Assessing the environmental impact of logistics sites through CO_2e footprint computation

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Abstract

The environmental sustainability of logistics facilities is widely acknowledged as an important issue, but a comprehensive standardised methodology for assessing their environmental impact is lacking. This study proposes a structured model for quantifying both consumptions and generated GHG emissions, adopting a three-phase methodology that combines multiple methods. A literature-based conceptual framework was leveraged to design an analytical model, and in-depth interviews with 11 logistics and warehouse managers contributed to both the framing and validation research stages.

The study offers a replicable methodology that considers heterogeneous sources of consumption and the related end-use types, further splitting consumptions and emissions by warehouses' functional areas. Also, it offers a set of Environmental Performance Indicators (EPIs) that could bolster a clearer understanding of the warehouses performance. A robust tool is offered to managers to support their decision-making processes, allowing for both internal assessments and benchmarking with competitors or other players along the supply chain.

Running title

Environmental impact of logistics sites

Keywords: Environmental sustainability; Logistics; Green warehousing; Carbon footprint.

Introduction

Warehousing is one of the critical processes within supply chains and logistics operations, accounting for about 20% of logistics costs (Dhooma and Baker, 2012). A substantial evolution of warehouses has also been observed over time (Baglio *et al.*, 2019), as they have transformed from simple repositories for inventory into multi-functional logistics hubs (Baker, 2004; Onstein *et al.*, 2019). This brought along significant challenges not only in terms of efficiency and service level fulfilment (Kembro *et al.*, 2018), but also concerning the environmental impact of the building and the related operations (Kembro *et al.*, 2017; Shaw et al., 2021). The environmental impact has been often related to greenhouse gas (GHG) emissions (Oberhofer and Dieplinger, 2014; McKinnon, 2015), and measured in terms of carbon dioxide equivalent tons emitted (CO_2eq) (Yang *et al.*, 2019; Negri et al., 2021). According to the World Economic Forum (2016), logistics and transport activities account for 13% of the overall GHG emissions worldwide, where logistics sites represents 11%.

Both practitioners and academics have been showing increasing awareness and interest towards improving environmental sustainability of logistics facilities (Wehner *et al.*, 2020; Shaw et al. 2021). For instance, growing investiments have been observed in the real estate industry, with reference to green building projects, such as improving building thermal insulation and utilities, e.g. photovoltaic and solar panels (IEA, 2019, and 2020). Green building rating systems, such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM), have also become available as sustainability assessment methods to be applied during both building design and construction (Baglio et al., 2021). Besides, higher attention to energy-efficient solutions has been highlighted, e.g. through the adoption of technologies such as LED lighting, lithium-ion batteries and energy-saving fast-chargers (Rai *et al.*, 2011; Rajput *et al.*, 2020). From the academic side, the literature dealing with logistics environmental sustainability, which was initially more focused on transport processes, has been now turning the attention on warehousing operations (Ries *et al.*, 2017; Agyabeng-Mensah *et al.*, 2020). A rising number of contributions emerged, to investigate how logistics sites may reduce their footprint and resource consumption, and to identify the entire range of drivers affecting warehouses' energy efficiency (Bartolini *et al.*, 2019; Minashkina and Happonen, 2020). However, to date there is a scarcity of contributions about the impact of warehousing on overall emissions, and even specific warehouse consumption and emission data are often incomplete (Shaw et al., 2021). For instance, widely-adopted green building certifications such as LEED and BREEAM are helpful to provide an environmental rating of a facility but do not provide any quantification of the related consumption or emission figures. Overall, the novelty of the subject has brought a variety of documents, but a comprehensive standardised methodology for assessing the environmental impact of logistics sites is still lacking. A structured and holistic assessment of the environmental performance of logistics facilities could support internal analyses and comparisons with competitors to drive actions for improvement, thus leveraging sustainability as a critical success factor (Carter and Rogers, 2008; Baglio *et al.*, 2019). As acknowledged by Shaw et al. (2021; p. 382), "it enables organisations to measure and externally report their environmental performance and helps them to internally control and analyse such performance to understand their business better and continually improve".

Given these premises, the present paper aims to fill the gap highlighted by proposing a structured methodology for quantifying the environmental impact of warehouses, in terms of both consumptions and generated GHG emissions. To ensure both robustness and practical relevance, the model builds on the analysis of the extant literature on green warehousing and energy-efficient logistics buildings, including the managers' perspective during both the framing and validation research stages (Sodhi and Tang, 2014).

The contribution of this study is twofold. From an academic perspective, the present research offers a replicable methodology for assessing the environmental impact of logistics sites and provides metrics and measures related to warehouse environmental footprint. This help overcome the current lack of a shared methodology for the quantification and understanding of the environmental impact of logistics sites. From a managerial perspective, a robust tool is offered to managers willing to monitor the environmental performance of their logistics sites over time, as well as to support their decision-making processes. This could be beneficial for reducing waste and being more operationally efficient, thus mitigating the impact on the natural environment (Shaw et al., 2021).

The remainder of the paper is organised as follows. The next section includes a literature review of the environmental impact of warehouses, and examines how such an impact has been computed for logistics sites. The research objective and methodology are then described, followed by the illustration of model design and validation. Finally, the related discussion and implications are provided and conclusions are drawn, along with recommendations for further studies in this field.

Literature review

Environmental impact of warehouses

Logistics networks are complex systems involving multiple players, interactions and – potentially – numerous transport and warehousing phases (Prataviera et al., 2021), and the warehouse itself apparently seems a fairly simple component (Baker, 2004). Nonetheless, it involves several and heterogeneous processes to guarantee efficiency and effectiveness (Rushton *et al.*, 2017; Richards, 2018). Besides receiving, shipping and material handling, distribution centres usually involve put-away, storage and picking functions, whereas transit points are normally associated to cross-docking flows with sorting and shipping being the primary processes (Kreng and Chen, 2008; Baker and Canessa, 2009). Together with traditional activities, logistics site often provide also value-added services, such as labelling/relabelling, kitting, packing, assembling, or product customisation according to specific customer's requirements (Selviaridis and Norrman, 2015; Kembro *et al.*, 2017). To cope with all these operations, logistics sites require a considerable amount of energy and materials so that the related environmental impact is remarkable and deserves attention (Colicchia *et al.*, 2013; Goh, 2019). This is critical today, with increasingly demanding supply chains, greater omnichannel complexity, restrictive environmental regulations (Tricoire and Parragh, 2017), and higher awareness from both the company's and the consumer's sides (Bartolini *et al.*, 2019; Negri et al., 2021).

According to several scholars (e.g. Dhooma and Baker, 2012; Fichtinger *et al.* 2015, Ries *et al.* 2017, Bartolini *et al.* 2019), the primary end-use consumption types within a logistics site are lightling,

heating, ventilation, and air conditioning (HVAC) (often including refrigeration and cooling), and Material Handling Equipment (MHE) (also including Automated Storage and Retrieval Systems (AS/RS)). Additional causes of energy consumption can involve the provision of computer systems, office equipment, and miscellaneous equipment such as catering appliances (Lee *et al.*, 2017).
The adoption of energy-efficient solutions could bring along significant improvements from both the environmental and economic perspectives. Focusing on lighting, LED bulbs could allow up to 80% energy saving and 20% emission reduction with respect to the conventional incandescent bulbs (Ries *et al.*, 2017). Moreover, thermal building insulation interventions could lead to 6÷15% reduction of energy required for HVAC, and 4÷12% CO_2eq emission decrease (Ries *et al.*, 2017). Looking at material handling processes – involving either conveyor systems, automated cranes, or mobile MHE such as forklift trucks (Dhooma and Baker, 2012) – they represent a crucial improvement area to reduce warehouse emissions (Meneghetti *et al.*, 2013; Bartolini *et al.* 2019; Ekren, 2020).
Therefore, it is essential to adequately measure and compare the energy efficiency of logistics sites, both in terms of energy consumption and generated emissions (Freis *et al.*, 2016). An adequate set of indicators and measurement system need to be set up not only to monitor the warehouse performances over time, but also to support managers' decision-making process (Waltho et al. 2019; Torabizadeh *et al.*, 2020).

Environmental impact calculation for logistics sites

Heretofore, studies on warehouse management systems have mainly focused on time, cost, and profit (De Koster and Balk, 2008), whereas environmental aspects have been largely disregarded (Torabizadeh *et al.*, 2020). Despite the researchers' increasing attention to sustainable supply chains, incorporating sustainability measures in warehousing is an understudied and important research topic (Oberhofer and Dieplinger, 2014; Ene *et al.*, 2016; Nilsson *et al.*, 2017).
Companies often look at carbon footprint protocols for guidance on measuring their GHG emissions, basing their environmental impact quantification on the CO_2eq emission calculation (Yang *et al.*, 2019). This method allows for turning every process and activity into a comparable measure that can be used for benchmarking purposes, also considering the system boundaries (i.e. the 'Scope' under assessment, e.g. Nilsson *et al.*, 2017; Helo and Ala-Harja, 2018). Existing protocols generally estimate direct emissions (Scope 1) and emissions from direct purchases of energy (Scope 2), but focus less on indirect emissions upstream and downstream of the supply chain (optional Scope 3) (Huang *et al.*, 2009; Waltho et al., 2019). Table 1 illustrates the main recent contributions that addressed the calculation of the environmental impact for logistics sites or included environmental factors in the assessment of warehousing operations.

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Table_1

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First, some contributions focused on building design features and their environmental impact. Rai *et al.* (2011) evaluated alternative design strategies for logistics sites' envelope, and investigated embodied and operational implications of changing the envelope characteristics. Ries *et al.* (2017) analysed three different types of warehouse to simulate how different warehouse design factors could affect GHG emissions. They summarised preliminary studies of warehouse-related emissions, and introduced a macro-level classification scheme to systematically assess the carbon footprint of warehouse operations. Lee *et al.* (2017) introduced a data-driven approach to compare and cluster different warehouse buildings according to various characteristics. Such characteristics were used to train a decision tree model that provided a classification of the factors affecting energy consumption. A linear regression method was then developed to predict the energy consumption based on relationships between strongly correlated variables, such as climate zone, number of working hours, and floor area. Accorsi *et al.* (2017) proposed a multi-objective model for warehouse building design in the food and beverage industry, to define the most efficient sizing and minimise the carbon footprint during its lifetime.

Second, other scholars investigated energy savings opportunities, and how green warehousing could bring a reduction of both GHG emissions and costs. Dhooma and Baker (2012) leveraged the traditional energy audit approach to design a framework that identifies energy savings opportunities, considering the energy usage by warehousing end-use consumption types. Bank and Murphy (2013) proposed some sustainability standards for warehouses, including electric energy usage, recycling, liquid fuel usage, and water consumption as the main environmental metrics to be considered. Rudiger *et al.* (2016) expanded their framework to develop a method for assessing GHG emissions of warehousing and cross-docking activities considering a set of environmental performance indicators (EPI). They adopted a holistic perspective of the energy consumption within logistics facilities divided by energy, maintenance, and packaging/waste, and proposed a classification scheme for logistics facilities based on ecological aspects.

Third, other authors investigated the environmental impact of specific warehousing activities (e.g. inventory management, picking, or material handling) or warehouse function areas. Fichtinger *et al.* (2015) developed an integrated simulation model to examine the interaction between inventory and warehouse management, highlighting the key effects of inventory management policies on warehouse-related GHG emissions. Ene *et al.* (2016) studied picking operations to determine the storage policy that minimises energy consumption, while Facchini *et al.* (2016) focused on material handling operations and developed a model to select the best environmental material handling equipment to minimise the carbon footprint of inbound logistics activities. Freis *et al.* (2016) developed a mathematical model to evaluate the energy demand and GHG emissions of three types of logistics facilities, and assessed the electric energy amount for some end-use types (e.g. HVAC systems, or MHE). Lastly, Carli *et al.* (2020) developed a model to optimise the battery charging of a fleet of electric forklifts by minimising the economic and environmental impact of material handling activities in labor-intensive warehouses.

Finally, some studies analysed the relationship between warehouse automation and its environmental implications. Meneghetti and Monti (2013) proposed a model to evaluate the energy usage related to crane movements in AS/RS, evaluating different storage location assignments and related to energy consumption figures. Meneghetti and Monti (2014) further investigated AS/RS environmental performances, considering storage policies to develop optimisation models for designing sustainable automated warehouses. They also studied storage assignment policies in AS/RS considering retrieval time and energy requirements simultaneously (Meneghetti *et al.*, 2015), evaluating the energy savings connected with different rack shapes. Lerher *et al.* (2014) offered a model to estimate the energy-efficiency performance of mini-load AS/RS, considering the related energy consumption and CO_2eq emissions. Also Tappia *et al.* (2015) proposed a model to evaluate the energy consumption and environmental impact of automated warehousing solutions, further considering the tote as the handling unit. Bortolini *et al.* (2017) developed a time and energy bi-objective model to solve a storage assignment problem for a single-deep stationary rack AS/RS, minimising the energy consumed by cranes and the travel time simultaneously. Finally, Ekren *et al.* (2020) studied shuttle-based storage and retrieval systems design to identify significant factors affecting the related performance metrics, including energy consumption.

Objective and methodology

Previous approaches do not consider the environmental performance of logistics sites from a holistic perspective, i.e. by examining the diverse sources of consumption, nor split the figure by individual operations or functional areas. Moreover, a standardised methodology is lacking (Freis et al., 2016; Shaw et al., 2021) but benchmarking and comparing the environmental performances of different warehouses would be useful, both academically and managerially (Minashkina and Happonen, 2020). This study aims to overcome some of the main gaps and limitations identified in the literature by proposing a replicable model to assess the environmental impact of logistics sites. The following research question was formulated:

RQ: *How can the environmental impact of logistics sites be modelled and assessed?*

To address this research question a three-phase methodology was adopted (Figure 1), combining multiple methods as this helps explore multiple perspectives of a problem (Choi *et al.*, 2016).

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Figure_1

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Sodhi and Tang (2014) pointed out that addressing a research problem involves four stages, namely motivation, framing, modelling, and validation. To tackle the first two stages, the first research phase encompassesd an in-depth analysis of warehousing processes and related sources of consumption and emissions. Besides, available methodologies and tools to compute the environmental impact of logistics sites were carefully examined. The academic contributions published on the topic were first reviewed and then triangulated with secondary sources (e.g.

research reports, consultancy and real estate reports, material handling providers websites, company sustainability reports, and international regulations). Also, four exploratory interviews were conducted, involving logistics managers working for companies (i.e. logistics service providers, manufacturers and retailers) that embraced sustainable programmes in their warehouses and a consultancy company involved in green logistics analyses. This approach helped enhance research integrity and connect research with practice (Choi *et al.*, 2016), as the involvement of practitioners improved the study's practical relevance (Stentoft and Rajkumar, 2018). The first phase led to the development of a conceptual framework (Figure 2). The framework reports the main warehousing processes, main end-use types (i.e. lighting, HVAC, refrigeration, and MHE), and main sources of consumption (i.e. electric energy, fuels, refrigerants, water, and waste).

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Figure_2

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In the second research phase (i.e. modelling), a model to assess the environmental impact of logistics sites was developed. An analytical approach was selected, as it offers flexibility (i.e. changes and modifications can be applied to each single modelled activity with limited effort) and transparency (i.e. hypotheses are clear and evident from the equations) (Prataviera *et al.*, 2020). The model was developed using Microsoft Excel with Virtual Basic for Application (VBA) programming. Leveraging the proposed conceptual framework, consumption and CO_2eq emissions figures rising from warehousing activities were assessed to illustrate the environmental impact of logistics sites. Indeed, CO_2eq allows for measuring warehouse environmental impact by embracing the polluting effects of very different sources of consumption (Helo and Ala-Harja, 2018; Yang *et al.*, 2019). Moreover, it offers practical opportunities for benchmarking different logistics sites (Lee *et al.*, 2017). The model outputs included both figures related to the environmental performance of the entire logistics site and individual EPIs related to different warehouse functional areas.

Third, as recommended by Fichtinger *et al.* (2015) and in line with Dhooma and Baker (2012) and Tappia *et al.* (2015), in-depth interviews with logistics and warehouse managers were conducted to validate the model. As previously acknowledged, existing models' significance in application to real companies is mostly unknown. Analytical models often rely upon a set of assumptions, and their insights are sometimes criticised as being too theoretical but not practical enough (Choi *et al.*, 2016). To overcome this challenge, interviews were crucial to validate whether the insights are logical and applicable in the real world, thereby addressing the last validation stage (Sodhi and Tang, 2014).

Leveraging the wide contact database available to the authors' research group, a provisional list of companies was drawn up. A group of 26 companies were first identified, selected based on their past experience and projects dealing with environmental sustainability at logistics facilities. Among those, 11 companies confirmed their availability to share data, so that detailed information was collected on one warehouse for each company. Since confidentiality was ensured, company names cannot be revealed. Sampling choice was driven by the fact that they had already introduced a monitoring system (offered by a commercial tool) to assess the environmental impact of their warehouses, also distinguishing among different sources of consumption. Consequently, at least partial (e.g. not splitting by functional areas) consumption and emission data were available to make comparison and validate the model's results. The key informants for the 11 companies were wide-acknowledged experts in the field, with a more-than-ten-years' experience and a long history of involvement in energy efficiency projects for logistics facilities. The considered warehouses differed in terms of industry sector, building features, flows, consumption figures, and energy efficient solutions currently in place. This increased the external validity of the study, while internal validity was guaranteed by framing the conceptual framework leveraging the previous literature (Yin, 2014). Data triangulation was broadly applied, and multiple sources including industry reports, news articles, and other available public documents corroborated evidence and improved the study's construct validity. Internal and construct validity were also supported by the adoption of an analytical approach for model development, thus providing clear functions and making explicit the underlying assumptions. Lastly, the draft of notes taken during the interviews and the model's outputs were sent back to the interviewees to check the level of validity and accuracy, increasing the study's reliability (Yin, 2014). As such, comparisons were made between the model's results and the partial data already available to the companies.

Model design

To calculate GHG emissions of logistics facilities, it is important to determine the system boundaries (organisational, spatial, and temporal) based on standardised criteria (Freis *et al.*, 2016). As concerns organisational and spatial boundaries, the GHG Protocol Corporate Accounting and Reporting Standard (WRI and WBCSD, 2013) provides requirements and guidance to assess the GHG emissions caused by logistics activities at warehouses (Rudiger *et al.*, 2016). Then, a meaningful comparison of emissions over time requires a consistent timeframe. In line with the GHG Protocol Corporate Standard, the proposed model considers one year as a timeframe. Moreover, the GHG Protocol requires to categorise emissions as either direct or indirect (WRI and WBCSD, 2013), thereby identifying their Scope (Huang *et al.*, 2009). Most companies could find it manageable to obtain primary consumption data (i.e. measured values) for Scopes 1 and 2. Instead, including Scope 3 emissions into a GHG balance is often problematic, as they could relate to a broad range of sources (Rudiger *et al.*, 2016). As a high accuracy level can be obtained only when primary consumption data is used, the model proposed in this study limits its boundaries to Scope 1 and 2 emissions.

The architecture of the model, presented in Figure 3, is composed of four sections: inputs, where the user fills in the data required to run the model; contextual data; model algorithms, i.e. where the mathematical formulas are applied to assess the environmental impact associated to the logistics site; and outputs, to display results. Each section is illustrated hereinafter.

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Figure_3

Model inputs

Inputs are grouped into three main categories:

- Warehouse information, including warehouse type (e.g. plant warehouse, central warehouse, regional hub, transit point, distribution centre), industry sector, location, year of construction, floorspace [m^2], maximum clear building height [m], temperature range [°C], throughput capacity [pallets/year], and solutions currently adopted for energy saving;
- Data related to warehouse flows, equipment used (e.g. material handling equipment, number and types of lamps) and features (e.g. floorspace [m^2], height [m], volume [m^3], temperature range [°C]) of each functional area, with particular reference to receiving/shipping, put-away/storage/picking, cross-docking/sorting, and offices;
- Consumptions data on an yearly basis, related to electric energy usage, fuels, refrigerants, water and waste.

As far as electric energy is concerned [kWh/year], additional inputs are required, namely: (i) Scope, (ii) energy coming from renewable resources (if any), including both self-produced electric energy from photovoltaic panels or electric energy bought from certified renewable resources [kWh/year]; (iii) composition in terms of electric energy mix [%], with consumption percentages related to different end-use types. In case no estimation is available, the model allows for considering pre-set average values taken from secondary sources.

Looking at fuels, for each type (e.g. diesel, liquefied petroleum gas (LPG), or compressed natural gas (GNC)), Scope, consumption figures [l/year or kg/year] and related purpose (i.e. HVAC or MHE) have to be specified. Data about refrigerants include the type(s) of refrigerants used, and the yearly quantity topped-up (if any). Information about water usage is also required (m^3/year).

Finally, according to DEFRA (2019) waste classification, data about waste are clustered into: construction materials, refuse (i.e. discarded materials such as organic and waste), electrical items (including batteries and Waste Electrical & Electronic Equipment), metal, plastic, paper, and others. For each waste type, the related quantity and disposal method(s) have to be specified among these options: i) reuse; ii) open loop recycling into other products; iii) closed loop recycling into the same product; iv) combustion through incineration and subsequent electricity generation; v) composting; vi) landfilling.

Contextual data

Contextual data refer to conversion factors associated with the model inputs. Multiple sources have been considered, such as DEFRA (2015 and 2019) and CLECAT (2012). DEFRA conversion factors were originally developed for UK-based companies, but their use has been previously acknowledged and extended also to other countries (Mangiaracina *et al.*, 2015). Table 2 summarises the main contextual data considered for data computation in terms of electric energy, fuels, refrigerants, water, and waste. Waste deserves a specific attention, as several types of waste need to be considered. Furthermore, their related contextual factor change according to the waste disposal method (DEFRA, 2019). Therefore, specific conversion tables were used to encompass all the possible scenarios.

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Algorithms for data computation

GHG emissions are often calculated on the basis of measured or statistical values related to resource consumption. As a direct measurement of GHG emissions is not practical, it is important to identify appropriate emission/conversion factors (Rudiger *et al.*, 2016). However, the validity of results strongly depends on the accuracy of consumption values. To estimate the logistics site environmental impact five main sources of consumption have been considered, as per the literature review. Concerning electric energy, the total consumption is obtained starting from the yearly electric energy usage (kWh/year). In case of production from renewable sources (e.g. self-production by means of photovoltaic panels, or else purchase of 'green' energy from the grid), the model subtracts such amount of electric energy to compute the overall emission figure (kg CO_2eq). The following Equation 1 is then applied to estimate the emissions due to electric energy that is not produced from renewable sources:

$$\text{Electric energy emissions } [kg\ CO_2e] = \text{Electric energy usage } \left[\frac{kWh}{year}\right] * \text{ Conversion factor of Energy generated } \left[\frac{kg\ CO_2e}{kWh}\right] \tag{1}$$

Looking at fuels, emissions are calculated for each fuel type depending on their quantities and related conversion factors. Both direct and indirect energy consumed, as well as direct and total emissions, are calculated as proposed in the following Equations 2,3,4, and 5:

$$\textit{Direct energy [MJ/year] = Fuel quantity } \left[\frac{l}{year}\right] \left(or \left[\frac{kg}{year}\right]\right) * \textit{ Direct energy conversion factor } \left[\frac{MJ}{l}\right] \left(or \left[\frac{MJ}{kg}\right]\right) \tag{2}$$

$$\textit{Total energy [MJ/year] = Fuel quantity } \left[\frac{l}{year}\right] \left(or \left[\frac{kg}{year}\right]\right) * \textit{ Total energy conversion factor } \left[\frac{MJ}{l}\right] \left(or \left[\frac{MJ}{kg}\right]\right) \tag{3}$$

$$\textit{Direct emissions [kg } CO_2\textit{eq/year] = Fuel quantity } \left[\frac{l}{year}\right] \left(or \left[\frac{kg}{year}\right]\right) * \textit{ Direct emission conversion factor } \left[\frac{kg\ CO_2eq}{l}\right] \left(or \left[\frac{kg\ CO_2eq}{kg}\right]\right) \tag{4}$$

$$\textit{Total emissions [kg } CO_2\textit{eq/year] = Fuel quantity} \left[\frac{l}{year}\right] \left(or \left[\frac{kg}{year}\right]\right) * \textit{Total emissions conversion factor} \left[\frac{kg\ CO_2eq}{l}\right] \left(or \left[\frac{kg\ CO_2eq}{kg}\right]\right) \tag{5}$$

The model also provides an estimation of the total emissions per Scope and the split by end-use type. As far as refrigerants are concerned, the total emissions are computed by summing the contributions provided by each refrigerant type (Equation 6):

$$\text{Emissions related to refrigerant j } [kg\ CO_2e] = \text{Topped-up refrigerant j} \left[\frac{kg}{year}\right] * \text{Total emission conversion factor j} \left[\frac{kg\ CO_2e}{kg}\right] \tag{6}$$

Total emissions related to water usage are computed as the sum of:

- Supply emissions, i.e. due to the activities performed by the water supply company, from water withdrawal to the supply to the user's site;
- Treatment emissions, i.e. related to water returned into the sewage system through mains drains.

To estimate water-related emissions, the following equation (7) is applied:

$$\text{Water emissions } [kg\ CO_2e] = \text{Water consumption} \left[\frac{m^3}{year}\right] * \text{Supply emission factor} \left[\frac{kg\ CO_2e}{m^3}\right] + \text{Water consumption} \left[\frac{m^3}{year}\right] * \text{Treatment emission factor} \left[\frac{kg\ CO_2e}{m^3}\right] * 2 \tag{7}$$

Emissions coming from water treatments are doubled to consider both the sewer and purifier activities. Emissions related to waste are then computed for each type and eventually added together into one figure, as shown in Equation 8.

$$\text{Waste emissions } [kg\ CO_2e] = \sum_{waste\ type}(\text{Consumption} \left[\frac{tonnes}{year}\right] * \text{Disposal method} \left[\frac{kg\ CO_2e}{tonne}\right]) \tag{8}$$

Finally, the emissions allocation to each individual functional area of the logistics site is performed by considering the following main sources of consumption: electric energy, fuel, and refrigerants.
First, emissions related to electric energy can be computed as the sum of four end-use types: lighting, HVAC and refrigeration, handling (MHE), and other (e.g. servers). As far as lighting is concerned, both the number of spotlights and the type of lighting technology are taken into account, as different types of lighting systems have different emission factors. Considering cooling/heating, the main driver for emission allocation is the volume of each functional area. When the logistics site is composed of both ambient-temperature and controlled-temperature areas, specific conversion factors are adopted. Looking at MHE, the number of forklifts used within each functional area is considered. As the emission factors depend on the forklift technology, the model associates specific

weights to forklifts based on data available from secondary sources. Moreover, if the same forklift is shared among multiple functional areas, different conversion factors are considered.
Second, emissions related to fuel consumption are allocated. When fuel consumption is referred to heating purposes – as it mostly happens in logistics sites as per Fichtinger *et al.* (2015) –, the model allocates the related emissions based on the volume of each functional area. Lastly, emissions related to the use of refrigerants are also allocated depending on the volume of each functional area, applying specific conversion factors if the logistics site is composed of both ambient-temperature and controlled-temperature areas.

Model outputs

As an output, the model offers a dashboard with EPIs, and tables and graphs displaying the results with different views and aggregation levels (e.g. total emissions, direct emissions per source, and emission mix composition).
Logistics facilities undergo significant changes in order quantities, logistics items, or demanded services per year (Rudiger *et al.*, 2016). To define appropriate EPIs, it is recommended to analyse how the material flow within logistics facilities is usually described and processed (Dhooma and Baker, 2012; Richards, 2018). Consequently, in addition to the absolute value of GHG emissions, specific EPIs that put the annual amount of GHG emissions in reference to the relevant logistics performance (e.g. number of goods handled and stored at a logistics facility) are proposed. Further, having introduced an allocation scheme for warehouses' functional areas, additional EPIs can reflect the impact of the different types of logistics activities. Overall, EPIs depicting the current scenario can include:

- Direct emissions [kg CO_2eq] due to warehousing activities controlled by the company (Scope 1);
- Total emissions [kg CO_2eq], as the sum of direct and indirect emissions (Scope 2);
- Emissions per m^2 [kg CO_2eq/m^2], to allow comparisons among logistics sites differing in building features such as floorspace or height;
- Emissions per pallet stored within the logistics site [kg CO_2eq/pallet];
- % saved emissions [%] by sourcing electric energy from certified renewable resources and/or self-production from photovoltaic panels;
- Emissions [kg CO_2eq and as a % of the total emissions] associated to specific warehousing functional areas, such as receiving/shipping, put-away/storage/picking, cross-docking/sorting, and offices.

Finally, the model provides a list of the top consumption areas (i.e. with higher generated emissions) so as to identify potential directions to reduce the environmental impact.

Model application and validation

The model was applied to eleven warehouses, belonging to as many companies, where a monitoring system was already in place to assess the environmental impact of the logistics site. Therefore, a set of updated reliable data – although partial – were available for comparisons. Table 3 reports a summary of the main features related to the examined cases. The companies were either logistics service providers, retailers, and express couriers. It should be noted that some logistics sites have been subject to recent revamping with the installation of energy-efficient solutions. In some cases renewable energy sources were used, or photovoltaic panels were adopted for self-production. As all the companies were promised anonymity, no names can be displayed.

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Table_3

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The model outputs were carefully checked and validated with each company individually. This showed that the model outputs were aligned to the partial available EPIs provided by the assessment tool in use by the companies, and also attested the robustness of the proposed model. Besides, the model provided companies with additional figures that were unavailable before. Such figures were found particularly valuable since they helped promote a more holistic view of the environmental performance of their logistics sites.

Table 4 and Figure 4 respectively provide examples of results in terms of emissions, namely: (i) split by source of consumption and, in case of electric energy, by end-use type; (ii) split by functional area of the logistics site. Most of the total emissions were due to electric energy consumption, where either lighting – in case of ambient warehouses – or HVAC plus refrigeration – in case of temperature-controlled goods – were found as the primary end-use types. Looking at warehouse functional areas, the one with higher incidence in terms of emissions was picking/storage.

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Table_4

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Figure_4

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Discussion

Today, the awareness about the relevance of sustainability has sharply increased, and how to assess, monitor, and manage warehouse GHG emissions is a major research and practical concern (Oberhofer and Dieplinger, 2014; Fichtinger *et al.*, 2015; Rudiger *et al.* 2016). However, there is no holistic methodological approach to estimate the total energy demand of different types of logistics centres (Freis *et al.*, 2016; Shaw et al., 2021). This study offers a comprehensive assessment and allocation model for warehouse consumption and GHG emission estimation. Overall, the following characteristics of the proposed model could be pointed out:

- ***Inclusiveness:*** Unlike the majority of available models about energy efficiency, which are focused on one or few warehousing sources of consumptions, the proposed model takes into account all the main warehouse energy consumption areas, providing a comprehensive output that can be also split by both source (electric energy, fuel, refrigerants, water and waste) and warehousing functional area. In line with previous contributions (e.g. Dhooma and Baker, 2012; Ries *et al.*, 2017), the model distinguishes among different end-use types for each source of consumption, e.g. lighting, HVAC systems, and MHE. Besides, the proposed model is able to take into account different MHE and related technologies, i.e. electric and fuel-based (i.e. diesel, LPG, or CNG). Indeed, nowadays companies may use energy generated from different sources and technologies, and this variety is reflected in the complexity of data gathering. For example, companies can buy energy from the national electrical grid, from renewable sources or directly produce it for self-consumption. Also, electricity GHG emissions are dependent on the energy mix used (Fichtinger *et al.*, 2015);
- ***User-friendliness:*** The model interface is simple and uses drop-down menus and pre-filled grids to be more user-friendly;
- ***Actionability:*** It allows to split consumption and emissions for each functional area within warehouses, to prioritise the efforts to improve them with the least waste of time and resources;
- ***Flexibility:*** The model outputs can be used by the company either to analyse the current situation, or else to take actions for future improvements. This model can be applied the first time to identify the major weaknesses of a logistics site in terms of energy efficiency and environmental performance, and evaluate areas of intervention. The model can be also applied over time to monitor the environmental performance of a single logistics site or even multiple warehouses within a logistics network.

As its contribution, the study first extends previous research by considering a broad set of sources of consumption, including not only electric energy (as per Lee *et al.*, 2017) but also fuels, refrigerants, water, and waste (Bank and Murhpy, 2013; Fichtinger *et al.*, 2015). Second, the proposed model not only offers a comprehensive figure related to the environmental performance of the entire logistics site, but also provides individual EPIs splitted by warehouse main functional areas, thus associating emissions to the specific warehouse operations being performed, i.e. receiving/shipping, put-away/storage/picking, cross-docking/sorting, and offices. This addresses an identified need in the academic literature (Bartolini *et al.*, 2019). Indeed, the few available studies (e.g. Dhooma and Baker, 2012; Fichtinger *et al.*, 2015; Rudiger *et al.*, 2016) considered the entire warehouse as the unit of analysys, without distinguishing the environmental performance of individual functional areas, nor developing separate EPIs. Other previous contributions focused on specific warehousing operations, such as storage and order picking, being the most labor-intensive – as well as most energy consuming (Ene *et al.*, 2016) – in warehouses equipped with manual systems, and very capital-intensive in warehouses with automated systems (e.g. Meneghetti and Monti, 2014; Tappia *et al.*, 2015). However, they did not provide a comprehensive view of the impact of each warehousing area on the overall environmental performance of the logistics site. Third, the proposed model considers the main end-use consumption types to investigate the environmental impact at a micro-level (i.e. for a particular warehouse) also offering applications that leverage real-world empirical data. This allows for developing insights related to existing scenarios, while the literature review highlighted a lack of analytical models being supported by empirical data (Bartolini *et al.*, 2019). Finally, the proposed model offers comparability in terms of carbon footprint figures ad EPIs thanks to standardised emission factors and a set of interpretation parameters, as recommended by Rudiger *et al.* (2016). Therefore, it provides wide and practical opportunities for benchmarking the environmental performance of logistics sites (Ries *et al.*, 2017). This can be valuable for both company internal assessment and comparisons with competitors or other supply chain actors (Minashkina and Happonen, 2020). The model can enable organisations to measure and externally report their environmental performance. Important benefits could reside both within companies boundaries (e.g. waste reduction and operational efficiency) and beyond, improving reputation/brand image and collaboration and transparency with different stakeholders (customers and suppliers) (Shaw et al., 2021).

Conclusions

The key role of logistics sites from a sustainability perspective has been progressively recognised from both academics and practitioners. However, to date they both acknowledge a scarcity of data about the impact of warehousing on global emissions, and a lack of a comprehensive standardised methodology for assessing the environmental impact of logistics sites. This study provides a structured methodology to quantify the environmental impact of warehouses, in terms of both consumptions and generated GHG emissions. It combines multiple methods, offering a tool that is built upon analytical modelling but also leverages interviews with practitioners as triangulation can help validate the findings, boosting the scientific merit of the research (Choi *et al.*, 2016). Involving practitioners provided motivation for the problem, and later allowed for collecting real-world data and validating model's results to exhibit its concrete relevance. The proposed tool could thus be a useful, user-friendly instrument for companies willing to improve warehouses environmental performance.

Both academic and managerial implications could be drawn. As concerns the former ones, the study addresses the need for a standardised and replicable methodology to assess the environmental impact of logistics sites. It leverages previous contributions to include different sources of consumption and the related end-use types, further splitting consumptions and emissions by warehouses' functional areas. Also, the model offers a set of EPIs that may be valuable also for practitioners to have a clearer understanding of their company's performance. Today companies' reputation is increasingly linked to its environmental stewardship, and environmental performance has been widely acknowledged as an important competitive advantage (Waltho et al. 2019; Shaw et al., 2021). Our study contributes to this research field by providing a robust support for environmental impact quantification. This also has relevant managerial implications, because a structured and holistic assessment of the environmental performance of logistics facilities could support internal analyses and benchmarking actions, also driving actions for improvement that leverage sustainability as a critical success factor.

Lastly, study's limitations must be acknowledged as they could pave the way for promising future research avenues. First, analytical modelling required to introduce some assumptions, the main one being that multi-temperature and multi-heights warehouses were excluded. Indeed, for data computation it has been assumed that each warehouse has a homogeneous temperature as well as a homogeneous clear building height (i.e. taken as the highest one in case of multi-heights). Therefore, complexity due to multi-temperature and multi-heights warehouses was neglected, but could be addressed in future expansions of the model. Second, the model calculates CO_2eq emissions due to electric energy usage, fuel, refrigerants, water, and waste. However, the split by functional areas considered only electric energy usage, fuel, and refrigerants as main sources of consumpions, and future studies could broaden the perspective to include the impact due to water and waste. Third, the proposed model allows to estimate the emissions of one warehouse at time; for this reason, companies that have more than one warehouse and are willing to compute the emissions generated by each of them have to apply the model multiple times, one for each warehouse. From this viewpoint, future studies could explore network effects related to managing multiple warehouses.

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Reference	Year	Functional areas				Sources of consumption									Application of assessment methods to warehousing contexts (Y/N)	Scope
						Electric energy				Fuel						
		Receiving	Put-away, storage, picking, sorting	Shipping	Unspecified	Lighting	HVAC + Refrigeration	Handling (MHE)	Other	HVAC	Handling (MHE)	Refrigerants	Water	Waste		
Rai *et al.*	2011				x	x	x			x					Y	unspecified
Dhooma and Baker	2012				x	x	x	x		x	x				Y	unspecified
Bank and Murphy	2013				x	x		x			x		x	x	N	unspecified
Meneghetti and Monti	2013		x					x							N	unspecified
Meneghetti and Monti	2014		x					x							N	unspecified
Lerher *et al.*	2014		x					x							N	unspecified
Meneghetti and Monti	2015		x				x	x							Y	unspecified
Meneghetti *et al.*	2015		x					x							N	unspecified
Fichtinger *et al.*	2015				x	x	x	x		x	x				N	unspecified
Tappia *et al.*	2015		x					x							Y	unspecified
Ene *et al.*	2016		x					x							N	unspecified
Facchini *et al.*	2016		x					x			x				N	unspecified
Freis *et al.*	2016	x	x	x		x	x	x							N	unspecified
Rudiger *et al.*	2016				x	x	x	x		x	x	x		x	Y	2
Accorsi *et al.*	2017		x			x	x	x		x	x				Y	unspecified
Bortolini *et al.*	2017		x					x							Y	unspecified
Lee *et al.*	2017				x	x	x	x	x (servers and computers)	x	x				N	unspecified
Ries *et al.*	2017	x	x	x		x	x	x		x	x				N	unspecified
Carli *et al.*	2020		x			x	x	x							N	unspecified
Ekren *et al.*	2020		x					x							N	unspecified

Table 1 – Literature review: main contributions examined

Contextual data	Description	Figure	Unit of measure	Source
Electric Energy	Energy generated	0.25	kg CO_2eq/kWh	DEFRA (2019)
Fuels*	Diesel	3.90	kg CO_2eq/kg	CLECAT (2012)
	LPG	3.43	kg CO_2eq/kg	CLECAT (2012)
	GNC	3.07	kg CO_2eq/kg	CLECAT (2012)
Refrigerants	R717	0.00	kg CO_2eq/kg	DEFRA (2015)
	R134a	1,410.00	kg CO_2eq/kg	DEFRA (2015)
	R404A	3,922.00	kg CO_2eq/kg	DEFRA (2019)
	R407A	2,107.00	kg CO_2eq/kg	DEFRA (2019)
	R407C	1,774.00	kg CO_2eq/kg	DEFRA (2019)
	R410A	2,088.00	kg CO_2eq/kg	DEFRA (2019)
	R507A	3,985.00	kg CO_2eq/kg	DEFRA (2019)
	R12	8,100.00	kg CO_2eq/kg	DEFRA (2015)
	R32	670.00	kg CO_2eq/kg	DEFRA (2015)
	R125	3,450.00	kg CO_2eq/kg	DEFRA (2015)
Water	Water supply**	0.34	kg CO_2eq/m^3	DEFRA (2019)
	Water treatment***	0.71	kg CO_2eq/m^3	DEFRA (2019)
Waste	Paper and board – Closed-loop	21.35	kg CO2e/ton	DEFRA (2019)
	Paper and board – Composting	10.20	kg CO2e/ton	DEFRA (2019)
	Plastics – Combustion	21.35	kg CO2e/ton	DEFRA (2019)
	Plastics – Landfilling	8.99	kg CO2e/ton	DEFRA (2019)

* *Well-to-wheels (vehicle and energy processes), i.e. direct and indirect emissions. Consumption here refers to primary energy consumption including all losses from the upstream chain.*

** *Used to account for water delivered by the water supply network to the warehouse.*

*** *Used for water returned into the sewerage system through main drains and then cleaned.*

Table 2 – Main contextual data: examples

Case No.	Tenant	Type of logistics site	Year of construction	Total floorspace [m^2]	Max clear building height [m]	Temperature [°C]
Case 1	3PL	Transit Point	1991	6,260	6.5	0-4
Case 2	3PL	Central Distribution Centre	1995	20,050	9.5	0-4
Case 3	Retailer	Distribution Centre	1980	20,000	8,3	Ambient
Case 4	Retailer	Distribution Centre	2003	20,000	9,.3	Ambient
Case 5	3PL	Central Distribution Centre	2008	32,000	14.5	Ambient
Case 6	3PL	Distribution Centre	2008	12,000	5.4	Ambient
Case 7	Retailer	Central Distribution Centre	1992	41,900	11.0	Ambient
Case 8	3PL	Central Distribution Centre	2008	33,360	15.0	Ambient
Case 9	Retailer	Distribution Centre	2017	140,000	12.5	Ambient
Case 10	3PL	Distribution Centre	2002	43,000	10.5	Ambient
Case 11	Retailer	Distribution Centre	1995	8,000	10.5	Ambient

Table 3 – Model application and validation: main features of the examined cases

Case No.	Emissions by source of consumption			Electric energy: Emissions by end-use type [%]			
	Electric energy [ton CO_2eq]	**Fuels [ton CO_2eq]**	**Refrigerants [ton CO_2eq]**	**Lighting [%]**	**HVAC + Refrigeration [%]**	**MHE [%]**	**Other [%]**
Case 1	600.3	24.7	147,5	5%	80%	3%	12%
Case 2	1,551.1	0	119,6	5%	73%	2%	20%
Case 3	452.0	122.0	0	38%	5%	18%	29%
Case 4	451.0	123.0	0	38%	5%	18%	29%
Case 5	503.6	0	0	80%	0%	20%	0%
Case 6	142.7	43.0	0	14%	0%	85%	1%
Case 7	585.9	0	0	45%	0%	55%	0%
Case 8	252.8	81.7	0	96%	0%	2%	2%
Case 9	1,003.5	0.5	0	20%	0%	80%	0%
Case 10	212.1	0.1	0	65%	10%	25%	0%
Case 11	16.0	0	6.0	49%	0%	12%	39%

Table 4 – Model application and validation: examples of emissions related to different sources of consumption and end-use types

Figure legends

Figure 1 – Research design: research stages

Figure 2 – Conceptual framework: warehousing activites and related sources of consumption

Figure 3 – Model architecture

Figure 4 – Example of model outputs: emissions split by warehouse functional areas

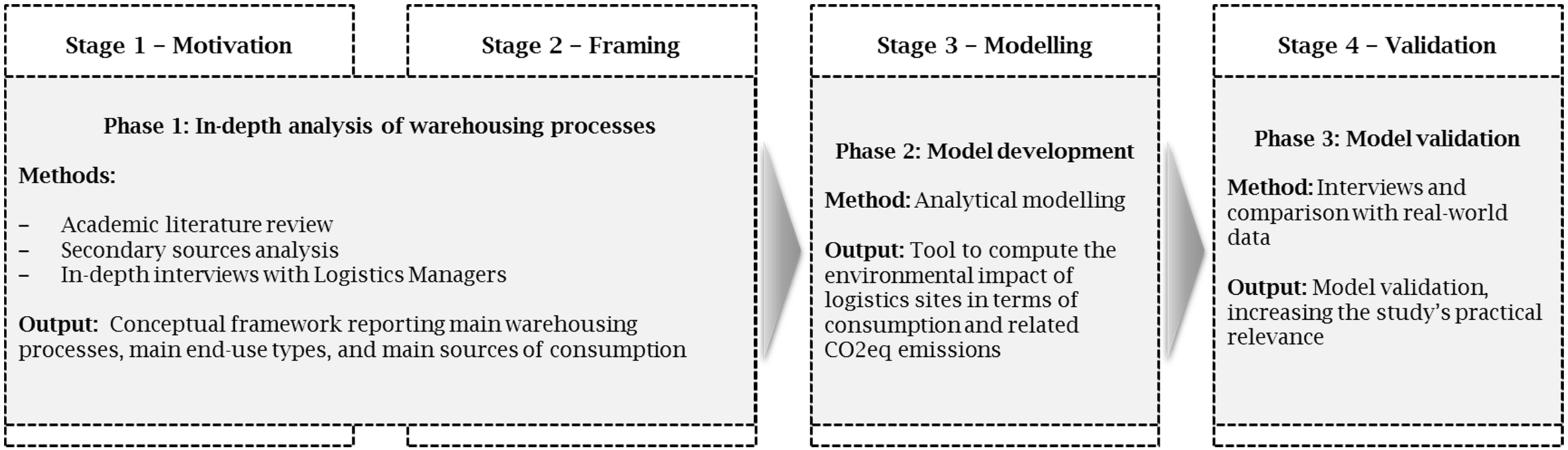

Figure 1 – Research design: research stages

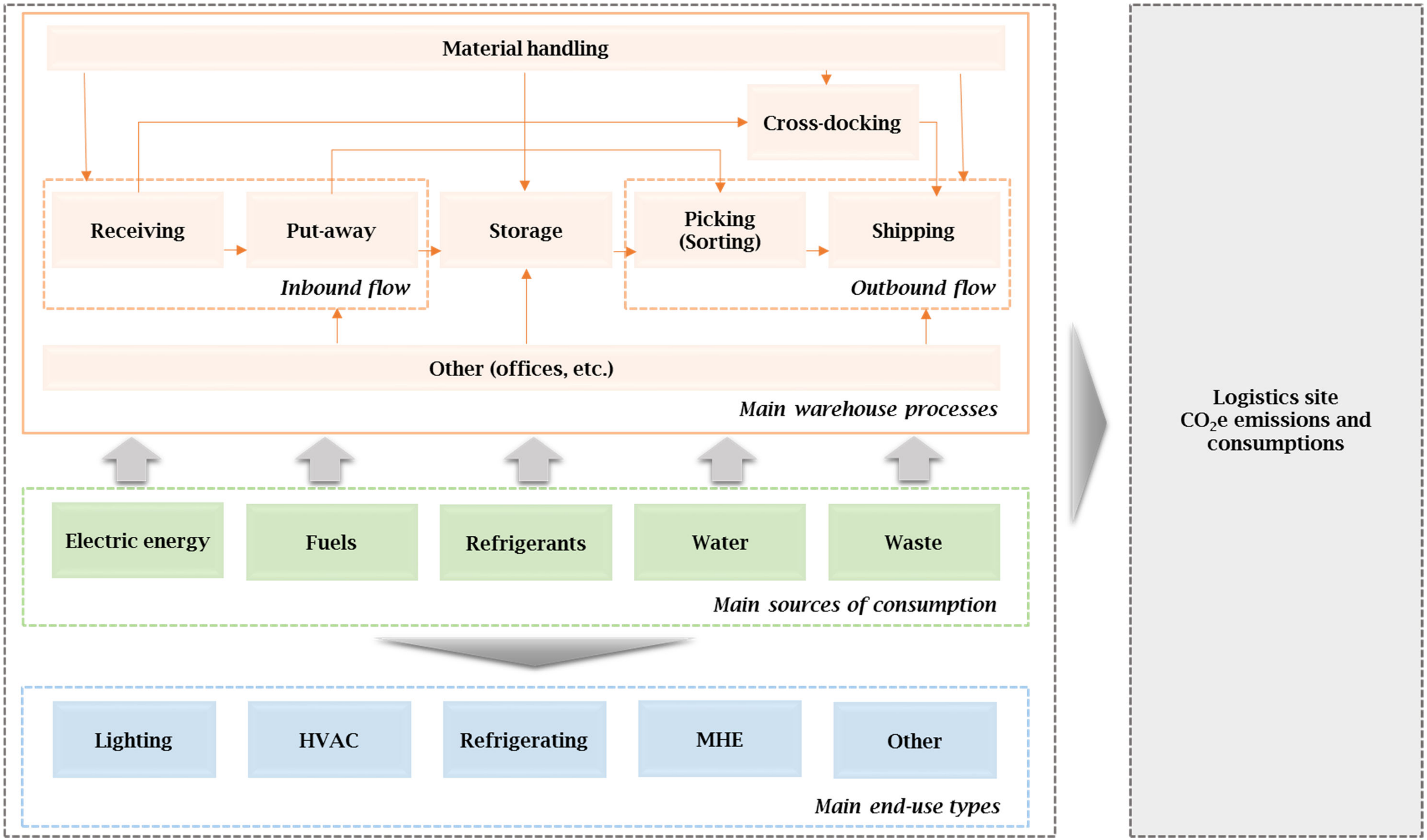

Figure 2 – Conceptual framework: warehousing activites and related sources of consumption

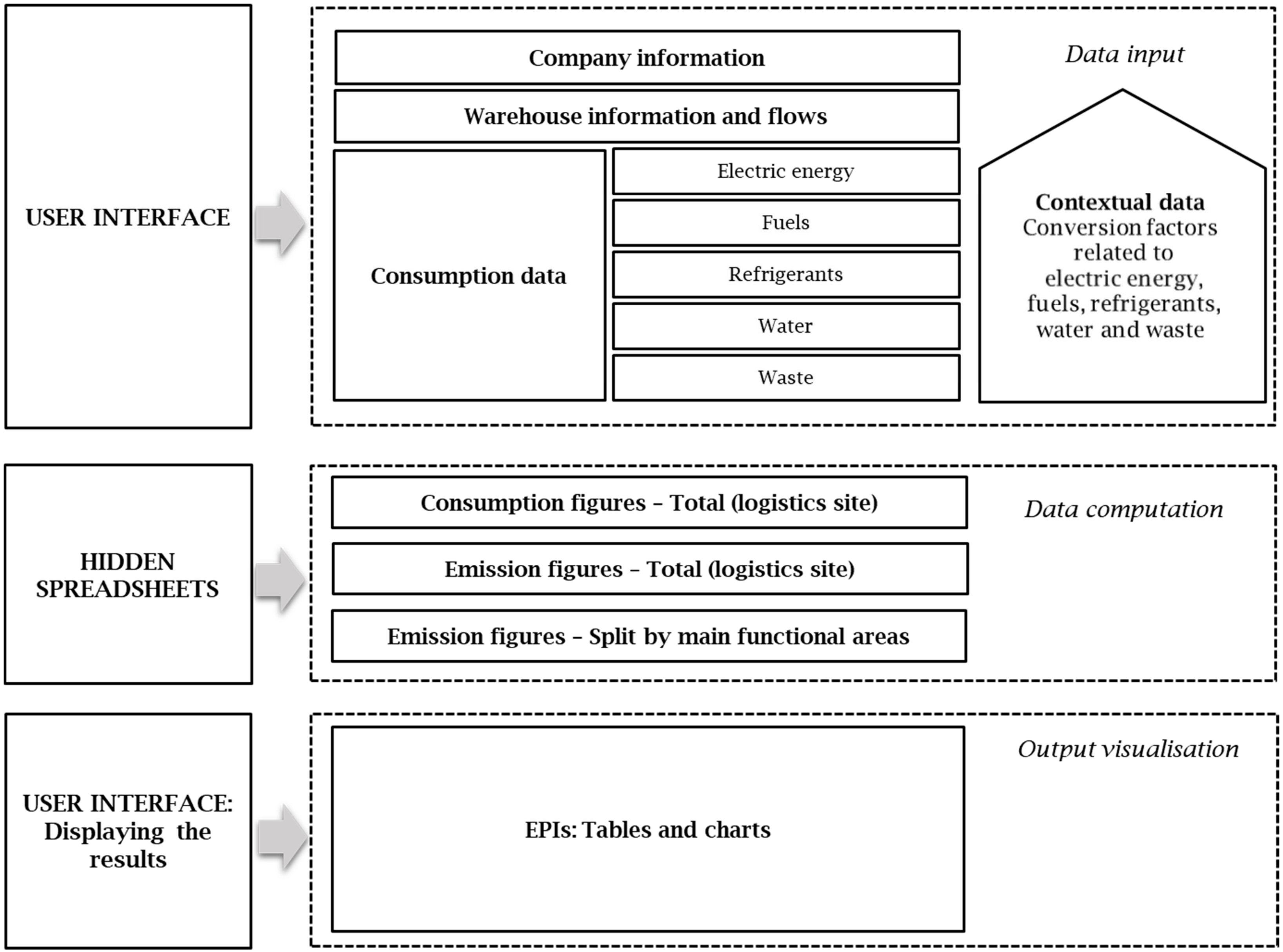

Figure 3 – Model architecture

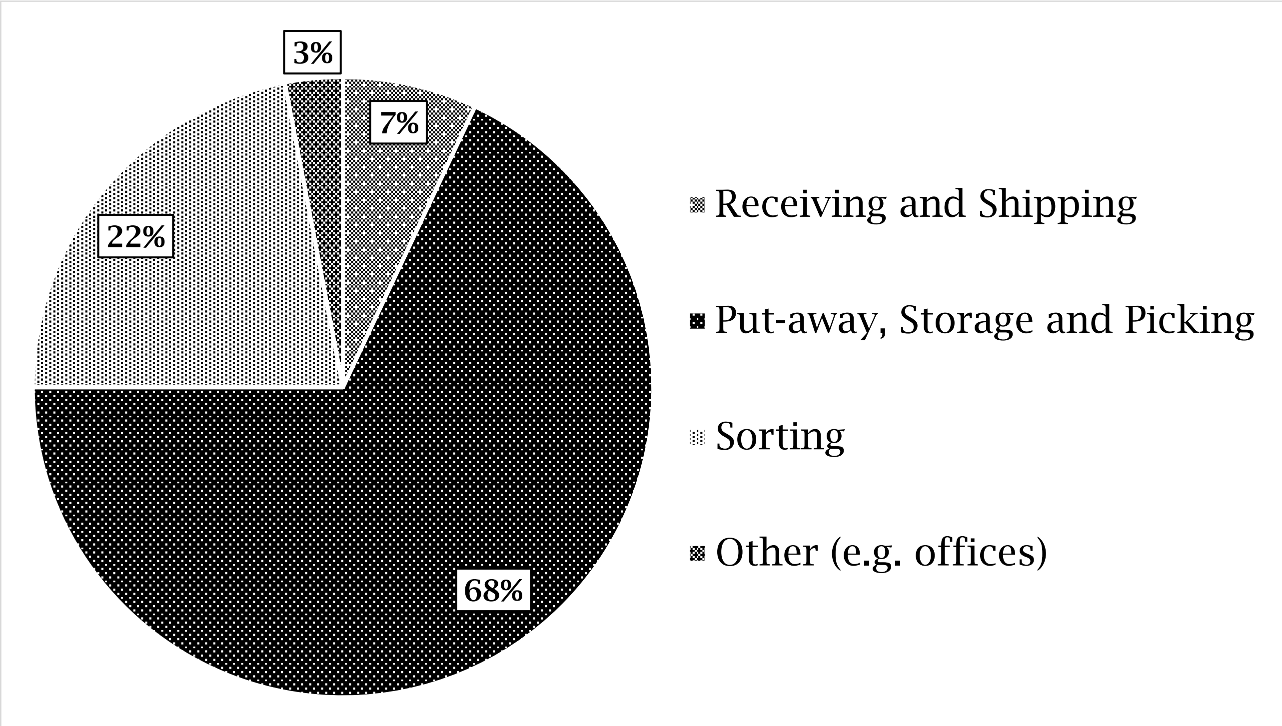

Figure 4 – Example of model outputs: emissions split by warehouse functional areas