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Life cycle assessment of grocery, perishable, and general merchandise multi-facility distribution center networks☆

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ABSTRACT

Buildings consume half the global electricity and generate one third of greenhouse gas (GHG) emissions. Distribution centers (DCs) have an important role in food distribution and sustainability. Omitting food distribution from food life cycle assessments (LCAs) is a data gap that may affect the overall impacts of food. We showed multi-facility state-level environmental impacts of the largest DC network in the United States. Our method included regional resolution of the life cycle inventory (LCI) combined with the regional life cycle impact assessment (LCIA) method. Three types of food DCs in different climate zones were assessed using the LCA method. Primary energy use in grocery and perishable DCs was refrigeration (80%) and in general merchandise were conveyor systems (50%). Building material and lighting became relevant for non-refrigerated spaces and in low-energy impact states. The location-specific provenance of electricity energy sources such as coal affected the process and substance impact contributors and magnitude of the environmental impacts, for example, in the energy, climate, water, and land nexus. Water impact depended on energy sources and local water availability. Land use was dominated by activities in the supply chain and not building construction area. Achieving a low environmental impact supply chain is a major goal of producers, distributors and retailers. Energy efficiency through green building standards and distributed energy may improve sustainability of DCs.

1. Introduction

The generation and distribution of electricity comprises nearly 40% of U.S. greenhouse gas (GHG) emissions [1]. Buildings account for 70% of electricity use [2]. In the coming years, GHG emissions of commercial buildings will increase at a rate of 1.8% per year [3]. Commercial buildings include office buildings, lodging, amusement, distribution centers (DCs), and retail centers (RCs) such as supermarkets. In 2012, the construction of RCs and warehouses accounted for 43% of the total commercial building revenue [4]. Warehouses used 300,000 TJ of energy in 2012. This is about 7% of total energy use of all commercial buildings [5].

Product and food distribution includes processes that occur between producers, retailers, and customers. Fig. 1 shows food distribution in the United States. DCs and RCs are primary food distribution components. A DC and RC network is defined as sum of DCs and RCs in one state. Post-processing distribution and consumption was rarely included in food life cycle assessments (LCAs), which may affect overall product sustainability. Food LCAs that reported cradle-to-grave LCA results accounted for the average RCs' energy use and excluded DCs [6,7]. One exception in this data gap is research by Burek et al., which accounted for average DC energy use in the United States [8]. With nearly 0.93 billion square meters of floor space in the United States, DCs have an important role in food distribution and sustainability, and their life cycle energy and environmental performance need to be assessed.

Energy savings are the most important metrics of buildings' sustainability because operational energy use is primary cost and environmental impact driver [9]. In the United States, 30% of commercial building energy is used inefficiently or unnecessarily, for example, due to overcooling [10]. EnergyPlus is one of many building simulation tools to evaluate energy efficiency of commercial buildings [11,12]. For a more informed approach than energy efficiency evaluation, the building and construction sectors have been using the LCA method. Researchers used LCA to analyze improvements in the United States cold storage warehouses by defining the best roof insulation materials for each climate zone [13]. Both the EnergyPlus software and LCA have been used in combination to evaluate environmental sustainability of concrete material and identified improvement opportunities [14]. However, most build-

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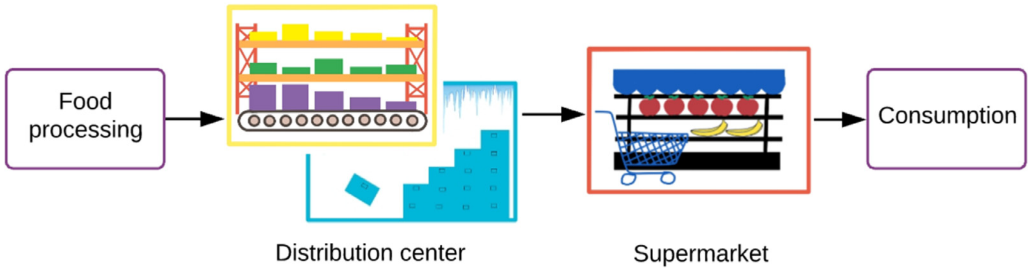

Fig. 1. Food distribution in the United States includes processes between producers, retailers, and consumers.

ing LCA studies focused on energy use, GHG emissions, and water consumption [9,15,16].

In a whole-building LCA, building use and operation phases had the highest environmental impact driven by electricity generation, transmission, and distribution rather than material for building construction [17–19]. Earlier research showed that environmental impact of residential buildings varied for different locations due to site-dependent electricity production characteristics, i.e. fuel mix [20,21]. Regional electricity generation energy sources determined impact contributors, the magnitude of impacts, and which substance flows affected specific environmental impacts the most [21]. The U.S. regional electricity GHG emission factors are well documented [1,20]. In special cases, building materials and manufacturing became the largest contributor to the GHG emissions [22]. That was the case when local electricity generation energy sources were renewable.

The goal of this research was to conduct LCAs of distribution networks in the United States, which will bridge the data gap and enable full sustainability assessment of food and products. In this paper, we assessed the environmental impact of grocery (G), perishable (P), and general merchandise (GM) DCs using the LCA method. Primary hypotheses are that climate conditions, the year of building construction, building materials, state-level sources of electrical power, energy demand of refrigerated and non-refrigerated spaces, and conveyor length change the magnitude of the environmental impacts across the U.S. First, the research identified environmental impact similarities and differences among different types of DCs. Second, the research investigated relationships between climate zones, energy demand, electricity generation energy sources, building materials and the environmental impact of individual DCs and state-level DC networks. For our case study, we chose locally, regionally, and globally impactful business Wal-Mart Stores, Inc. The evaluation is science-based, independent, and objective, and it does not disclose or use the company's internal data on energy use. Results will serve as a benchmark of the environmental performance of the DC networks and for future work, which will include strategies to obtain net-zero energy food distribution networks [23]. DCs networks models will allow LCA food and product practitioners to include DC burdens in their LCAs, which will enable science-based, environmentally sound decisions in the supply chain management.

2. Materials and methods

The LCA method is used as the mainstream quantitative method to assess environmental impacts of products, processes, services, and whole buildings over the entire life cycle [24]. At the time of this writing, it has been over ten years since the establishment of ISO 14040/44 series LCA standards [24,25]. The ISO revises and appends existing standards and develops new standards [24–27]. In building environmental assessment, the LCA is used to make environmental design decisions at the product-, assembly-, and whole-building level, which includes structural components and operating effects [19,28–31]. Interest in sustainable buildings and infrastructure is growing, which prompted development of several building specific LCA-based sustainability tools [16]. The Building for Environmental and Economic Sustainability (BEES) tool measures the environmental performance of building products [32]. Athena Impact Estimator 5.2 evaluates whole buildings and assemblies [33]. Finally, the Building Industry Reporting and Design for Sustainability (BIRDS) measures energy, environmental, and cost performance of prototype commercial buildings [34]. Currently, BIRDS neither includes DCs nor allows the modeling of custom buildings. Thus, we built LCA models for our custom distribution center buildings in Athena Impact Estimator 5.2 [35] and SimaPro 8.4 software [36].

2.1. Goal and scope

This research is LCA of a globally impactful business and it will contribute to rethinking the global supply chain through network analysis. The research outcomes are based on comprehensive whole-building LCA of different three types of DCs and their multi-facility state-level networks. The goal of this research was to (1) assess the environmental impacts of three types of food DCs in the United States using the LCA method, (2) show environmental impact similarities and differences among three types of DCs, (3) investigate relationships between climate zones, energy demand, electricity generation energy sources, and (4) quantify total state-level environmental impact based on current number and sizes of Wal-mart Inc. Stores DCs in each state.

LCA models were based on process-LCA method, which includes itemized inputs and outputs for each LCA stage [36]. System modeling was based on the attributional approach. In the attributional approach, inputs and outputs are attributed to the functional unit and multi-output system processes are partitioned based on allocation rules [37]. In this research, allocation was avoided because the functional unit was based on the whole building and data were available separately for each building operation. The choice of LCA method and approach was based on need to include U.S. state-level electricity production for regional assessment, available only in the process-based attributional LCA DataSmart 2016 database [38].

2.2. System boundary and functional unit

The system boundary was at the whole-building level from cradle-to-grave as shown in Fig. 2a and b. Primary LCA stages were (1) building use and operation and (2) infrastructure. Infrastructure LCA models included construction material production (envelope and insulation), building construction, and the end of the building life (building demolition and material disposal) [16]. Building use and operation stage included refrigeration, refrigerant loss, lights, heating, ventilation, and air conditioning (HVAC), machinery, water consumption, and conveyors for each location. The main difference between DCs is existence of refrigeration and insulation in GDCs and PDCs (Fig. 2a) and conveyor in GMDCs (Fig. 2b). The cho-