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E-grocery: Comparing the environmental impacts of the online and offline purchasing processes

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The growth of e-commerce has been accompanied by concerns about its environmental sustainability compared to that of bricks-and-mortar offline shopping. The media often considers e-commerce to be less sustainable despite the lack of conclusive studies to support this viewpoint. There are a few quantitative studies available in the literature that demonstrate that the differences in overall emissions strongly depend on the type of industry and the boundaries considered. This study applies an activity-based approach to assess the environmental impacts (in terms of $kgCO_2e$) of the online and offline purchasing processes in the grocery industry for all shopping phases: replenishment, pre-sale and sale, picking and assembly, delivery and post-sale. The assessment model was applied in Italy, where e-grocery has experienced significant annual growth. Overall, the results indicate that e-grocery is potentially more sustainable than bricks-and-mortar shopping, with emissions ranging from 10%–30% lower, depending on the specific context.

Keywords: e-grocery, environmental impact, sustainability, last-mile delivery, e-commerce, logistics

1. Introduction

The environmental sustainability of B2C (business-to-consumer) e-commerce has become an important issue, and its relevance is expected to increase in the future with the growth of online sales, both in terms of market value and penetration rate (Rizet et al., 2010; Bertram and Chi, 2018; Seghezzi and Mangiaracina, 2021). In this regard, a major concern is the environmental sustainability of the logistics activities that are required to deliver the products ordered online (Zhao et al., 2019). E-commerce is often referred to by the media as being a less-sustainable solution than bricks-and-mortar commerce (B2C eCommerce Observatory, Politecnico di Milano, 2019), mainly because of the last-mile delivery step. However, as detailed in the next section, there is not a general consensus in the literature on the real impacts of e-commerce on the environment. Indeed, the results of the relevant studies must be interpreted according to the specific conditions of the considered scenarios (Van Loon et al., 2014), such as the number of processes, means of transport, distribution network and last-mile delivery solutions. In particular, many of these factors depend on the industry.

This study focuses on the grocery industry, which has numerous peculiarities. First, the order composition is different from that in most industries. The typical e-grocery order is made up of multiple single-piece lines, with a wide product range (including dry, frozen and fresh perishable items). By contrast, in other retail sectors (e.g., fashion, consumer electronics), orders are generally composed of one or a few pieces (Agatz et al., 2008; Gee et al., 2019). Second, the distribution network for e-grocery is tailored to its specific needs. In particular, the distribution centres that fulfil e-grocery orders are generally built close to customers to shorten the transport lead time (Hays et al., 2005). Third, e-grocery shopping has a lower, almost null, return rate than other sectors (Cairns, 2005). In summary, e-grocery deliveries are rapid, with tight time windows and peculiar temperature requirements to accommodate ambient, chilled and frozen items (Cairns, 2005; Heard et al., 2020).

When comparing the environmental impacts of online and offline shopping, all emissions from the point of divergence of the two processes should be included (Edwards et al., 2011). This approach has been employed when investigating other industries (e.g., fashion, book) (e.g., Mangiaracina et al., 2016; Williams and Tagami, 2002), but there has not been an in-depth study on the grocery industry from this perspective. To address this gap in the literature, this study aims to assess the environmental impact of the purchasing process in the grocery industry by comparing the online and offline scenarios. Specifically, the environmental impact is measured in terms of carbon dioxide equivalent (CO_2e) emissions. The assessment is done using an activity-based model, and therefore, all the basic activities performed in both the online and offline distribution systems are analysed in detail. This paper presents the results obtained by applying this model to the case of Italy. This topic is currently becoming a focus of debate in this country because e-grocery has exhibited significant growth over the last few years (+45% in 2019), even though its penetration rate (0.8%), an expression of online sales as a percentage of overall retail sales, is still low compared to those of other e-commerce sectors, such as consumer electronics (penetration rate equal to 27%) and fashion (9%) (B2C eCommerce Observatory, Politecnico di Milano, 2020).

The remainder of the paper is organised as follows. The next section presents the evidence obtained from a literature review. Then, the study's objective and the methodology are described. Section 4 reports the structure of the activity-based model. The results and sensitivity analyses are shown in section 5. In the final section, conclusions are drawn, and research limitations are identified.

2. Literature review

The literature analysis aims to illustrate the main contributions to the research on the environmental implications of B2C e-commerce, specifically from a logistic perspective. First, a summary of the environmental impacts of e-commerce, regardless of the industry, is presented. Second, a discussion that focuses on e-grocery is provided.

2.1 E-commerce's environmental impact

Some studies in the literature compare the B2C e-commerce processes with the bricks-and-mortar offline channel from an environmental perspective. Table 1 presents the main papers on this topic (the list may lack minor contributions because it does not reflect the results of a systematic literature review, as the aim was to collect the most representative studies in the field). In about 50% of the studies, the results seem to indicate that e-commerce is more environmentally sustainable than bricks-and-mortar commerce. Slightly less than half of the studies concluded that the results depend on several factors with only a paper displaying a negative opinion in this regard. As described by Velásquez et al. (2009), either a qualitative or quantitative approach can be used to study this topic. However, when comparing the environmental impacts of the online and offline purchasing processes, a quantitative approach is particularly appropriate. Siikavirta et al. (2002) applied a supply chain perspective and identified five potential processes that affect the environmental impact of e-commerce: sourcing, production, distribution, retailing and consumption. In each of these mentioned areas, emissions may increase or decrease depending on the conditions. By contrast, Bertram and Chi (2018) identified four differential factors that influence emissions: packaging, transportation, return and disposal.

Several studies have focused on only transport emissions. Most of these studies compared the online and offline purchasing processes considering the activities related to the last-mile delivery (e.g., Siikavirta et al., 2002; Kim et al., 2009; Edwards et al., 2010; Wiese et al., 2012). In particular, they compared the trip made by the customer to reach and return from the store and the delivery tour of the carrier. As an example, Edwards et al. (2010) proposed an analytical method to assess the carbon intensity of e-commerce, with a specific focus on last-mile delivery and personal shopping trips. Herein, they found that home delivery was likely to result in a decrease in emissions when compared to offline shopping. However, the results of their study are applicable only to non-food purchases. Products with very different characteristics, such as refrigerated items, may require different delivery conditions, thus leading to different outcomes. E-grocery deliveries are indeed rapid, with tight time windows and specific conditions to comply with ambient, chilled and frozen temperature regimes (Cairns, 2005). Some studies enlarged the scope of transport activities and considered all distribution activities. As an example, Carling et al. (2015) developed a method to empirically measure the CO_2 footprints of bricks-and-mortar retailing and online retailing from the regional entry point to the consumer's residence: in bricks-and-mortar shopping, the route extends from the entry port via the store to the consumer's residence, while in online shopping, it extends from the entry port via the distribution points to the customer's residence. Moreover, Wiese et al. (2012) compared the transport-related CO_2 emissions of online and bricks-and-mortar shopping based on supply, delivery, order and travel data for a multi-channel clothing retailer and found that online retailing produced less CO_2 emissions under many conditions. The bricks-and-mortar channel tended to be more environmentally friendly when travel distances were short. Thus, when considering transport activities, emissions generated by the online channel are generally considered to be lower than those generated by the bricks-and-mortar channel. However, there are some conditions under which the results suggest the opposite. Aside from the distance (e.g., Wiese et al., 2012), customer behaviour has a strong influence on the results. As an example, the customer may use public transport or walk to the store (Siikavirta et al., 2002), which would have a positive effect on the emissions generated by offline shopping. Moreover, the customer may stop to shop during a previously planned trip (McLeod et al., 2006), such as when driving home from work. Customers may also have different attitudes regarding returns. In general, the importance of the consumer's behaviour was demonstrated by Van Loon et al. (2015), who underlined how choices related to travel, e-fulfilment solutions and basket size determine the environmental sustainability of e-commerce.

In addition to transport activities, emissions related to warehousing activities have been considered in some studies (e.g., Rizet et al., 2010; Van Loon et al., 2015; Mangiaracina et al., 2016). As an example, Rizet et al. (2010) found that shops are less efficient in terms of Greenhouse Gases (GHG) than online fulfilment centres. Moreover, Mangiaracina et al. (2016) assessed the carbon footprint of the purchasing process in the apparel industry and highlighted the huge impact of logistics on total emissions. Warehousing activities are at times linked to the consumption of packaging materials. Packaging materials used by the logistics networks for product fulfilment and delivery make the e-commerce process less environmentally sustainable (Scott Matthews et al., 2001). According to Williams and Tagami (2002), who compared B2C e-commerce with bricks-and-mortar retail in the Japanese book sector with a focus on urban areas, e-commerce seems to use more energy per book delivered than conventional retail because of the high impact of packaging. In addition to packaging, other intervening factors increase the carbon footprint and amount of waste in the environment, in particular shipping speed and returns (especially in the apparel industry) (Bertram and Chi, 2018).

A recent field of study in e-commerce regards omni-channel solutions. First environmental assessments are in industries where e-commerce is more developed. As an example, Giuffrida et al. (2019) compared click and collect (C&C) and mobile shopping in store for fashion products, showing that C&C is more sustainable, mainly due to the heavier impact of transport. Melacini and Tappia (2018) investigated three distribution configurations in omni-channel retailing in the consumer electronics industry: they highlighted that the search for synergies between online and traditional flows, in both warehouse and transport activities, is a key factor for the environmental sustainability of omni-channel systems.

[Take in Table 1]

2.2 E-grocery's environmental impact

The impact of e-grocery on traffic and pollution in cities has been frequently studied (Taniguchi and Kakimoto, 2003; Cairns, 2005; Durand and Gonzalez-Feliu, 2012). As an example, one study showed that the direct replacement of car trips with van trips could reduce vehicle-km by 70% or more (Cairns, 2005). Taniguchi and Kakimoto (2003) developed models of vehicle routing and scheduling with time windows and traffic simulation to evaluate the effects of e-grocery on urban freight transport and the environment. Tehrani and Karbasi (2005) estimated the reduction in emissions related to fuel consumption following a shift from the use of cars (in the offline shopping case) to the use of delivery vans (in the e-commerce case). The unit of analysis was the emissions of an entire area—a whole district in Theran—and the study was conducted under the hypothesis that all bricks-and-mortar purchases are replaced by online orders. By considering the average daily number of vehicles that access the shopping district of that area, an 88% reduction in fuel consumption was estimated, representing a reduction of 20.12 tons/year in air emissions. Moreover, Durand and Gonzales-Feliu (2012) focused on last-mile transport and compared bricks-and-mortar grocery shopping with two e-commerce scenarios: store-picking and warehouse-picking. The whole area of Lyon (France) was examined in the study, and the comparison was based on the total tons of CO_2 generated in a year and considered the different levels of diffusion in the two picking solutions.

For e-grocery, the broader food supply chain has also been investigated. As an example, Siikavirta et al. (2002) identified grocery e-commerce as an important opportunity for carbon footprint reduction in the food supply chain. Moreover, the introduction of e-grocery brings substantial changes to the food supply chain: producers and wholesalers become directly involved in B2C e-commerce, whereas intermediaries are skipped; however, extra work is required for the storage and transport of fresh food (Saskia et al., 2016). Rizet et al. (2010) adopted a supply chain perspective to estimate the overall GHG emissions of a kilogram of yogurt in both bricks-and-mortar (hypermarket, supermarket, minimarket) and e-commerce cases, thus comparing four scenarios. They considered emissions related to transport and buildings. In particular, they stated that the GHG emissions of a conventional shop should be compared to the sum of the emissions of the fulfilment centre and of the last depot in the e-commerce case. Their results indicated that for conventional distribution, the consumer trip emissions are directly related to the size of the shop; in the e-commerce case, delivery is instead very efficient. Finally, among the observed yogurt supply chains, the e-commerce option seemed to be the most efficient from the perspective of GHG.

The literature also contains studies on initiatives and projects intended to make a process or operation more environmentally sustainable. Leyerer et al. (2018) discussed an alternative logistics concept for e-grocery operations using an urban network of refrigerated grocery lockers. Koiwanit (2018) described the changes supermarkets are making to be more environmentally friendly, such as reducing discharges from refrigeration units or implementing new low-temperature systems. Another initiative a grocery operator can undertake for the specific goal of preventing food losses is the joint optimisation of their inventory and delivery strategies (Fikar, 2018). This study was based on the consideration that in bricks-and-mortar operations, customers select products based on quality and expiration date, but in e-grocery, it is the provider who makes this selection, impacting both food waste and customer satisfaction. A recent field of study has focused on collaboration and crowdsourcing logistics in urban distribution as a way to decrease emissions (e.g., Zissis et al., 2018; Guo et al., 2019).

3. Objective and methodology

Several general considerations were identified in the literature analysis. First, when studying the environmental impact of e-commerce, the industry and, therefore, the product features significantly influence the results (Cairns, 2005; Edwards et al., 2010). Above all, groceries are extremely unique compared to other retail products, mainly in terms of characteristics, order composition and deliveries (Hays et al., 2005; Heard et al., 2019). Furthermore, the topic of environmental sustainability is typically examined from a last-mile perspective. Here, authors tend to agree in stating that a delivery tour (online shopping) is generally more environmentally sustainable than the customer's trip to reach the store and return home (offline shopping) (e.g., Carling et al., 2015; Edwards et al., 2010; Wiese et al., 2012). However, the results can change significantly under certain circumstances, such as when public transport is used or the customer walks (Siikavirta et al., 2002). This consideration becomes more important when e-grocery deliveries are considered. The delivery conditions, characterized by the use of refrigerated vans and tight time windows, make comparisons between online and offline shopping more difficult. Moreover, only a few assessment models take into consideration warehousing activities (e.g., Rizet et al., 2010; Van Loon et al., 2015; Mangiaracina et al., 2016), and none of them is tailored to the grocery industry. In the end, it is not possible to trace the results—in terms of emissions—to specific purchasing process phases.

Based on these considerations identified in the literature review, this study aims to contribute to the extant literature on the environmental sustainability of B2C e-commerce by carrying out the following. (i) Investigating the grocery industry, whose peculiarities can lead to different results than have been obtained for other industries. In fact, when making an environmental assessment, the findings are conditional on both the type of product category selected and the peculiarities of its particular supply chain (Edwards et al., 2011). By (ii) considering not only emissions related to the last-mile delivery but also those related to warehousing and all transport-related activities in the e-grocery distribution network. This places the focus only on activities that lead to different emissions in the online and offline scenarios, and thus, only differences in emissions among purchasing processes are considered. This approach has been widely adopted by other authors (e.g., Williams and Tagami, 2002; Weber et al., 2010; Mangiaracina et al., 2016). In particular, Edwards et al. (2011) suggested that the environmental impacts of the fulfilment of one item should be compared from the point of divergence to the point of consumption. (iii) Breaking down and analysing the emissions for all phases of the purchasing processes: pre-sale and sale, replenishment, order picking and assembly, delivery and post-sale (Mangiaracina et al., 2016). The main objective is thus to assess the environmental impacts of both online and offline purchasing processes in the grocery sector, with a particular focus on logistics activities.

An analytical model was developed, and an activity-based approach was used. The application of analytical models is common in the literature (e.g., Scott Matthews et al., 2001; Bertram and Chi, 2018; Melacini and Tappia, 2018; Giuffrida et al., 2019), as is the ABC (i.e., activity-based costing) approach, which is considered suitable for measuring the performance of logistics processes (Drew et al., 2004). The innovative contribution of the model is related to the considered scenarios, which have not been previously investigated in the literature.

A five-step methodology, which is presented in Figure 1, was followed. In brief, the distribution configurations were identified. The reference processes for the online and offline channels were then mapped: they represent the starting point for the modelling of the emissions because an activity-based approach was employed. Visits to retailers' warehouses and stores, as well as interviews with managers, were extremely useful for the analysis. The assessment model was developed and then applied.

[Take in Figure 1]

3.1 Distribution configuration (phase 1)

The first phase involved the definition of the distribution network to be investigated and, in particular, of the fulfilment solution to be considered. Indeed, the assessment of emissions strictly depends, first of all, on the selected distribution configuration. In this regard, a retailer has different fulfilment options. An online order can typically be fulfilled (i) in a warehouse dedicated to the online channel or (ii) in a store (Vanelslander et al., 2013). The adoption of a dedicated warehouse requires a huge initial investment compared to in-store picking, but it is more efficient from an operational viewpoint, especially when volumes increase (Hübner et al., 2016). Moreover, the e-grocery market is growing significantly (see section 1 for further details), and the 2020 pandemic situation has boosted this market in all the major Western countries, revealing the need to identify efficient solutions (Dannenberg et al., 2020; Grashuis et al., 2020). Based on these considerations, a warehouse dedicated to the online channel was considered. Specifically, a grocery retailer is assumed to have (i) stores for offline shopping, (ii) a dedicated warehouse for fulfilling online orders and (iii) a central warehouse which replenishes both the stores and the dedicated warehouse.

3.2 Reference purchasing processes (phase 2 and phase 3)

The second phase involved the preliminary definition of the reference processes for both the e-commerce and bricks-and-mortar channels, considering the distribution configuration defined in phase 1. Each of the two processes was divided into macro-phases, and the macro-phases were further divided into activities, as has been done in other works that adopted an activity-based approach (e.g., Melacini and Tappia, 2018; Giuffrida et al., 2019). Each activity consumes resources and therefore generates an environmental impact. Moreover, the activities can be clustered based on their typology: communication, management, purchasing (e.g., Mangiaracina et al., 2016), transport and warehousing/handling (e.g., Van Loon et al., 2015).

Two main sources were used: the literature, especially regarding warehousing processes such as receiving, storage, picking and shipping (De Koster et al., 2007), and interviews with retailers to obtain detailed information on warehouses—both central and dedicated—and store activities. The use of interviews is particularly suggested when addressing logistics (Marchesini and Alcântara, 2016). Interviews were based on visits to retailers' central warehouses (four), dedicated warehouses (two) and stores (four): the sample can be considered representative given the number of Italian e-grocery retailers and the aim of phases 2 and 3 to frame reference processes for e-commerce and bricks-and-mortar. These visits were extremely important, as useful insights were obtained on the processes by directly observing them while they were being executed (Kotzab and Teller, 2005; Mangan et al., 2004). Even though the present study focused on the configuration with a warehouse dedicated to the online channel, the authors decided to interview retailers that rely on a dedicated warehouse and those that use stores for the fulfilment of online orders. All of them have a central warehouse for replenishing stores; in this regard, the authors wished to check the similarity of the activities conducted in the different central warehouses. This is a useful approach when a reference case has to be identified for an analysis (Dinwoodie and Xu, 2008). Interviews were conducted during the visits to the sites; they consisted of asking the logistics or supply chain managers who guided the authors through the warehouses for details about the execution of processes. The interview protocol used was the semi-structured, which is generally helpful in acquiring qualitative data, defining the significant variables to be considered and the associated values to feed the model, as well as to discuss and validate the results (Harland et al. 2019). During the visits to the stores, the store managers were interviewed following the same approach used for the warehouse visits. After the mapping of the processes, some of the people interviewed were asked to check the results, and any necessary refinements were made (phase 3). Because of the time-consuming nature of this phase for the interviewee, three people agreed to the second interview.

The online and offline processes are described in sections 3.2.1 and 3.2.2. Before these sections, a rough description of the two warehouses, the central and dedicated warehouse, is provided as follows. In particular, the central warehouse and the dedicated warehouse are both divided into three areas. The central warehouse includes a storage area, a sorting area and a shipping area. The dedicated warehouse instead contains a storage area optimised for picking; a stock-order area, where orders are temporarily stored and assembled; and a packing and shipping area. This specific division of space was observed in the visited warehouses, and it has been confirmed in the literature (e.g., Rouwenhorst et al., 2000; De Koster et al., 2007).

3.2.1 E-commerce process

The generic e-commerce purchasing process is composed of five phases (cf. Figure 2).

1. Stock replenishment—Replenishment consists of transferring goods from the central warehouse (upstream) to the dedicated warehouse to fulfil online orders (downstream). Goods are handled in large quantities, and the unit loads are typically pallets (Whiteoak, 2004). The flow of goods for replenishment is transported by rigid trucks (18 tons).
2. Pre-sale and sale—The customer adds all desired items to the cart, and the payment is made. The pre-sale and sale activities are performed entirely online, including payment (Ramus and Nielsen, 2005).
3. Order picking and assembly—The order is received and managed by the retailer. Then, a picking list is created, and the picking activity is performed in the dedicated warehouse—consistent with the distribution configuration selected for the analysis. The order is picked following a batch-picking policy (Eriksson et al., 2019). Products are then sorted, and all items are placed directly in the packaging (typically bags) used for deliveries (Mkansi et al., 2019).
4. Delivery—After the order is fulfilled in the dedicated warehouse, it is shipped directly to the customer. Distribution centres for fulfilling e-grocery orders are generally built close to customers to shorten the transport lead time: because of the large number of products per order, they do not require consolidation and sorting activities as other e-commerce industries typically do (Hays et al., 2005). Refrigerated diesel vans (payload = 1.5 tons) are used for the last-mile delivery routes (Figliozzi, 2020). The delivery point of online orders is the customer's house. Moreover, 100% first-time delivery success is assumed; thus, there are no failed deliveries because a customer is not at home: this is possible in this specific industry because limited time-windows (e.g. two hours) are defined for the deliveries, and the time window is chosen by the customer (Punakivi and Saranen, 2001).
5. Post-sale—If needed, the product can be picked up from the customer's house and brought to the dedicated warehouse (Diggins et al., 2016).

[Take in Figure 2]

Each phase is further divided into activities to compute the environmental impact. These activities are described in Appendices 1 and 2.

3.2.2 Bricks-and-mortar purchasing process

Similar to the e-commerce process, the bricks-and-mortar commerce process is divided into phases and activities. The phases are kept similar to those in the e-commerce process to ensure a robust comparison. However, an important difference involves the lack of an order picking and assembly phase, as it is performed by the customer at the store and is included in the sale activity. Figure 2 illustrates the bricks-and-mortar process according to the assumed distribution network.

1. Replenishment—When the stock level in the store decreases, a replenishment order is sent (Whiteoak, 2004). The order is received by and managed in the central warehouse, and the goods are sent to the store using a rigid truck (payload = 18 tons).
2. Pre-sale and sale—The customer leaves his/her home with the intention of making a purchase and reaches the store by car (no use of public transport is considered), following the assumption used in most studies that all grocery shopping trips are made by car (Rotem-Mindali and Weltevreden, 2013). At the store, all the products are collected, and the customer pays at the cashier. Moreover, only one store is visited by the customer to purchase the products. This assumption applies specifically to the grocery industry: in other types of industries, such as fashion or consumer electronics, customers often visit more than one shop before making a purchase (Birtwistle and Moore, 2007), which has an impact on the environmental assessment of offline purchases.
3. Delivery—The delivery is equivalent to the return trip from the store back to the home of the customer after the purchase.
4. Post-sale—The post-sale phase may include the return process. If the customer wants to return the product, he/she goes back to the store, requests the exchange and returns home with the new product (or his/her money back) (Mangiaracina et al., 2016).

3.3 Model development and application (phase 4 and phase 5)

The fourth phase involved the construction of the analytical activity-based model, relying on the mapped processes. This model was used to compute the environmental impacts of the e-commerce and bricks-and-mortar purchasing processes in terms of CO_2e. The unit of analysis is a single purchasing order, either online or offline. Both the metric (CO_2e) and the unit of analysis have been widely used in previous studies in the field.

In the final phase, the model was applied, using both primary and secondary data. In particular, data regarding the consumption of resources and conversion factors were based on secondary data (further details are provided in section 4). The primary data included information about retailers' building characteristics, flows, execution times for activities and other input data specific to the sector and were obtained from retailers (further details in section 4). The authors provided the interviewees—before the visits—with a list of specific data to be collected.

4. Environmental assessment model

The model is organised into five sections: general input data, activity data, consumption data, model algorithms and output. Figure 3 summarises the model structure. The model was structured in this way so it could be used by researchers or practitioners (referred to later as 'users') interested in assessing the environmental impact of B2C e-grocery.

[Take in Figure 3]

4.1 General input data

This section presents the input variables that can be modified by the user. The main clusters of data are (i) customer data, including the number of websites visited and the return rates of both online and offline shopping; (ii) purchase profiles, in terms of items per order and lines per order; (iii) packaging type, size, capacity, weight and amount of raw material; (iv) features of the retailer's central warehouse and (v) features of the retailer's dedicated warehouse, both in terms of size and number of orders fulfilled per day; and (vi) features of the retailer's store.

[Take in Table 2]

4.2 Activity data

This section includes all data regarding the duration of online, warehousing, store and transport activities.

Online activities—These include all activities performed online by the customer, both in the e-commerce and in the bricks-and-mortar scenarios. They are executed through an electronic device (a smartphone, a tablet or a laptop) by the customer (e.g., to search for information or to do the online shopping), by the retailer (e.g., order reception and management) and/or by store assistants (e.g., to send the waybill) (Mangiaracina et al., 2016). The energy consumed during the use of such devices was evaluated by considering the time needed, on average, to complete these activities (Weber et al., 2010).

Warehousing activities—These include the activities performed in the central warehouse (which replenishes both the dedicated warehouse and the stores) and in the warehouses dedicated to online orders. Warehousing activities include storage, picking, material handling, packaging, sorting and shipping (De Koster et al., 2007).

Store activities—These include all activities that take place in the stores when the offline purchasing process is considered. They are performed by a store assistant or by the customer, and they include, as an example, communication, product search and management of stock.

Transport activities—In both the e-grocery and the bricks-and-mortar cases, there are various transport activities, which are performed using different modalities and different means of transport. The main transport activities include the following:

i. *Delivery*: This involves the delivery of the goods from the dedicated warehouse to the customer's home (only in the e-commerce process). A refrigerated diesel van (1.5 ton capacity) is assumed to perform these activities (Cairns, 2005; Figliozzi, 2020).
ii. *Replenishment*: This involves transport activities needed to supply the stores and the dedicated warehouse. The assumed means of transport is a rigid truck (18 ton capacity).
iii. *Customer trip*: This represents the distance between the store and the customer's home. The assumed means of transport is a gasoline car.

The main values for the transportation activities, which are then used for the application of the model, are displayed in Table 3.

[Take in Table 3]

4.3 Consumption data

This section includes all data regarding the following:

i. *Energy consumption*, which is the energy consumed during all activities performed (e.g., online searches, handling with forklifts) (Sivaraman et al., 2007; Mangiaracina et al., 2016) and by buildings (e.g., heating and air conditioning in the warehouses and the stores) (Van Loon et al., 2014). To perform online activities, customers and retailers use electronic devices. For the activities carried out in the warehouses, all equipment is powered by electricity. An order picker truck is used for picking, and a forklift truck is used for moving and handling goods (Fichtinger et al., 2015). The main energy consumption values, which are then used for the application of the model, are displayed in Table 4.

[Take in Table 4]

ii. C*onversion coefficients*, which are used to determine the emissions emitted while consuming a unit of a certain type of resource (Seo and Hwang, 2001). The emissions are expressed in terms of $kgCO_2$ equivalents ($kgCO_2e$).

[Take in Table 5]

4.4 Model algorithms

This section includes all the mathematical formulas connecting general input data, activity data and consumption data to the output. The model equations can be explained according to the type of activity. Appendices 1 and 2 present all the formulas implemented to calculate the outputs, and they are organised as follows: first, the phase of the overall purchasing process (i.e., pre-sale and sale, replenishment, order picking and assembly, delivery, post-sale) is indicated. Second, each activity of each phase—for which the environmental impact is assessed—is detailed. Third, the typology of each activity (i.e., purchasing, communication, management, warehousing/handling, transport) is indicated. Fourth, the formula for computing the emissions related to each specific activity is proposed. However, because some of the multipliers in the formulas are derived from other formulas, some of these are explained further below.

i. *Online activities equations*—The environmental impact mainly involves the use of electricity (Weber et al., 2010). The following reference equation is used:

$$AF_{online} = D \cdot PS \cdot ECC \qquad (1)$$

where AF_{online} is the activity footprint [$kgCO_2e$], D is the activity duration [h], PS is the power supply of the device [kW] and ECC is the electricity conversion factor [kgCO2e/kWh].

ii. *Warehousing activities equations*—These concern the computation of the environmental impact of the activities performed within the warehouses in both the online and offline cases. It is necessary to consider both the resources used for the building (e.g., lighting, heating) and the resources needed to perform the specific activities (e.g., picking) (Fichtinger et al., 2015). For illustrative purposes, only the equations related to picking are detailed below.

Warehouse consumption—It is necessary to take into consideration the indirect environmental impact caused by the building itself and to allocate it to the activities performed (Van Loon et al., 2014; Mangiaracina et al., 2016).

$$BFA = \frac{DBC}{DNP} \cdot AP \qquad (2)$$

$$DBC = \frac{YC \cdot BV}{WD} \qquad (3)$$

BFA is the building footprint for a certain activity [kgCO2e], DBC is the daily energy consumption for the building [kWh], DNP is the daily flow of products [#products] and AP is the percentage of space allocated to the activity under analysis [%]. Note that DNP can be the daily flow related to bricks-and-mortar or to e-commerce activities, according to the specific activity. YC is the yearly consumption [kWh], BV is the building volume [m^3] and WD is the number of working days per year [#days].

Picking—The picking activity is performed in the central warehouse to assemble the e-commerce order and to replenish the stores. The operator rides onboard an order picker truck, which is powered by electricity (Fichtinger et al., 2015). The following reference equations are used to compute the impact of the picking activity:

$$AF_{picking} = PCP \cdot ECC \qquad (4)$$

$$PCP = \frac{TT \cdot PST}{N \cdot NPL} \qquad (5)$$

where PCP is the energy consumed while picking a piece [kWh], ECC is the electricity conversion factor [kgCO2e/kWh], TT is the travel time [h], PST is the power supply of the order picker truck [kW], N is the number of picks in a tour [#] and NPL is the number of pieces per line in a tour [#]. For the computation of PCP, it is necessary to clarify that the consumption of electricity is only related to the travel time onboard the order picker truck. To assess TT, random storage and traversal routing policies were assumed.

iii. *Transport activities equations*—The customer trip equation is given below as an example. In the bricks-and-mortar scenario, the customer uses his/her personal means of transport to reach the store and to return home.

$$AF_{transport\ customer} = HD \cdot VCC \qquad (6)$$

where HD is the average distance between the store and the customer's home [km] and VCC is the vehicle conversion coefficient [kgCO2e/km].

iv. *Store activities equations*—The carbon footprint of the store activities is mainly related to the electricity consumed for air conditioning, heating, lighting, etc. This impact is divided among the different activities, according to the percentage of time dedicated to each (Mangiaracina et al., 2016). In addition, a consumption value has to be allocated to each product purchased. Therefore, the activities performed by both customers and sales assistants should be considered. For the customers, the following reference equations are used:

$$AF_{store\_customer} = \frac{BFA}{NC \cdot NI} \qquad (7)$$

$$BFA = DBC \cdot AP \qquad (8)$$

where AF is the activity footprint [kgCO2e], BFA is the building footprint for a certain activity [kgCO2e], NC is the daily flow of customers in the store [#], NI is the number of items per purchase [#], DBC is the daily energy consumption for the building [kWh], and AP is the percentage of space allocated to the activity under analysis [%]. The daily energy consumption of the building is computed using equation (8).

The second equation refers to the activities performed by the store assistants.

$$AF_{store\_assistant} = \frac{BFA}{NS \cdot NCS \cdot NI} \qquad (9)$$

where NS is the number of store assistants [#], NCS is the number of customers served by each of them [#] and NI is the number of items per purchase [#]. BFA, the building footprint for a certain activity [kgCO2e], is computed using equation (8).

4.5 Output data

The output is the environmental impact generated by a purchase ($kgCO_2e$/order), either online or offline, in the grocery industry. The overall result can be broken down by phase (pre-sale and sale, replenishment, order picking and assembly, delivery) and by activity type (e.g., transport, warehouse/handling).

5. **Results and discussion**

5.1 Base case

The model described in section 4 was applied using the main input data presented in Tables 2, 3, 4 and 5. When considering these data, e-grocery was found to be more sustainable than bricks-and-mortar. Specifically, the environmental impact of the online purchasing process was determined to be about 15% lower than that of the offline shopping process. The respective emissions for the online and offline processes were 7.34 and 8.66 kgCO_2e per order. Figure 4 presents the emissions (measured in kgCO_2e) in both cases divided by phase. Figure 5 illustrates the emission percentages for the five macro-phases.

[Take in Figure 4]

[Take in Figure 5]

The replenishment activities represent the main source of emissions in both purchasing processes. They account for about 50% of the emissions in the bricks-and-mortar case and 46% in the e-commerce case. Indeed, the transport of goods from the central warehouse occurs in both cases because the goods are moved to the stores (offline) or to the dedicated warehouse (online). Emissions in the replenishment phase were found to be higher in the offline process when compared in absolute terms (4.40 kgCO_2e for bricks-and-mortar shopping vs. 3.38 kgCO_2e for e-commerce). On the one hand, the distances travelled to reach the two destinations may differ: the average distance to reach the store, given the number of stores replenished by a warehouse, can be considered to be greater. On the other hand, truck saturation is expected to be higher when replenishment is directed towards the dedicated warehouse (Whiteoak, 2004).

The pre-sale and sale phase represents the second most impactful phase in the bricks-and-mortar purchasing process, as it was found to account for almost 45% of the total emissions. This phase has two main sources of emissions: travel to the store and the energy consumed by the store. In the e-commerce phase, emissions in the pre-sale and sale activity are instead almost null because the only source of emissions is the electricity used to place the order.

The delivery phase accounts for about 5% of the total emissions in the offline case. On the contrary, in the online scenario, the delivery is instead the second most impactful phase, accounting for 28% of the total emissions. Delivery is followed by order picking and assembly (25%). Post-sale emissions are negligible in both purchasing processes, as the return rate is almost null.

Figure 6 shows the emissions related to the main clusters of activities (i.e., communication, management, purchasing, transportation, warehousing/handling).

[Take in Figure 6]

Warehousing activities represent a huge source of emissions (57%), particularly in the e-commerce case. In the bricks-and-mortar purchasing process, warehousing activities represent 27% of the total emissions, as they only include emissions related to the central warehouse. Notably, emissions related to the stores are not classified in the model as warehousing activities but as either communication or purchasing activities. Transport activities are the second highest source of emissions in both purchasing processes. They include the transfer of goods for replenishment and the last-mile delivery (for e-commerce purchases) or the customer trip (for bricks-and-mortar shopping).

5.2 Sensitivity analyses

To examine how the results vary when the main inputs change, sensitivity analyses were carried out.

The distances travelled by either the customer to reach the store or the delivery van were considered. Distances are indeed one of the most impactful parameters in the environmental assessment of offline shopping (Durand and Gonzalez-Feliu, 2012; Cairns, 2005). Another significant parameter is the basket size (Edwards et al., 2010; Van Loon et al., 2015). This parameter was included because typical e-grocery orders are made up of many products, which is different from orders in other retail sectors (Agatz et al., 2008; Gee et al., 2019).

First, the kilometres travelled by the customer to reach the store vary. A range from 1 to 7 km was used in the evaluation (McLeod et al., 2006), and the results are shown in Figure 7. These variations in distance may reflect different areas. In this regard, less-densely populated areas tend to have a lower number of stores: distance, and thus the time to reach grocery stores, increases (Scott Matthews et al., 2001; Liese et al., 2007). Logically, the greater the distance is, the higher the emissions because of the fuel consumed during the transport activity. The environmental impact of online shopping was found to be 10% lower than that of the offline case when the shortest distance (1 km) was considered, 15% lower when a 2 km distance was considered and 30% lower when the longest distance (7 km) was considered.

The customer's trip was indeed confirmed to be impactful because—without changing other conditions in the base case scenario—the overall e-commerce emissions were found to be 10% to 30% lower than the bricks-and-mortar emissions. However, other assessments in different industries have found that when the shortest distances are considered, bricks-and-mortar options become more environmentally sustainable (e.g., Scott Matthews et al., 2001; Wiese et al., 2012). In the grocery industry, even when the shortest distance travelled by the customer to reach the store was used, the environmental sustainability of e-commerce was confirmed.

[Take in Figure 7]

Second, different delivery densities were investigated (see Figure 8). Here, the total distance the van travelled in its delivery tour remained constant (60 km), but the number of performed deliveries was varied. Starting from the base case represented by 12 deliveries per tour, three scenarios were also examined: 10, 14 and 16 deliveries per tour. The limited number of deliveries is due to the peculiarities of the industry—specifically, the tight time windows (Cairns, 2005) and the relatively long time required for each drop off (Punakivi and Saranen, 2001). As in the previous analysis, the different distances may reflect the different typologies of specific areas, either urban or rural (Carling et al., 2015). The reduction in emissions—from the offline to the online purchase scenario—varied from 10% (10 deliveries) to 20% (16 deliveries). Previous studies that compared online and offline shopping have reported that e-commerce produces fewer emissions than bricks-and-mortar channels, even when considering the last-mile step (e.g., Siikavirta et al., 2002; Zhao et al., 2019), but results become controversial under certain conditions, especially regarding distances (e.g., Williams and Tagami, 2002; Carrillo et al., 2014). However, the results of the present study indicate that even under different conditions for the last-mile delivery step, in the grocery sector, e-commerce is associated with fewer emissions than bricks-and-mortar shopping.

[Take in Figure 8]

Third, the basket size of the order was considered. By increasing the number of purchased items (Figure 9), the results indicated that e-grocery was even more sustainable than offline shopping. Assessments in other industries have produced similar results (Mangiaracina et al., 2016). For example, when the order basket sizes of online and offline orders were both equal to 95 items (vs. 65 in the base case), the online option was found to generate 20% fewer emissions than offline purchases. On the contrary, emissions for online and offline purchases were almost equal when a smaller basket size of 35 items was considered. However, smaller basket sizes do not reflect the reality of online grocery shopping (Hanus, 2016). The number of items in the basket does indeed affect the emissions per item because of the transport activity performed during the last-mile step and in the consumer's trip, where emissions are allocated based on the number of items transported (Edwards et al., 2011).

[Take in Figure 9]

5.3 Managerial implications

The main managerial implications derived from the discussion of the results are detailed below.

(i) Return rates in e-grocery are very low (Seow et al., 2003), and the results confirm that they are almost negligible: emissions due to the post-sale phase represent 5% of overall emissions in the bricks-and-mortar scenario and less than 1% in the e-commerce scenario. Even though some industries (e.g., apparel) are working to adopt actions to make the return process more sustainable (Bertram and Chi, 2018; Diggins et al., 2016), it does not represent a priority for the grocery industry.

(ii) The choices made by customers have a strong influence on the results. First, the distance travelled to reach the store depends on not only the area—either urban or rural—where the customer lives but also the customer's preference—for example, the customer may choose to travel to a store farther away for dedicated (or not) trips for grocery shopping (Durand and Gonzalez-Feliu, 2012). Second, the sensitivity analysis of basket size confirmed that the number of items per purchase was extremely impactful. In this regard, a retailer may urge customers to place larger orders. At least in Italy, the home delivery of grocery items generally involves the payment of a fee, regardless of the quantity purchased. In this regard, free shipping or awards initiatives for purchases over a certain amount (Becerril-Arreola et al., 2013), could be helpful.

(iii) Last-mile delivery density also strongly influenced the results. While the distances related to replenishment activities do not have large margins that can be reduced unless the distribution network changes, distances travelled in the last-mile step are extremely variable (Leyerer et al., 2018). In this regard, retailers may adopt initiatives to increase delivery efficiency. One innovative solution that can be adopted is dynamic pricing for the delivery fee: the retailer can cite a lower fee for a delivery slot that maximises the efficiency of the tour (Vinsensius et al., 2020). Emissions related to transport activities can also be reduced by using green vehicles, such as electric vans or trucks (Siragusa et al., 2020). In summary, environmental sustainability—in addition to economic concerns—can be considered when establishing service parameters.

(iv) Building-related emissions represent the main source of emissions in both the online and offline channels. E-grocery, as stated, is developing quickly. In this regard, when considering an entire distribution system in a country, the number of points in the network could be leveraged according to economic and environmental trade-offs.

6. Conclusions

6.1 Gap and contribution

Previous studies on the environmental impact of e-grocery mainly focused on the last-mile delivery step, which is a unique factor compared to other industries. On the one hand, temperature constraints require the use of refrigerated vans (Heard et al., 2019). On the other hand, the tight time windows and longer times needed to deliver the grocery items to the customer limit the number of deliveries per tour (Cairns, 2005). However, when comparing the environmental impacts of online and offline shopping, all emissions from the point of divergence of the two processes should be included (Edwards et al., 2011). This approach has been employed when investigating other industries (e.g., fashion, book) (e.g., Mangiaracina et al., 2016; Williams and Tagami, 2002), but an in-depth study on grocery shopping using this perspective was lacking. In this regard, this study compared the two purchasing processes while not only considering last-mile delivery but also including the energy consumed (i) in all the other transport activities from the point of divergence (specifically, the replenishment of the store and of the dedicated warehouse that fulfils online orders) and (ii) by buildings, both warehouses and stores. Regarding the distribution configuration, a grocery retailer is assumed to have stores for offline shopping, a dedicated warehouse for fulfilling online orders and a central warehouse which replenishes both the stores and the dedicated warehouse. Using this configuration, the results indicate that the emissions associated with warehousing—and buildings in general—are responsible for a huge part of the entire environmental impact. In other industries, transport activities account for the main source of emissions, but in the grocery sector, buildings are a significant source. For example, in both purchasing processes, more than half of the emissions (60%) are related to buildings (warehouses in e-commerce; warehouses and stores in bricks-and-mortar shopping). As previous studies have noted, the distances travelled by the customers and the delivery density in the last-mile step strongly affect the results (Durand and Gonzalez-Feliu, 2012; McLeod et al., 2006). However, varying these distances does not affect the comparison between online and offline grocery shopping, as occurs in other industries (e.g., Williams and Tagami, 2002; Wiese et al., 2012; Carrillo et al., 2014). The results of the present study indicate that the last-mile step or customer's trip—which represent the core of most studies—is responsible for only a portion of the overall emissions. This study also confirmed that the basket size is crucial: the results indicate that when it decreases, e-commerce starts to lose its environmental advantage over offline shopping.

6.2 Research limitations and further developments

The results of the study are limited by the assumptions and the boundaries applied in the environmental assessment (Edwards et al., 2011). Even though this study looked at the most representative distribution configuration, a dedicated warehouse for fulfilling online orders, other options are possible (Hübner et al., 2016). For example, some retailers still use in-store picking (Galante et al., 2013). Moreover, even if the grocery sector has been slow to adopt omni-channel (Eriksson et al., 2019), retailers may evaluate this solution, as it happened with other retail sectors, such as fashion (Giuffrida et al., 2019) or consumer electronics (Melacini and Tappia, 2018). Omni-channel solutions represent thus an interesting development for further research in e-grocery. However, the modularity of the presented model allows practitioners (i) to investigate other types of configurations by selecting the appropriate activities from the ones proposed (see Tables 6 and 7). This approach allows practitioners (ii) to apply the model to their specific case and to use their own data. Moreover, the breakdown of the emissions according to phases and/or type of activity allows (iii) the study of the effect of a particular parameter, facilitating comparisons of potential alternatives. This modular approach—displaying all formulas for computing the output—is indeed useful for practitioners (Steubing et al., 2016; Seghezzi and Mangiaracina, 2020). For example, this study only considered a diesel van for the last-mile delivery step: by changing the input values related to this specific activity—the number of km travelled, or deliveries accomplished, resources consumed or conversion factors for the resource—new results can easily be obtained. In this regard, if a retailer is interested in evaluating which type of van to employ for the last-mile delivery step (e.g., diesel vs. electric), the model can be used to compare the emissions not only for local considerations (last-mile delivery only) but also for the entire environmental impact.

Moreover, this study used the same basket size for both online and offline purchases: a potential misalignment in this regard—which may imply more or fewer trips to the supermarket by the customers—can lead to different emission results. Thus, considering a broader range of shopping attitudes could be an interesting step in future studies. Moreover, the application of the model is limited to the Italian context. The characteristics of online and offline shopping in other countries—which involve different distances, delivery densities and basket sizes—can lead to different conclusions. Furthermore, deterministic data were assumed, and variabilities in these data were partially assessed through sensitivity analyses. However, this approach was considered appropriate for the purpose of the study and to be aligned with the extant literature (e.g., Van Loon et al., 2014; Giuffrida et al., 2019). Future studies may apply stochastic methods to further evaluate the impact of changes in the values of these inputs. In the end, warehouses with specific characteristics and an average yearly energy consumption were considered: no alternative sources for electricity were investigated. Because of the significant impact of building-related emissions, future studies could investigate the impact of renewable energy (e.g., use of rooftop solar panels) or of the implementation of energy-saving practices, such as the use of compact fluorescent lights or light-emitting diodes.

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Figure 1 – Five phases methodology adopted by the study

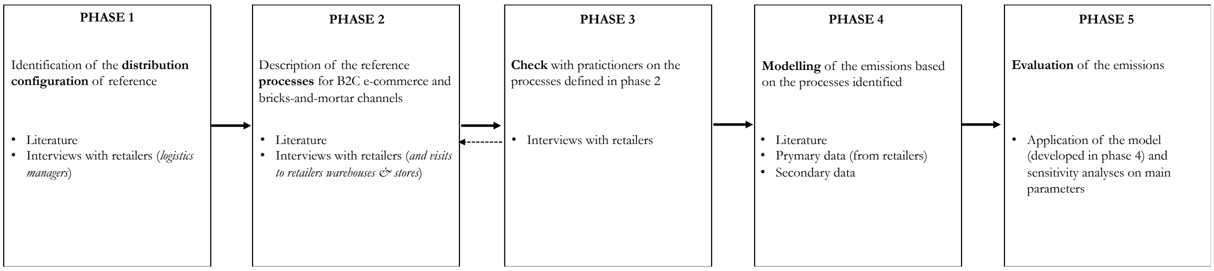

Figure 2 - Distribution network structure (e-commerce and bricks-and-mortar process)

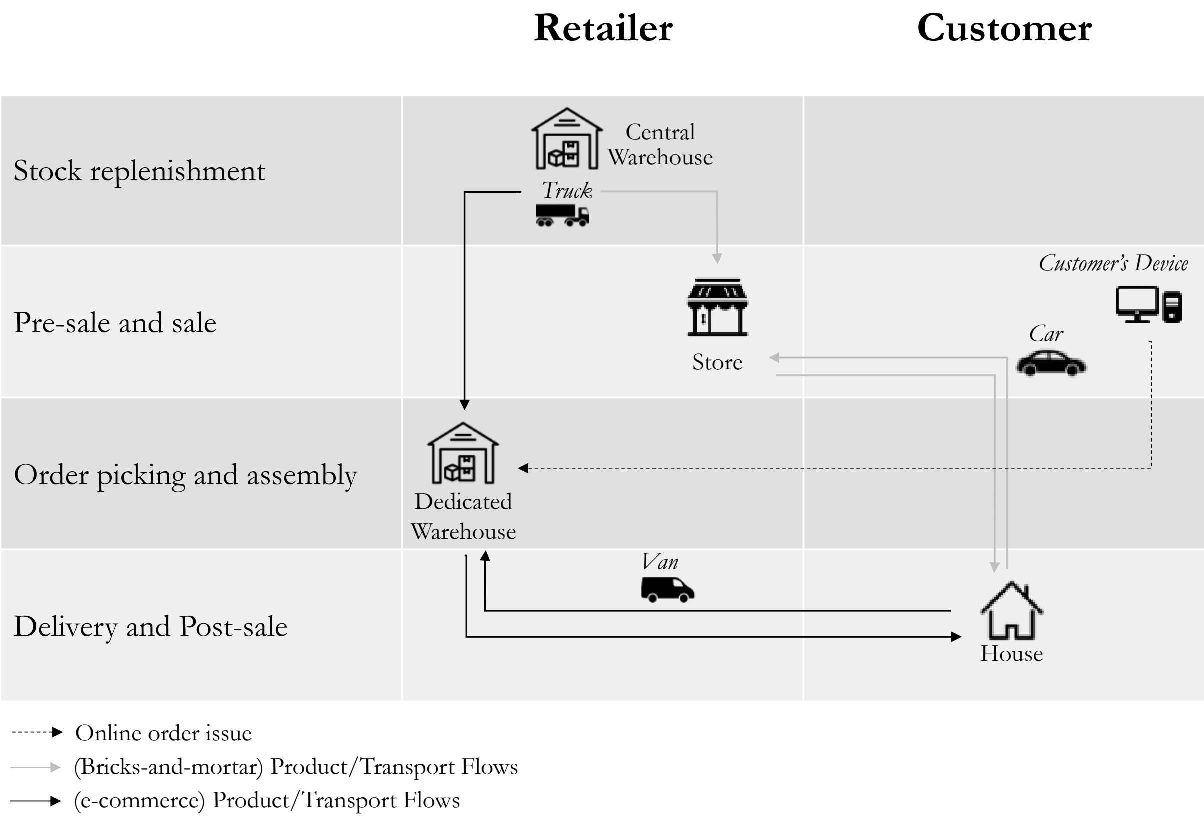

Figure 3 – Model structure

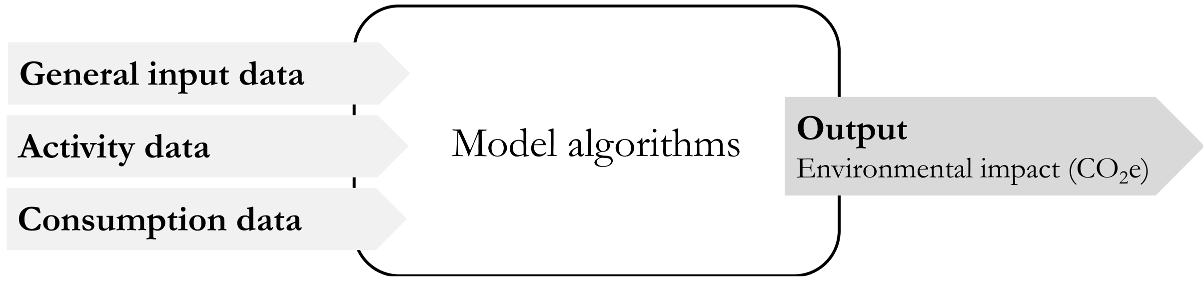

Figure 4 – Total GHG per order by phase (kgCO_2e/order)

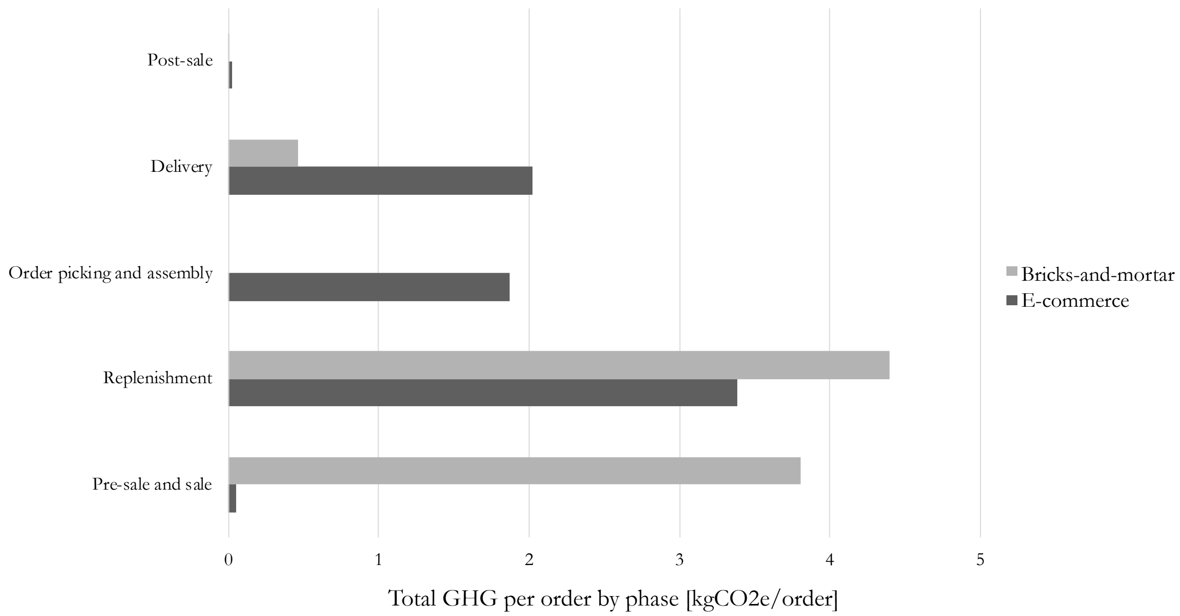

Figure 5 – GHG per order by phase - Percentage breakdown

Figure 6 – GHG per order by activity - Percentage breakdown

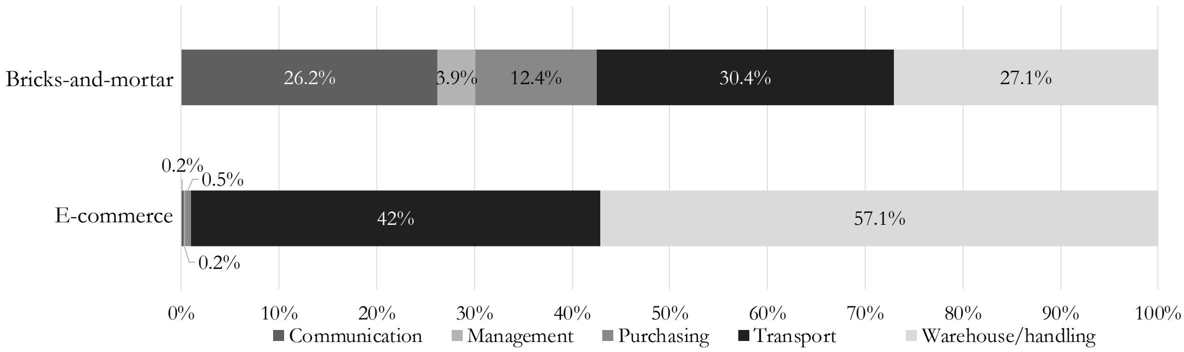

Figure 7 – Total GHG per order, distance between customer house and store (kgCO_2e/order)

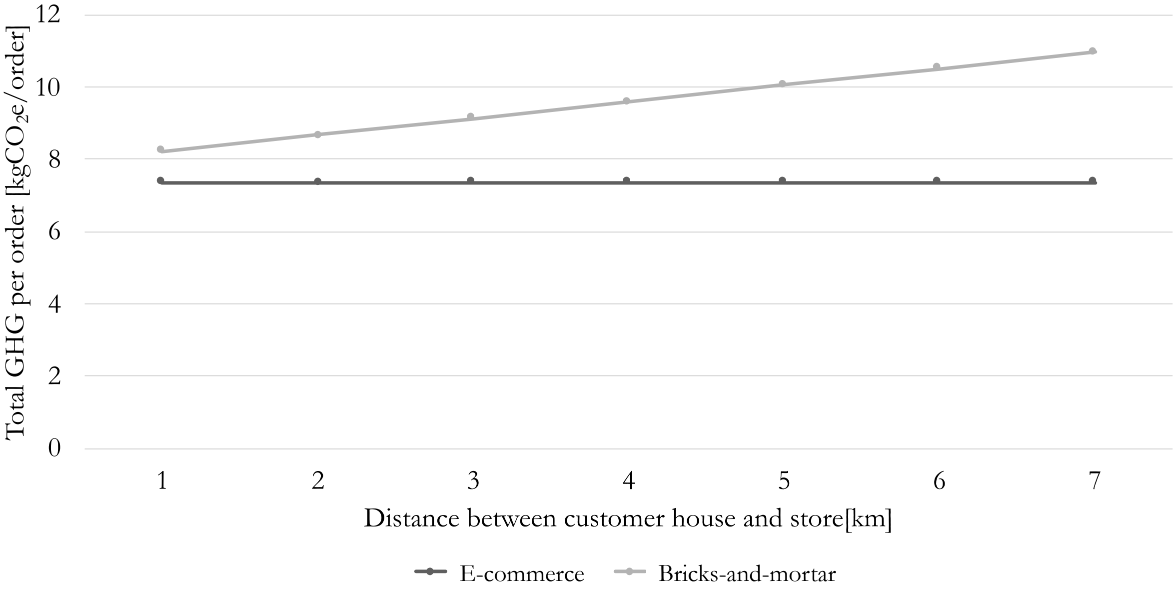

Figure 8 – Total GHG per order, number of deliveries ($kgCO_2e$/order)

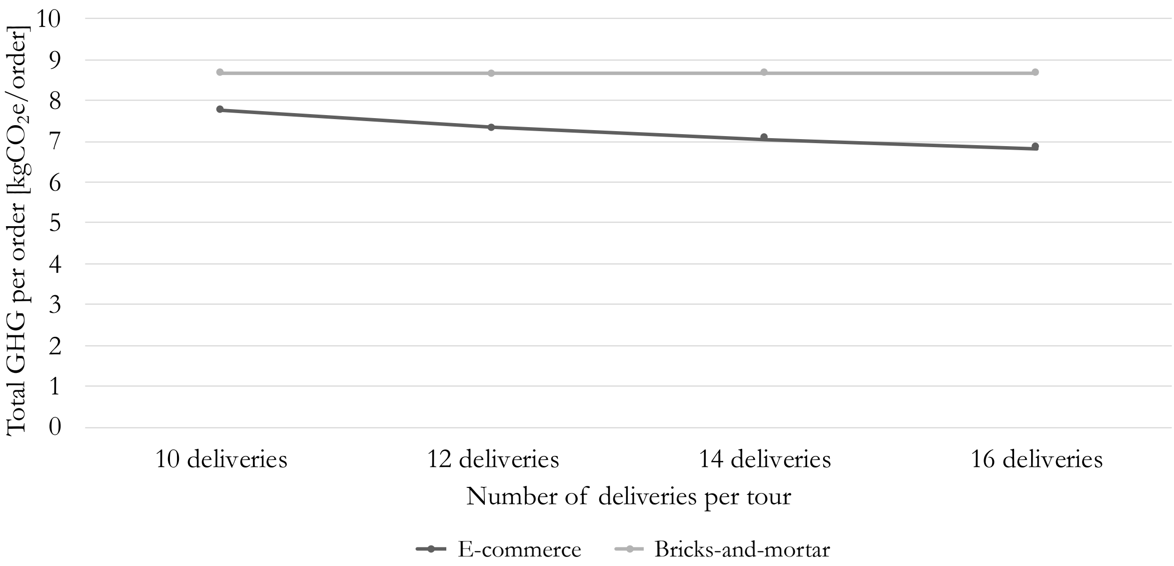

Figure 9 - Total GHG per order, different basket sizes (kgCO_2e/order)

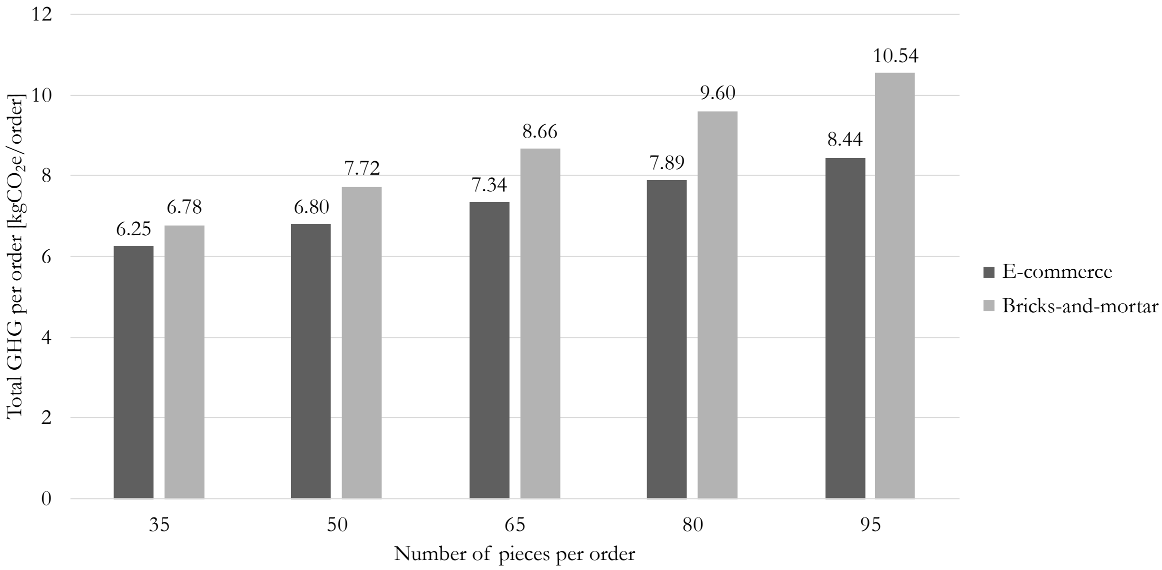

Table 1 – Selected literature on e-commerce environmental sustainability

Year	Title	Authors	Research Method	Is e-commerce more environmentally sustainable?
2001	Environmental and economic effects of e-commerce: A case study of book publishing and retail logistics	Scott Matthews et al.	analytical model	Controversial
2002	Effects of e-commerce on greenhouse gas emissions: A case study of grocery home delivery in Finland	Siikavirta et al.	simulation	Yes
2002	Energy use in sales and distribution via e-commerce and conventional retail: A case study of the Japanese book sector	Williams and Tagami	analytical model	Controversial
2005	Application of e-commerce in local home shopping and its consequences on energy consumption and air pollution reduction	Tehrani and Karbasi	survey	Yes
2005	Delivering supermarket shopping: More or less traffic?	Cairns	literature review	Controversial
2009	Designing and assessing a sustainable networked delivery (SND) system: Hybrid business-to-consumer book delivery case study	Kim et al.	case study	Yes
2010	Comparative analysis of the carbon footprints of conventional and online retailing: A "last mile" perspective	Edwards et al.	analytical model	Controversial
2010	GHG emissions of supply chains from different retail systems in Europe	Rizet et al.	survey	Yes
2010	The energy and climate change implications of different music delivery methods	Weber et al.	simulation	Yes
2011	Comparative carbon auditing of conventional and online retail supply chains: A review of methodological issues	Edwards et al.	conceptual analysis	Controversial
2011	A comparative study of environment impact in distribution via E-Commerce and traditional business model	Liyi et al.	analytical model, case study	No
2012	Transport-related CO2 effects of online and brick-and-mortar shopping: A comparison and sensitivity analysis of clothing retailing	Wiese et al.	survey	Yes
2014	Environmental implications for online retailing	Carrillo et al.	analytical model	Controversial
2014	The growth of online retailing: A review of its carbon impacts	Van Loon et al.	literature review	Controversial
2014	Carbon emissions comparison of last mile delivery versus customer pickup	Brown and Guiffrida	analytical model	Yes
2015	A comparative analysis of carbon emissions from online retailing of fast moving consumer goods	Van Loon et al.	analytical model	Controversial
2015	Measuring transport related CO2 emissions induced by online and brick-and-mortar retailing	Carling et al.	empirical analysis	Yes
2015	A review of the environmental implications of B2C e-commerce: a logistics perspective	Mangiaracina et al.	literature review	Controversial
2016	Assessing the environmental impact of logistics in online and offline B2C purchasing processes in the apparel industry	Mangiaracina et al.	analytical model, case study	Controversial
2017	Sustainable retailing in the fashion industry: A systematic literature review	Yang et al.	literature review	Yes
2018	A study of companies' business responses to fashion e-commerce's environmental impact	Bertram and Chi	literature review	Yes
2019	Comparison of life cycle environmental impacts from meal kits and grocery store meals	Heard et al.	analytical model	Yes
2019	Deliver Me from food waste: Model framework for comparing the energy use of meal-kit delivery and groceries	Gee et al.	simulation	Yes
2019	Environmental benefits of electronic commerce over the conventional retail trade? A case study in Shenzhen, China	Zhao et al.	case study	Yes
2019	How does consumers' omnichannel shopping behaviour translate into travel and transport impacts? Case-study of a footwear retailer in Belgium	Buldeo Rai et al.	case study	Yes

Table 2 – Main general input data

Input	**Value**	**Unit of measure**	**Source**
Return rate (online)	1	%	Primary data
Return rate (offline)	0,3	%	Primary data
Number of websites visited	1	#	Assumption based on Birtwistle and Moore (2007)
Number of pieces per order	65	pieces/order	Primary data; check in Van Loon et al. (2015); Seow et al. (2003)
Number of lines per order	50	lines/order	Primary data
Central warehouse	20,000	m^2	Primary data
Dedicated warehouse	5,000	m^2	Primary data
Store	2,000	m^2	Primary data

Table 3 – Transport activities

Type of consumption	Value	Unit of measure	Source
Average last mile delivery route distance	60	km	Primary data; check in Cairns (2005); Durand and Gonzales-Feliu (2012)
Average number of parcels per delivery route	12	parcels	
Average distance per route (replenishment)	500	km	Primary data
Distance customer's home – store (*base, urban case*)	2	km	Edwards et al., 2011; Kim et al., 2009; Matthews et al., 2001, 2002; Sivaraman et al., 2007; Weber et al., 2010; Wiese et al., 2012

Table 4 – Energy consumption of resources

Type of consumption	Value	Unit of measure	Source
Power supply of devices used during online activities of customers *(Average between different PC, tablet and mobile phones, 3 each)*	0.1157	kW	Technical sheets from producers; Mangiaracina et al. (2016)
Power supply of devices during online activities of retailer *(Average between 3 different PCs)*	0.2313	kW	Technical sheets from producers
Power supply of an order picker truck *(Average between 3)*	2.80	kW	Technical sheets from producers
Power supply of a forklift truck *(Average between 3)*	4.50	kW	Technical sheets from producers
Warehouses consumption	82.06	[kWh/m^3 year]	Primary data; check in CENED (2018)
Store consumption	112.49	[kWh/m^3 year]	Primary data; check in CENED (2018)

Table 5 – Conversion factors

Resource	**Value**	**Unit of measure**	**Source**
Electricity production conversion factor	0.491	kgCO2e/kWh	ISPRA (2017)
Plastics bag (*packaging*)	1.578	kgCO2e/kg	Environment Agency. (2011)
Cardboard boxes (*packaging*)	1.127	kgCO2e/kg	Swedish Environmental Research Institute (2010)
Refrigerated rigid truck 18 ton (*replenishment*)	1.3617	kgCO2e/km	DEFRA (2018)
Refrigerated diesel van 1.5 ton (*last mile delivery, urban emissions*)	0.4035	kgCO2e/km	DEFRA (2018)
Gasoline car (urban emissions)	0.26	kgCO2e/km	DEFRA (2018)

Appendix 1 – Formulas computing the environmental impact of each activity (online purchasing process)

Phase	Activity	Typology	Algorithm
Pre-sale and sale	Online products search on search engines or comparison websites	Purchasing	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Customer re-direction to the retailer website	Purchasing	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Product check	Purchasing	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Info request to retailer	Communication	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Answer to consumer request	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Product insertion into cart	Purchasing	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Info insertion and interaction with the retailer	Communication	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Interaction with the customer about data to insert	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Payment info insertion	Purchasing	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Payment confirmation mail	Communication	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
Replenishment	Replenishment order emission	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Replenishment order reception and management	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Order fulfillment	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Picking list emission	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Picking	Warehouse/handling	picking consumption per piece [kWh] * electricity conversion factor [kgCO2e/kWh] * number of items per order [#]
	Warehouse consumption in the storage area	Warehouse/handling	(warehouse daily energy consumption for storage [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) * number of items per order [#]
	Sorting	Warehouse/handling	sorting consumption per piece [kWh] * electricity conversion factor [kgCO2e/kWh] * number of items per order [#]
	Warehouse consumption in sorting area for sorting activity	Warehouse/handling	(warehouse daily energy consumption for sorting [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) * number of items per order [#]
	Packaging	Warehouse/handling	packaging footprint [kgCO2e/cardboard]*number of cardboard [#]
	Warehouse consumption in sorting area for packaging activity	Warehouse/handling	(warehouse daily energy consumption for packaging [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) *number of items per order [#]
	Goods moving	Warehouse/handling	goods moving consumption per piece [kWh] * electricity conversion factor [kgCO2e/kWh] * number of items per order [#]
	Warehouse consumption in sorting area for goods moving activity	Warehouse/handling	(warehouse daily energy consumption for goods moving [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh])*number of items per order [#]
	Waybill posting	Warehouse/handling	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kW]

	Goods transportation	Transportation	(average route distance [km] * percentage space occupied by a piece [%] * vehicle GHG conversion factor [kgCO2e/km]) * numer of items per order [#]
	Info request about delivery	Communication	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Interaction with the warehouse about delivery	Communication	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Tracking service activation	Communication	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Shelves replenishment	Warehouse/handling	goods transfer consumption per piece [kWh] * electricity conversion factor [KgCO2e/kWh]*number of items per order [#]
Order picking and assembly	Order reception and management	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Order fulfillment	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Picking list emission	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Picking	Warehouse/handling	picking consumption per piece [kWh] * electricity conversion factor [kgCO2e/kWh] * number of items per order [#]
	Warehouse consumption in storage area	Warehouse/handling	(warehouse daily energy consumption for storage [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) * number of items per order [#]
	Packaging	Warehouse/handling	packaging footprint [kgCO2e/cardboard]*number of cardboard [#]
	Warehouse consumption in shipping area (sorting, packaging, goods moving)	Warehouse/handling	(warehouse daily energy consumption for shipping [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) * number of items per order [#]
	Waybill emission	Warehouse/handling	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
Delivery	Product Pick-up from the retailer warehouse	Transportation	(average route distance [km] * percentage space occupied by a piece [%] * vehicle GHG conversion factor [kgCO2e/km]) * numer of items per order [#]
	Info request (e.g. on delivery process)	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Answer to customer request (e.g. on delivery process)	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Tracking service activation	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Customer delivery	Transportation	average distance per parcel [km] * vehicle GHG conversion factor [kgCO2e/km]
Post-sale	Info insertion about return	Communication	activity duration [h] * power supply of customer device [kW] * electricity conversion factor [kgCO2e/kWh]*probability of return rate offline [%]
	Confirmation mail sending	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]*probability of return rate offline [%]
	Product Pick-up from the customer	Transportation	average distance per parcel [km] * vehicle GHG conversion factor [kgCO2e/km]*probability of return rate offline [%]
	Tracking service activation	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]*probability of return rate offline [%]
	Return reception and management	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]*probability of return rate offline [%]

Appendix 2 – Formulas computing the environmental impact of each activity (offline purchasing process)

Phase	Activity	Typology	Algorithm
Pre-sale and sale	Travel to the tore	Transportation	distance between customer's home and store [km] * vehicle GHG conversion factor [kgCO2e/km]
	Product search in the store	Communication	activity consumption per day [kWh]/ number of customers per day [#] * electricity conversion factor [kgCO2e/kWh]
	Interaction of the customer with the salesman	Communication	activity consumption per day [kWh]/ number of customers per day [#] * electricity conversion factor [kgCO2e/kWh]
	Interaction of the salesman with the customer	Communication	activity consumption per day [kWh]/ number of salesmen [#] / number of customers per salesman [#] * electricity conversion factor [kgCO2e/kWh]
	Product purchase	Purchasing	activity consumption per day [kWh]/ number of customers per day [#] * electricity conversion factor [kgCO2e/kWh]
	Receipt release	Purchasing	activity consumption [kWh]// number of salesmen [#]/ number of customers per salesman [#] * electricity conversion factor
	Packaging	Purchasing	packaging footprint [kgCO2e/plastic bag]*number of plastics bag [#]
Replenishment	Replenishment order emission	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Replenishment order reception and management	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Order fulfillment	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Picking list emission	Management	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Picking	Warehouse/handling	picking consumption per piece [kWh] * electricity conversion factor [kgCO2e/kWh] * number of items per order [#]
	Warehouse consumption in the storage area	Warehouse/handling	(warehouse daily energy consumption for storage [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) * number of items per order [#]
	Sorting	Warehouse/handling	sorting consumption per piece [kWh] * electricity conversion factor [kgCO2e/kWh] * number of items per order [#]
	Warehouse consumption in sorting area for sorting activity	Warehouse/handling	(warehouse daily energy consumption for sorting [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) * number of items per order [#]
	Packaging	Warehouse/handling	packaging footprint [kgCO2e/cardboard]*number of cardboard [#]
	Warehouse consumption in sorting area for packaging activity	Warehouse/handling	(warehouse daily energy consumption for packaging [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh]) *number of items per order [#]
	Goods moving	Warehouse/handling	goods moving consumption per piece [kWh] * electricity conversion factor [kgCO2e/kWh]
	Warehouse consumption in sorting area for goods moving activity	Warehouse/handling	(warehouse daily energy consumption for goods moving [kWh] / items per day [#] * electricity conversion factor [kgCO2e/kWh])*number of items per order [#]
	Waybill posting	Warehouse/handling	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kW]
	Goods transportation to Store	Transportation	(average route distance [km] * percentage space occupied by a piece [%] * vehicle GHG conversion factor [kgCO2e/km]) * numer of items per order [#]
	Info request about delivery	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Interaction with the PoS about delivery	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]

	Tracking service activation	Communication	activity duration [h] * power supply of retailer device [kW] * electricity conversion factor [kgCO2e/kWh]
	Goods reception and management in the store reserve area	Management	activity consumption per day [kWh] / number of salesmen [#] / number of customers per salesman [#] * electricity conversion factor [kgCO2e/kWh]
Delivery	Travel back home	Transportation	distance between customer's home and store [km] * vehicle GHG conversion factor [kgCO2e/km]
Post-sale	Return trip to the PoS	Transportation	distance between customer's home and store [km] * vehicle GHG conversion factor [kgCO2e/km]*probability of return rate offline [%]
	Interaction consumer-saleman about return	Communication	activity consumption per day [kWh]/ number of customers per day [#] * electricity conversion factor [kgCO2e/kWh] *probability of return rate offline [%]
	Return trip with the new purchase	Transportation	distance between customer's home and store [km] * vehicle GHG conversion factor [kgCO2e/km]*probability of return rate offline [%]