kg CO_2/kWh, the emission intensity for electricity is dependent on the given energy mix and needs to consider regional conditions (EIA, 2015a). In 2014, about 66% of the electricity consumed in the United States was generated from fossil fuels, with coal being the major energy source with about 39% (note that the remaining 26% are generated by natural and other gases). Hydropower and other renewables account only for about 14% whereas the remaining part is produced in nuclear power plants (EIA, 2014). Based on the given energy mix and the respective conversion factors of the different energy sources the weighted average emission intensity of electricity was estimated as 0.793 tCO_2/MWh. However, as the US climate action report (cf. U.S. Department of State, 2014) indicates that there will be a development of renewable energy sources aimed at doubling renewable electricity generation from wind and solar by 2020, the conversion factor for electricity does not necessarily remain at 2014 level. Especially as this might also come along with an ongoing shift from coal to natural gas including investments in a range of energy technologies, such as clean coal, which will again contribute to a decrease of CO_2 emissions from electricity generation. Thus, beside the conversion factors being stable at the 2014 level, we also assumed a 20% decrease in emission intensity for the factorial analysis.

Energy sources	**Number of warehouses (thousand)**	**Total floorspace warehouses [million sqft]**	**Total floorspace warehouses [million sm]**	**CO2 emission [kgCO2/kWh]**
Electricity	675	12,523	1163.42	0.793
Natural gas	262	7,063	656.17	0.605
Fuel oil	26	1,773	164.72	0.835
Propane	45	1,516	140.84	0.234
Other	16	549	51.00	n.a.

Table 5: Primary energy sources for warehouses in the US

Results

Based on the systematic methodology for the assessment of warehouse-related CO_2 emissions and the empirical data for the United States, the following section discusses several implications of the analysis. Firstly, a sensitivity analysis of the current warehouse CO_2 footprint enables identifying the relative importance of all factors considered and allows calibrating the model before analysing several future scenarios for the overall warehouse emissions. Secondly, considering the identified trends and forecasts enables estimating the relevant factor levels required for factorial analysis to assess their influence on warehouse-related emissions in 2025. Beside a realistic forecast of potential emissions arising from the operation of warehouses, this also allows an evaluation of the influences of new and more environmental sustainable approaches and technologies for material handling in supply chains.

Sensitivity analysis for warehouse-related emissions

Given the parametric setting described, annual energy consumption for a median warehouse in the United States (note that the median warehouse describes the typical warehouse based on the descriptive statistics of warehouses in the United States allowing a more robust estimation of typical conditions given the wide spread of different warehouse characteristics) ranges between a low of 1025 and a high of 1256 MWh depending on the respective warehouse technology employed (note that these figures are in line with previous studies such as Dhooma and Baker, 2012 or Fichtinger et al., 2015). This leads to annual emissions of between 888 and 1087 tCO_2 for a typical US warehouse. As can be seen in Figure 5, the block-place store scenario exhibits the lowest emissions whereas narrow-aisle and AS/RS warehouses have the largest emissions. This may be explained by comparing the operational performance and building requirements of the different technologies. Assuming a given ground floor area, the more efficient narrow-aisle storage or AS/RS operate a higher amount of goods per year than the block-place or wide-aisle storage. In addition, narrow-aisle storage or AS/RS require considerably larger building heights that lead to increasing building volumes and surfaces which also increases heat losses due to transmission and ventilation.

Considering the different end-use categories, energy consumption for fixed and mobile material handling only accounts for 1.3% in the case of block-place storage, around 8% for the wide and narrow aisle storage and about 15% of total energy consumption for the AS/RS. Thus, an efficient means of reducing warehouse-related emissions has to take into account energy-efficient lighting and air conditioning systems while minimizing heat losses due to transmission and ventilation.

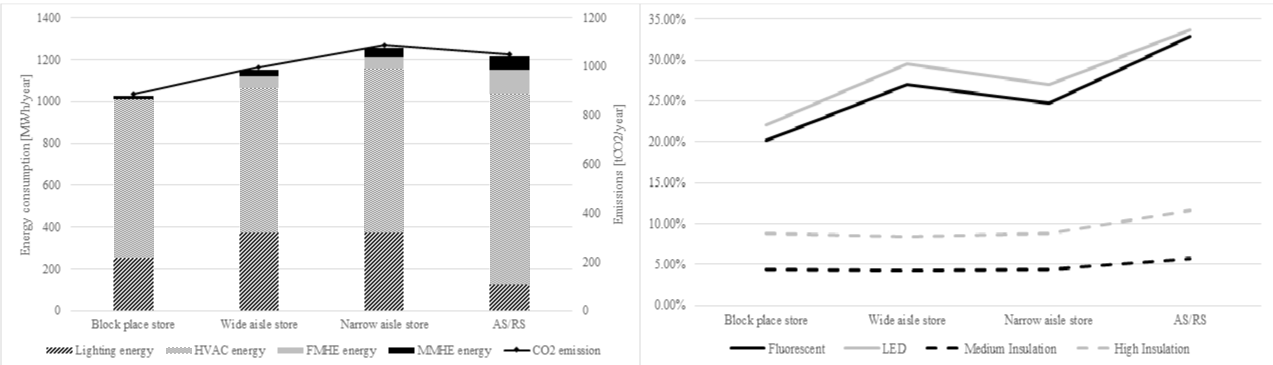

Figure 5: Energy consumption and emissions for different warehouse types and equipment

Considering the different warehouse technologies, changing the luminaires from standard incandescent lamps to fluorescents or even LEDs might reduce required lighting energy by 80% to 90% which leads to decreasing emissions of between 20% and 34% for the median warehouse (see Figure 5). On the other hand, improving building insulation (note that corresponding heat transmission coefficient was reduced to 0.2 and 0.15 respectively, see Rai et al., 2011) might reduce required HVAC energy by 6% to 15% which leads to a decrease of CO_2 emissions by 4% to 12% for the median warehouse.

Factorial analysis for warehouse-related emissions

Based on the development of macro-economic variables linked to relevant warehouse-related parameters, treatment combinations with different factor levels were developed and fed into the calibrated emission assessment model. The objective of the present study is to analyse potential developments of aggregated CO_2 emissions emanating from warehouses located in the United States by varying independent factor levels (warehouse space, operating technology, building equipment in terms of lighting and insulation and emission intensity). The factorial design enables all the factors to be varied simultaneously, allowing quantification of the effects caused by independent variables and are reported in Figure 6.

Based on estimated annual warehouse-related emissions of 380 $MtCO_2$ which corresponds to about one fifth of the emissions caused by the domestic transport sector (note that this value corresponds to the current estimated total warehouse-related emissions in the United States), possible variations range from a reduction of about 45% (S3) to a growth of about 60% (S22) until 2025. Considering a stable floor space demand, a high degree of automation required for storing and handling an increasing number of goods might increase CO_2 emissions by 12% on average (S13-S16). However, considering improvements of the building equipment such as lighting and insulation and the use of less carbon-intensive sources of energy, emissions might be reduced by almost 10% (S15). Similar results with an even higher amplitude may be achieved in the case of a reduced floor space demand and a high degree of automation that might even reduce emissions by 26% (S7; note that the scenarios with low degree of automation have not been discussed in detail as they might be more relevant for the case of an economic downturn with temporary decreasing inventories and a lower inventory turnover). In the case of an increasing overall floor space, emissions tend to rise in nearly all scenarios. Without any reduction measures this might even lead to an overall increase between 20% (S18) and 60% (S22) depending on the respective operational technology. Nevertheless, implementing improved warehouse equipment and using greener energy sources may limit or even revert the rise in CO_2 emissions. Consequently, especially in the case of increasing requirements of storage and handling capacities that induce the use of more efficient automated warehouse operations as well as an increasing number of storage buildings, the consideration of the environmental impact of warehousing becomes inevitable. Moreover, the present analysis reveals that even though warehouse-related CO_2 emissions only represent about one fifth of transport-related emissions, neglecting these aspects might induce a sharp increase in overall emissions that may even offset reduction measures in the transport sector.

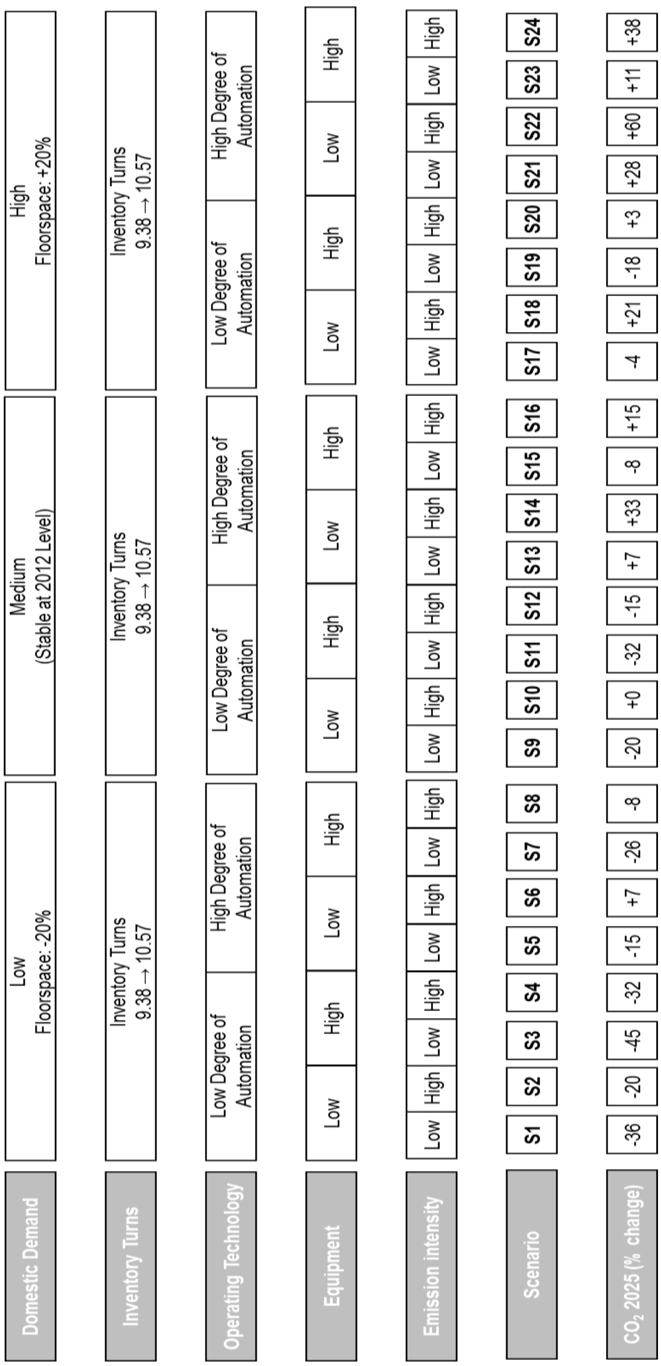

Figure 6: Scenario analysis for warehouse-related CO_2 emissions in the United States

Conclusion

Warehouses play a vital role in supply chains and are one of the major determinants of operational efficiency and business success. Thus, it is understandable that research on warehouse design and management has constantly been growing over the last decades. However, a topic within warehousing research that has been overlooked to a large extent is the environmental impact of warehousing operations. Although it has been recognized that logistic activities, such as transportation, are main drivers of CO_2 emissions globally, works that have focused on warehouse-related emissions are rare. This is surprising given the fact that warehouses require a significant amount of energy due to lighting, heating, cooling and air condition as well as fixed and mobile material handling equipment. This energy consumption leads to a considerable amount of carbon dioxide emissions and may thus facilitate many opportunities for improving the CO_2-footprint of warehouses and thus for decarbonizing warehousing operations.

The paper at hand addressed this research gap by conducting a systematic literature review to assess the state of the art of "green" warehouse management as well as by suggesting a classification scheme that enables researchers and practitioners to systematically assess warehouse-related energy consumption and emissions in order to measure the CO_2 footprint of warehouse operations. In addition, the systematic assessment framework of warehouse emission drivers and determinants was used in combination with empirical data for the United States to derive benchmark figures for warehouse emissions on a macro-level. Finally, a factorial analysis for long-term warehouse-related emissions in the United States was developed based on the estimation of future developments, which facilitated the deduction of valuable insights for identifying effective emission mitigation strategies for decarbonizing warehousing operations. However, due to the lack of empirical data of other countries, benchmark figures are limited to the United States. In addition, this study focused on the four most common types of warehouses, which could be extended for other types as well.

Despite these limitations, the present work has several implications for researchers, politics and warehouse managers. First, as there evidently is a lack of research in the area of environmental impact of warehousing, future works could develop mathematical models or simulation studies that integrate emission-reduction objectives in warehouse management and design approaches. Moreover, as there is a need for more empirical data related to actual warehouse emissions, the developed emission assessment methodology could be used in case studies to assess the CO_2 footprint of existing warehouses. Secondly, there is a distinct growth potential warehouse related emissions within the coming years. Thus, in order to achieve progress towards a low carbon economy, politics should not only focus on emissions caused by manufacturing or transport emissions but also take into account warehousing buildings and increase incentives for reducing their environmental impact.

Finally, although our analysis was focused on a macro-level, the results of our paper may be also interesting for warehouse managers. As for managerial implications, we conclude that the assessment methodology also facilitates the calculation of warehousing emissions on a micro-level (i.e. the CO_2 footprint of a particular warehouse). In addition, besides macro-economic and political implications for reducing CO_2 emissions, such as the energy mix of a specific country, several implications to reduce warehouse emissions on a micro-level were highlighted, that might enable companies to reduce energy cost and to cut warehouse-related emissions. This includes investments in building characteristics (e.g. wall and roof insulation, rooflights), heating improvements or lighting upgrades (in particular changing form standard fluorescent to LED lights or using smart lighting technologies in warehouses). In addition, new, energy efficient material handling equipment (such as forklifts with regenerative energy recovered from braking or newer, more efficient battery chargers) could increase the environmental performance in warehouses. In this line of thought, employing sophisticated planning approaches, such as energy efficient storage location assignments could be recommended. Finally, the possibility to purchase green energy, in particular reducing the amount of electricity produced out of coal could further reduce the CO_2 footprint of a warehouse.

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