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A Design Theory for Energy and Carbon Management Systems in the Supply Chain

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Abstract

Energy and Carbon Management Systems (ECMS) are a class of green information systems that has the potential to increase environmental sustainability in organizations and across supply chains. Employing a design science research approach, we define the scope of ECMS in the supply chain context, identify requirements, design an expository instantiation, and develop an information systems design theory, including key constructs and design principles. We instantiate this theory in four supply chain contexts to validate and revise the proposed design in two rounds. We identify six system components—data collection, energy monitoring, supply chain coordination, ECMS workflow engine, reporting, and carbon footprint estimator—that integrate and coordinate four types of information flows (transactional, contextual, energy, and product-environmental), and formulate design principles. Our evaluation indicates that the ECMS design theory, if instantiated, supports energy and carbon measurement and *environmentally aware decision-making and practicing in supply chains. We also highlight how considering energy information flows in combination with material features that afford environmentally aware decision-making and practicing are key to qualifying information systems as "green."*

Keywords. Energy and carbon management systems, green information systems, sustainable supply chain management, design science research

1 Introduction

Pressures from climate change and pollution, along with stricter regulations, rising energy prices, changing consumer behavior force organizations to develop sustainable supply chains (Ansari & Kant, 2017; Bové & Swartz, 2016; Rajeev, et al., 2017). While recent industry initiatives suggest that organizations seek to develop more energy-efficient facilities (e.g., Reuters, 2018; Yang, 2018), less than 20 percent of the industry participants of a recent survey report a comprehensive awareness of their supply chains' sustainability performance (Winston & Bonini, 2019), possibly because determining such performance remains challenging (Acquaye et al., 2018; Qorri et al., 2018; Sloan, 2010).

Using information systems (IS)' capabilities to standardize, monitor, capture, and use data and metadata and to evaluate financial and environmental performance indicators is key to implementing sustainable supply chains (Björklund et al., 2012; Dao et al., 2011; de Camargo & Jabbour, 2017; Lee & Wu, 2014; Melville, 2010). IS facilitate collaboration and information exchange by improving information flows among supply chain partners and allow for an inter-organizational perspective on sustainability (e.g., Banker et al., 2006; Gunasekaran & Ngai, 2004; Thies & Stanoevska-Slabeva, 2013).

Energy and Carbon Management Systems (ECMS) are a class of IS that receive heterogenous types of environmental data (e.g., electricity and fuel use, emission factors) as inputs, process them to calculate energy-related key performance indicators

(KPIs) and derive carbon emissions, and offer functionalities like supply-chain analytics, workflow management, and automated reporting (Melville & Whisnant, 2014). Still, how ECMS can assist the development of sustainable supply chains (de Camargo & Jabbour, 2017) and how one should design and implement these systems remain unclear. While some studies explore the design and implementation of various IS for environmental sustainability (Graeuler et al., 2013; Hilpert et al., 2011; Seidel et al., 2018), they do not attend to designing systems for supply chain management. Therefore, our objective is to *inform the design and implementation of ECMS for sustainable supply chain management.* This goal deserves our attention, as the supply chain context poses challenges that move beyond those involved in ECMS design and implementation within the boundaries of an organization.

We adopt a design science research (DSR) approach (Peffers et al., 2007), combined with elements from action design research (ADR) (Sein et al., 2011), to derive a design theory for ECMS in the supply chain context. Our approach is process-oriented, systematic, and iterative (Hevner et al., 2004; Gregor & Hevner, 2013; Peffers et al., 2007). We use the basic components of IS design theory (Gregor & Jones, 2007) as an abstract blueprint to formulate our design theory, and we instantiate and iteratively develop this theory in two DSR rounds in four organizations. These organizations operate in different sectors and have broad supply chains that ranges from the supply of raw materials to manufacturing to the point of sales. The four organizations consist of two textile manufacturers—a textile manufacturer for fashion and luxury markets and an international clothing company that seek to improve their energy-aware production—and two organizations in the fast-moving consumer goods (FMCG) sector—a grocery retailer and a major food manufacturer that seek to develop sustainable supply chains.

This article proceed as follows. First, we summarize the findings from studies on energy and carbon management (ECM) in supply chains, as well as from works on environmental sustainability in general and ECMS in particular. Then we introduce our research approach. After formulating a design theory in terms of purpose and scope, design requirements, core constructs, principles of form and function, and expository instantiation, we describe our implementation, including evidence from two rounds of theory instantiation as well as artifact demonstration and evaluation via proof-of-concept and proof-of-value research (Nunamaker et al., 2015). We conclude by highlighting our findings' contributions and practical implications and discuss limitations and suggestions for future research.

2 Research Background

2.1 Energy and Carbon Management in Sustainable Supply Chains

Organizations' transition to sustainable supply chains (SSCs) requires the development of performance measurement (Janssen et al., 2015; Qorri et al., 2018), as highlighted in the reviews of Ahi and Searcy (2015), Hassini et al. (2012), and Tajbakhsh and Hassini (2015). Such measurements help organizations monitor and evaluate their environmental performance, make environmentally aware decisions, foresee pitfalls, and be proactive (Gunasekaran et al., 2004; Gunasekaran & Kobu, 2007). Apart from guiding compliance with standards and regulations (Qorri et al., 2018; Seuring & Müller, 2008; Taticchi et al., 2013), such measurements support cost reduction, efficiency (Acquaye et al., 2018), supply chain innovation, and risk management (Schaltegger & Burritt, 2014).

Incorporating both environmental and non-environmental aspects in supply chain management is central to the ability to make the trade-offs among the dimensions of performance (Björklund et al., 2012), so a growing number of firms have integrated environmental indicators into the management of their supply chains (Hua et al., 2011; Lee, 2014; Rajeev et al., 2017; Sundarakani, 2010). Specifically, they consider energy and fuel consumption and carbon emission indicators as parameters for solving traditional operational problems, such as production optimization (Du et al., 2016; Nouira et al., 2014; Plitsos et al., 2017), inventory management (Arıkan & Jammernegg, 2014; Hua et al., 2011; Konur et al., 2017), vehicle routing (Ehmke et al., 2018; Xiao et al., 2019; Zhang et al., 2018), inventory routing (Cheng et al., 2016; Kuo et al., 2014), network design (Li et al., 2020; Martí et al., 2015), and even supplier selection (e.g., Genovese et al., 2013; Govindan et al., 2015; Zimmer et al., 2016). Zhou and Wen (2020) offer a comprehensive, updated review of carbon-constrained operations models.

Calculating environmental indicators and ensuring transparency in supply chains is feasible only if the appropriate measurement and management tools are available (Janssen et al., 2015). Janssen et al. (2015) and Qorri et al. (2008) provide overviews of performance measurement and management approaches developed over the last twenty years. These approaches are often linked to standards of environmental management (e.g., ISO 14000 series) or product life-cycle assessments (LCA) (e.g., ISO 14030), as well as to reporting initiatives like the Global Reporting Initiative (GRI) (1997) and the Carbon Disclosure Project (CDP) (2000).

Still, considerable debate remains to be held on how firms should measure SSC performance. Hassini et al. (2012) identify more than one hundred potential indicators and provide a list of frameworks for SSC management and environmental performance measurement, but Ahi and Searcy (2015) provide evidence that only products quality, air emissions, greenhouse gas (GHG) emissions, energy consumption are widely used. Tuni et al. (2018) classify these metrics into input and output categories and point out that most of the input metrics focus on resource and energy consumption, while the output metrics focus on GHG and carbon emissions. GHG emissions are typically reported as a single CO_2 equivalent using the global warming potentials weighting factors and are usually aggregated with carbon emissions into a single carbon emissions or CO_2-equivalent metric. Thus, energy consumption and carbon emissions are the two most prominent environmental performance metrics, and both public authorities and private companies (e.g., European Commission 2018; Techcrunch, 2019; TESCO, 2017) consider improving energy consumption and carbon emissions as key targets for regulatory emission-control policies and companies' carbon emission and energy cost reduction policies (Ahi & Searcy, 2013; Varsei et al., 2014).

The energy that is consumed by all supply chain activities—production, storage, transportation, and so on—includes electricity and fuel consumption from both renewable and non-renewable sources. Carbon emissions are based heavily on energy consumption, as the energy generation process directly affects their input-output relationship. Renewable energy creates much fewer carbon emissions than non-renewable energy extracted from fossil fuels does. Considering the still limited adoption of renewable energy (18.9% of total energy consumed in the European Union and 8.3% of that consumed in transport activities) (Eurostat, 2020), emissions remain strongly correlated with energy consumption.

Measuring environmental performance is challenging because of limited data availability (Bjorklund et al., 2012; Veleva et al., 2003), diverse supply chain players (Ahi & Searcy, 2015; Hervani et al., 2005), incompatibility of classic supply chain measures with an intra-organizational scope, rather than an inter-organizational scope (Lehtinen & Ahola, 2010), lack of trust and fear about data confidentiality (Hassini et al., 2012), and current enterprise systems' insufficient capture of non-traditional performance data (Hervani et al., 2005). As a result, organizations require IS for capturing and analyzing data for every supply chain activity and for each aspect of sustainability (Maestrini et al., 2017; Qorri et al., 2018); that is, the success of the measurement system in the supply chain depends on the ability of each supply chain members' IS to capture data related to the sustainability dimensions for every supply chain activity (Qorri et al., 2018). It is against this background that we seek to show how IS can address energy management's and carbon management's requirements that allow for SSC management and to highlight pertinent implementation issues.

2.2 Information Systems and Sustainability Transformations

IS can play a pivotal role in sustainability transformations in terms of organizational sensemaking (Seidel et al., 2013), decision-making and knowledge creation (Butler, 2011), belief formation (Melville, 2010), automation (Dao et al., 2011), and innovation (Melville, 2010). IS can facilitate the cognitive activities through which individuals across an organization can frame, interpret, and understand the multilayered and complex issues related to environmental sustainability transformation to develop sustainability-related action (Seidel et al., 2013). IS support decision-making related to the environmental sustainability regulations with which firms increasingly must comply (Butler, 2011), assessment of the environmental practices or technologies that a firm should adopt (Bose & Luo, 2011; Dao et al., 2011; Watson et al., 2011; Zhang et al., 2011), and the consequences of such an adoption (Bengtsson & Ågerfalk, 2011; DesAutels & Berthon, 2011).

Considering this variety of applications, we can broadly conceive of green IS" as "types of IS that assist individuals and organizations to become more environmentally sustainable" (Recker, 2016, p. 4477); so it focuses on *outcomes*. Recker (2016) describes these outcomes in terms of environmentally sustainable work practices and decisions, and Seidel et al. (2013) identify sustainable practices and environmental sensemaking as outcomes. The green IS discourse acknowledges that green IS help organizations implement sustainable business processes (Watson et al., 2008; Watson et al., 2010).

From this discussion we make two primary observations: Any IS can be a green IS if it helps organizations accomplish sustainability related outcomes and the key challenge from a design perspective is to extend the view from ends—that is, the outcome perspective—to the means—that is, the material features that help organizations produce these outcomes. We argue that IS can accomplish the ends of improving supply chains' environmental performance by combining several means —measurement and monitoring through capturing and analyzing data across the supply chain, making decisions regarding improvement measures, tracking the progress in environmental performance, identifying potential problems, and providing insights into future actions (Janssen et al., 2015; Lee & Wu, 2014; Qorri et al., 2018).

Since IS in general and ECMS in particular are rarely mentioned in academic papers on SSCs (Qorri et al., 2018), rigorous scholarly research is needed to explore their design and determine how and to what extent they can improve sustainability in supply chains and logistics (Hoang et al., 2017).

2.3 Energy and Carbon Management Systems

ECMS are a type of environmental management information system (EMIS) (El Gayar & Fritz, 2006; Teuteberg & Straßenburg, 2009). EMIS are "organizational-technical systems for systematically obtaining, processing, and making available relevant environmental information in companies" (El Gayar & Fritz, 2006; p. 756). As a sub-category of EMIS, ECMS focus on energy consumption and carbon emissions. In what follows, we discuss the broader category of EMIS, given the limited research on ECMS.

The rich literature on EMIS resides in a fragmented landscape because of the lack of a clear definition and taxonomy. Our literature analysis identified several terms that refer to EMIS and fit the description El Gayar and Fritz (2006) provide, including "environmental information systems" (Cherradi et al., 2017), "environmental ERP" (Melville, 2012), "environmental enterprise systems" (Hoang et al., 2016), "sustainable enterprise resource planning systems" (Chofreh et al., 2018), "energy information systems" (Effenberger & Hilbert, 2016), "energy management information systems" (Martirano et al., 2018), "energy management control systems" (Schulze et al., 2018), and “carbon management systems” (Corbett, 2013). Because of the interdisciplinary nature of EMIS research—scholars from disciplines like accounting, energy engineering, environmental informatics, IS, logistics, and industrial engineering contribute - obtaining a complete literature map is challenging. We found a considerable amount of work on EMIS and the intricacies of energy measurement, their architectural design, micro-grids (e.g., Elkazaz et al., 2020; Mazidi et al., 2020; Whittle et al., 2020), and carbon accounting (e.g., Gibassier et al., 2020; Luo & Tang, 2016).

Following Malhotra et al.'s (2013) value space of research classification, we found that most of the studies belong to the design-oriented dimension (e.g., Bensch et al., 2015; Corbett, 2013), while the evaluation of the developed artifacts in actual cases falls into the category of impact-oriented research that uses action research or in vivo real-time approaches (e.g., Stindt, 2014). A few studies fit into the conceptual value space (e.g., Bensch et al., 2014; Effenberger & Hilbert, 2018; Guenther et al., 2016; Setiyoko et al., 2017; Teuteberg & Straßenburg, 2009) and the analytic space, including case studies, ethnographic analyses, and quantitative empirical analyses (e.g., Hoang et al., 2016; Hoang et al., 2017; Leyh et al., 2014; Melville & Saldanha, 2013; Nishant et al., 2017). Most studies address the application of EMIS in a certain environment or industry, such as logistics (Hilpert et al., 2013b; Iacob et al., 2013), manufacturing (Bruton et al., 2018; Zampou et al., 2014b), higher education (Scholtz et al., 2016), or recycling processes (Schweiger, 2016).

The design science stream produces several EMIS instantiations, including systems to assess the availability of critical raw materials (Bensch et al., 2014), assist ISO 50001 implementation in manufacturing (Bruton et al., 2018), support energy-aware manufacturing (Zampou et al., 2014b), gather real-time data for products’ carbon footprints in transportation processes based on vehicles’ on-board systems and smart phones (Hilpert et al., 2011), report energy consumption and GHG emissions at the product level (Hilpert et al., 2013a), improve reverse logistics (Stindt, 2014), and track the GHG emissions of logistics processes (Hilpert et al., 2013b). Some EMIS instantiations focus on persuading employees to engage in ecologically responsible behaviors (Corbett, 2013; Kotsopoulos et al., 2018), or on enabling urban planning (Culshaw et al., 2006) and mobility tracking (Kugler et al., 2014), fostering sustainable decision-making in the energy sector (Nuss, 2015), and supporting the end-of-life vehicles' recycling processes (Schweiger, 2016). These studies suggest various EMIS and ECMS functionalities and system components, including data storage, validation, analytics, and reporting (Melville et al., 2017) or discuss process automation and integration with other systems (Hoang et al., 2017). However, the proposed design knowledge is often highly context-specific and not at the level of design theory that one can apply across contexts and time. We found only one publication that identifies specific requirements for a specific type of EMIS, an IS for sustainability reporting (Hilpert et al., 2014).

Scholars also discuss the impact of EMIS on energy efficiency and carbon performance (e.g., Hoang et al., 2017; Schulze et al., 2018) and the factors associated with their adoption (e.g., Hoang et al., 2019; Melville & Saldanha, 2013). The extent of ECMS implementation is positively associated with a firm's energy efficiency (Schulze et al., 2018), and an exploratory investigation of four case studies shows that these systems can improve the quality of environmental data, generate various reports with ease and at low cost, and reduce risk (Hoang et al., 2017). Beyond processing environmental information, ECMS also facilitate decision-making and knowledge creation related to energy consumption and environmental impacts, such as in reverse logistics (Stindt, 2014) or manufacturing operations (Böttcher & Müller, 2016).

3 Research Approach

We use a DSR approach to develop prescriptive knowledge and formulate the key components of a design theory (Gregor & Jones, 2007) for ECMS. We employ a staged process based on Peffers et al.' (2007) incremental and iterative refinement approach. We move through the phases of problem identification, identification of purpose and scope, design and development, demonstration and evaluation, adjusting Peffers and associates' original formulation in three ways. First, we formulate an initial version of a design theory for ECMS in the design and development phase; that is, we develop an abstract blueprint that includes key constructs and principles of form and function and then a concrete instantiation that is consistent with that blueprint and in response to the identified problem situation.

Then, considering that the artifact emerges from interaction with the organizational context, even when its initial design is guided by the researchers' intent, we use the key activities of ADR (Sein et al., 2011): ongoing reflection activities throughout the phases, where a group of stakeholders involved in the design and implementation activities—practitioners, software-engineers, researchers, end-users—give feedback before the final evaluation, thereby attending to theoretical, technical, and practical perspectives. This resembles Mullarkey and Hevner's (2019) approach. Finally, we add a phase of reflection and formalization of learning that supports the generation of design theory (Mandviwalla, 2015; Sein et al., 2011). We formulate the design theory components based on reflection on the outcomes of the DSR process and subsequent formalization of key findings. Thus, we move conceptually from building a solution for a single instance of an ECMS to a solution for a broader class of problems (Sein et al., 2011).

We performed two rounds of a sequence of five phases over a period of thirty-three months. Figure 1 visualizes the iterations, describes the methods and outcomes, and highlights how we articulated the results in the form of a new IS design theory for ECMS.

Figure 2 highlights the progress over time. The research team coordinated all DSR activities, from identifying and elucidating user requirements to ECMS design, demonstration, and evaluation.

We developed the ECMS artifacts in the context of two research projects on energy efficiency and carbon efficiency in manufacturing and in the supply chain[1]. The development team consisting of people from seven information technology (IT) companies who had expertise in supply chain modelling tools, LCA tools, manufacturing systems, energy sensors, monitoring tools, and IT integration also supported the DSR activities and especially the design, development, and demonstration of ECMS artifact. The research team and the development team met regularly with the organizations' representatives to present the progress at the various phases and get early feedback on the developments.

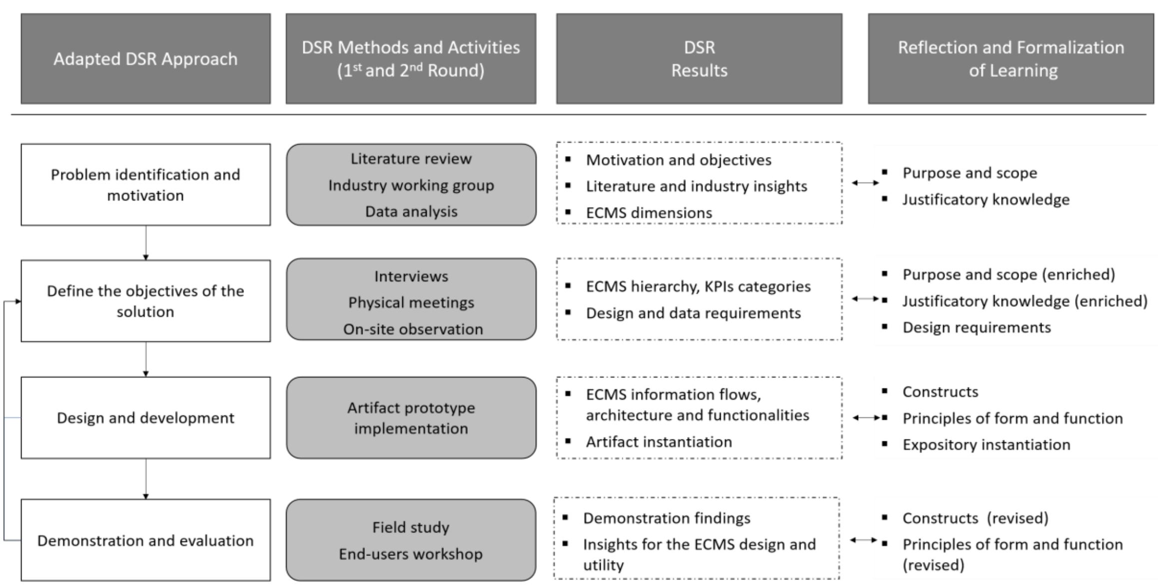

Figure 1. Design Science Research Approach

[1] ARTISAN: Energy-aware enterprise systems for low-carbon intelligent operations (Project Number: 287993)

e-SAVE: Energy Efficiency in the Supply Chain through Collaboration, Advanced Decision Support and Automatic Sensing (Project Number: 288585)

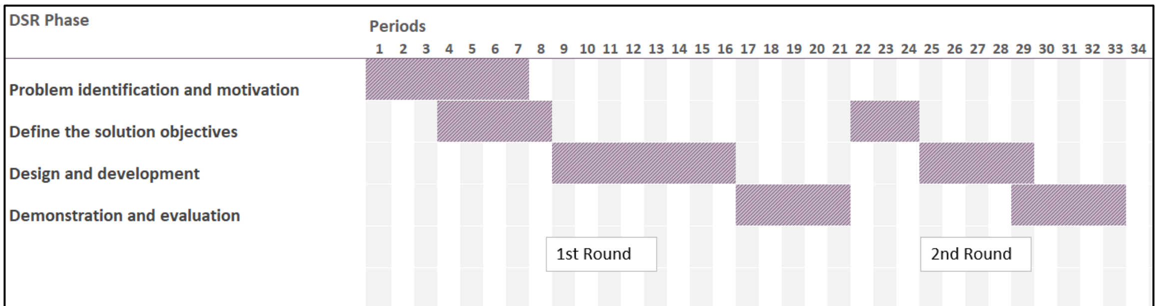

Figure 2. Design Science Research Approach Gantt Chart

To apply the DSR approach we adopted, we identified four organizations (Table 1) to:

a) cover end-to-end supply chains and capture the specificities of the manufacturing, warehousing, and distribution stages of the supply chain;

b) investigate the application of ECMS in industries with various sustainability objectives; for example, the textile industry is cost-driven, whereas the FMCG adopts a collaboration perspective to address consumers' environmental concerns;

c) cover multiple contexts, each with its own implementation challenges in terms of, for example, data quality and availability, data capturing and integration, and information-sharing.

Table 1: Organizations

A	Organization A is an Italian medium-sized enterprise with 210 employees and a production of more than 700,000 meters of fabric per year. It is one of the oldest manufacturers in the textile industry and is interested in enhancing the energy efficiency in manufacturing and collaboration with its suppliers.
B	Organization B is a clothing company with 735 employees in Germany and an annual turnover of 184 million euros. Another 2,000 people are employed in Eastern Europe for the manufacturing of garments. The company has 109 retail stores in 58 countries and more than 1,500 up-market fashion stores.
C	Organization C is a major Greek retailer with a supply chain consisting of a central warehouse and 94 stores. The central warehouse accommodates the products received from most of its more than 600 suppliers and distributes them to the stores using its own fleet of vehicles. Its internal mechanisms portray an environmentally aware enterprise. The organization has implemented environmentally friendly facilities, such as motion sensors operating the lights in the warehouse and collaborative distribution processes to improve the company's environmental performance.
D	Organization D is a multinational food manufacturer, one of the main suppliers in the FMCG sector, and has an environmentally aware profile. The organization has an extensive and complex supply chain network with presence in Europe, North and South America, Asia, and Oceania. Its distribution network is vast, with partners in more than 100 countries. It has implemented several environmental practices over the years, including energy saving programs, LCA methods, environmental product declaration, business intelligence, and sustainable packaging in logistics.

Next, we describe the key activities we carried out and provide an overview of key outcomes. For brevity, we do not present the intermediate results of the applied DSR process.

We grounded the **problem identification** in a review of studies on ECM and on practitioners' environmental sustainability reports. We identified ECM requirements and challenges using a working group of corporate decision-makers who are responsible for supply-chain management, environmental management, and reverse logistics. This group included nine companies'[2] supply chain/logistics managers or directors who met approximately monthly for seven months. We used these meetings and two semi-structured interviews to ensure we understood the companies' specificities and sectorial challenges. We also had access to six months of distribution data provided by one grocery retailer and one food manufacturer,[3] which helped us estimate energy consumption and carbon emissions and investigate the potential for difficulties related to data availability, quality, and granularity. This process allowed us to define the purpose and scope of ECMS and to elaborate on design and implementation issues related to data capture and integration, data quality and availability, definitions of energy and carbon performance metrics, collaboration, and information-sharing.

To elucidate the purpose and scope and decide on a set of ECMS design requirements, we worked closely with the four organizations (Table 1), two of which also participated in the previous phase, in conducting semi-structured interviews with their representatives and discussed the design requirements in several meetings over a period of five months. This data collection was supplemented by on-site observations,

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[2] METRO - MyMarket, AB Vassilopoulos (part of Delhaize Group), Barilla, Beiersdorf, Colgate-Palmolive, Nestle, Procter & Gamble, Unilever, Kassoudakis Logistics Partner

[3] AB Vassilopoulos (Part of Delhaize Group), Barilla

including at their factories, warehouses, and distribution centers. We included for each dimension (manufacturing, warehousing, distribution, and supply chain) the respective ECM KPIs and hierarchies, as well as the data necessary for their calculation. We translated the end users' views into six ECMS design requirements that we aligned with those described in Melville et al. (2017) and validated them using information from existing artifacts (Mandviwalla, 2015), a process that allowed us to develop the "design requirements and justificatory knowledge" theory component.

In the **design and development** phase, we derived a set of key ECMS constructs in terms of (1) the information flows related to key data types required for ECM and (2) system components. We then identified initial principles of form and function and incorporated those constructs to guide the artifact's design and development. With the support of the development team, we then translated these principles into technology features. During this phase, the research and development team met regularly to monitor the development process. By reflecting on the outcomes of this phase, we refined the initial constructs, the principles of form and function, and the expository instantiation.

For the purpose of **demonstration and evaluation**, we performed an ex-post naturalistic evaluation (Venable et al., 2012) by deploying the artifacts in the four organizations to establish proof-of-concept and proof-of-value (Nunamaker et al., 2015). We applied an observational design evaluation using a field study approach (Pries-Heje et al., 2008; Venable et al., 2012) in both rounds and descriptive methods in the form of scenarios in the second round. The first round of demonstration and evaluation focused on validating the design theory and investigating its design and implementation challenges and feasibility regarding, for instance, data availability and granularity. We also consolidated our proof-of-concept and proof-of-value in the second round by assessing the ECMS utility the organizations perceived and collecting evidence on how the ECMS theory instantiation yielded an ECMS implementation that supported ECM and environmentally aware decision-making and practicing.

As part of the field study and with the active support and involvement of the development team, we deployed, demonstrated, and evaluated artifacts based on the suggested ECMS design theory at the four organizations. The development team installed several hardware elements like energy sensors and developed interfaces to capture or retrieve energy- and fuel-consumption data from legacy systems like material requirements planning (MRP), manufacturing execution systems (MES), enterprise resource planning (ERP), and warehouse management systems (WMS). Daily transactional data were obtained from these systems and were uploaded to the ECMS for a period of twelve months in the first round and five months in the second.

The end users, the first and the second author, who have expertise in IS design, green IS, and supply chain management; the third author, who has expertise in manufacturing operations; and domain experts from the development team—analyzed and identified the design and implementation challenges in the first round, revising constructs where necessary before initiating the second round of demonstration and evaluation. Workshops with end users at the four organizations allowed the research team to assess the artifact instantiation's utility in the second round. The group of fourteen end users consisted of three high-level directors in the areas of supply chain, environmental sustainability, and customer service; six mid-level managers from supply chain and logistics to production; a research director; and four IT directors and integrators. Thus, this group included decision-makers and IT facilitators who represented all four elements of the ECMS scope and were sufficiently heterogeneous for our purposes. Tables A.1 and A.2 in the Appendix depict additional details about this group for the sake of transparency and reproducibility. We revised the design theory—

specifically, the ECMS information flows, components, and design principles—only after the demonstration and evaluation phases of the first and second round.

4 Initial ECMS Design Theory

4.1 Purpose and Scope

All managers and directors involved in the working group recognized the ECMS core aims in terms of cost reduction, operational improvement, and response to regulatory and consumer requests for more sustainable solutions. Eight of the nine companies that participated in the working group did not have energy-monitoring systems in place and identified the lack of environmental information as a critical barrier to the development and implementation of SSC practices. These companies recognized the need to collect more detailed environmental information (e.g., per day or per route), integrate this information into supply chain processes (e.g., routing and inventory management), and present it in combination with traditional supply chain performance indicators (e.g., vehicle fill rates, inventory levels) to make their decision processes more environmentally aware. Monitoring environmental performance indicators like energy consumption and carbon emissions in the supply chain context remains costly and time-consuming.

To meet these needs, the scope of an ECMS in the supply chain context should involve various dimensions of monitoring, reporting, and decision support while also addressing all stakeholders (Ahi & Searcy, 2015). We adapted Ahi and Searcy's (2015) conceptual framework for measuring performance in green supply chains to define the key stakeholders in an SSC: the supplier, the manufacturer, the distributor, the retailer, and the customer (Figure 3). We omitted end-of-life management like recyclers, re-users, and disposers since reverse logistics is not in the scope of this study.

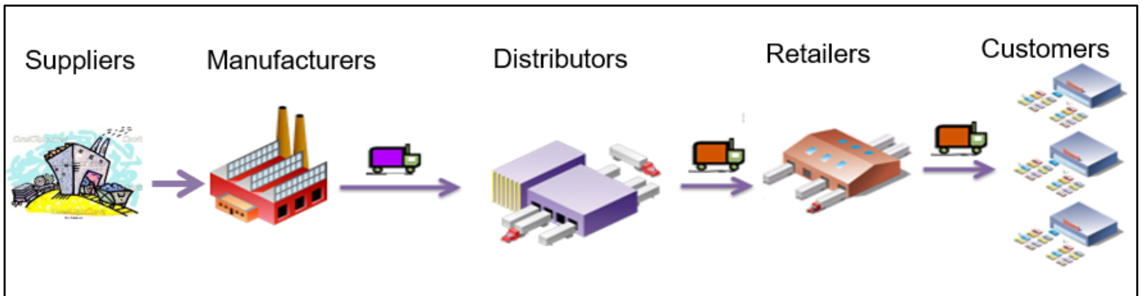

Figure 3. The Scope of ECMS in the Supply Chain

The study addresses three main types of activity types: manufacturing activities related to the production of raw materials, semi-finished goods, or finished goods; warehousing activities related to the storage and handling of raw and packaging materials at the source or semi-finished or finished goods at the destination markets; and inbound and outbound transportation activities across all modes of transportation, including road, rail, sea, inland waterways, and multimodal transportation. Thus, the supply chain context includes that of manufacturing but moves significantly beyond it (Figure 3).

Table 2: ECMS' Purpose and Scope

ECMS Scope	ECMS Purpose
Manufacturing	Track energy consumption to quantify potential savings related to manufacturing processes and to improve the performance of their ECM. Track the energy consumption of production machines, which are responsible for the greatest part of energy consumption. Measure indirect energy consumed by activities that are not directly involved in product manufacturing, such as lighting, cooling/heating, and ventilation.
Warehousing	Track energy consumption and quantify potential savings related to specific nodes of the supply chain (e.g., warehouse, store) and energy-greedy infrastructures like refrigerators and lighting. Use power supply meters in combination with sensors.
Distribution	Track vehicles' fuel consumption to control and improve distribution processes' environmental impacts. Collect fuel-consumption data and integrate them with traditional indicators like vehicle fill rate, distance travelled, and weight distributed.
Supply Chain	Measure the energy consumption and carbon emissions across the supply chain, combining the two previous views of warehousing and distribution, collecting data from various organizations (3PLs, retailers, suppliers), and supporting decisions that impact the sustainability performance and choices of supply chains.

Single and aggregated measurements can only partially satisfy regulatory and consumer requirements and cannot deliver operational improvements or shed light on strategic aspects of SSCs. For example, organizations can use annual energy consumption and carbon emission data in annual corporate social responsibility reports, but this data does not support decision-making at the process level for, for instance, routing or replenishment decisions. To support such decisions, more detailed data, such as fuel consumption per vehicle, should be input to an ECMS.

Effective SSC management requires that sustainability indicators be associated with traditional operational indicators (Bai et al., 2012; Maas et al., 2016). Three types of KPIs must be considered: environmental KPIs, including distinct energy consumption and carbon KPIs like total energy consumption, total CO_2 emissions, energy efficiency, and CO_2 efficiency; operational KPIs like average number of products stored and service level; and integrated KPIs like inventory and transport CO_2 efficiency that combine environmental and operational efficiency (Zampou et al., 2014a). These KPIs must be estimated at multiple levels of granularity, such as total energy consumption at the process or machine level. Therefore, we need a hierarchy to estimate KPIs at an overall level and then to decompose them into finer levels for certain nodes and processes.

Because a hierarchical representation presents supply chains as being comprised of manufacturing, warehousing, and logistics nodes, as well as links among them (Jain et al., 2013), we employ a hierarchy of physical components—facility, store, warehouse, vehicle, and machines—and processes—production, warehousing, and distribution. That is, our hierarchy puts the processes of manufacturing, distribution, warehousing, and supply chain (Table 2) at the top level and decomposes each process into the machine (manufacturing), store section (warehousing and supply chain), and vehicle (distribution and supply chain) components, as the smallest physical components. It then adds the product category and the product level to monitor products' lifecycles across processes (Figure 4).

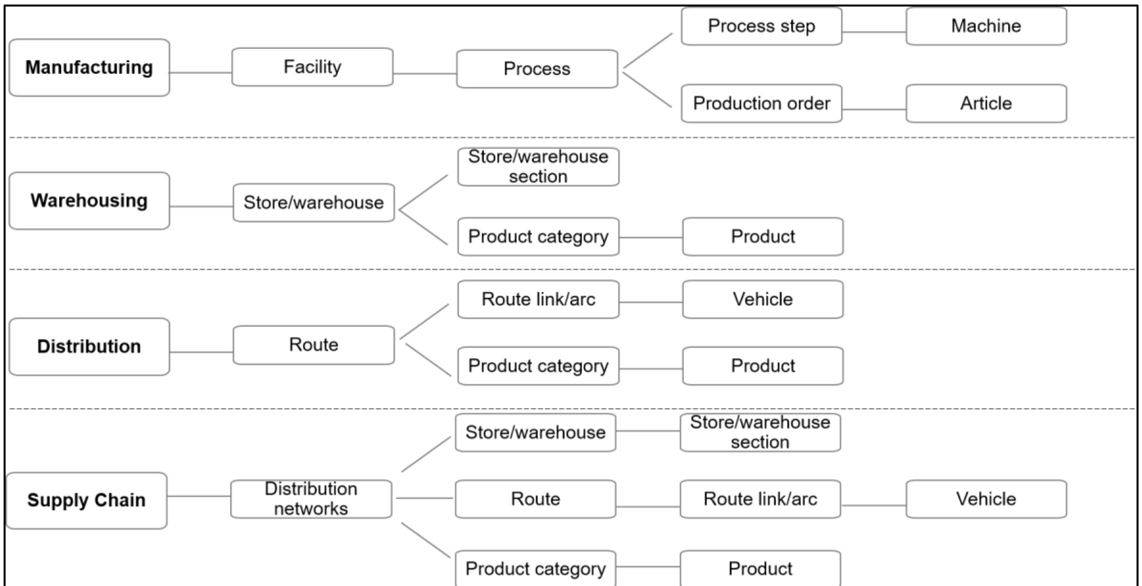

Figure 4. ECMS Supply Chain Hierarchy

In summary, we suggest that the scope of an ECMS in the supply chain context should address the key stakeholders in the supply chain (Figure 3); consider the key supply chain activities of manufacturing, warehousing, distribution, and the overall supply chain (Table 2); and include the dimensions and hierarchies of monitoring, reporting, and decision support (Figure 4). The ECMS purpose and scope is to support the key stakeholders in calculating their environmental performance for the type of activity they perform (the ECMS intrafirm scope) and support environmental performance calculation at the interface between two successive stakeholders of a supply chain and their activities (the ECMS supply chain scope). The overall goal is to support tracing the environmental impact "from cradle to grave." For example, a distributor sells products via a retailer to an end customer, and both the distributor and the retailer want to track the environmental product performance up to the customer. Each of them implements an ECMS instantiation to calculate the product's environmental burden in their scope. Then the retailer collects environmental product data from the distributor and adds the environmental burden of its own activities.

The end-users in the four organizations also envisioned that ECMS would support them in integrating energy and carbon indicators into their operational decisions. Specifically, A and B sought processes to:

- optimize energy-aware scheduling in various stages of textile production, particularly those with a considerable energy burden, such as the finishing mill;
- trade energy and carbon permits, that is, to exchange energy contracts and carbon permits among supply chain partners or with an external energy provider.

For their part, organizations C and D sought processes to:

- redesign their supply chain networks, that is, to generate “what if” scenarios of re-design decisions (e.g., whether to add a new warehouse or store or merge two warehouses) based on environmental performance and evaluation through simulation;
- promote and distribute packaging redesign, that is, to collaborate on assessments of the environmental impact of various possibilities for retail-ready packaging, particularly ways in which consumer units can be bundled into a single package for suppliers and retailers to deliver to points-of-sales;
- create collaborative ordering and replenishment practices to assess policies like changing replenishment frequencies and safety stock levels in terms of cost, efficiency, and environmental impact;
- collaborate on distribution practices like backhauling;
- inform consumers about a product’s environmental profile and examine the impact of providing this information on consumers’ attitude and buying behavior.

4.2 Design Requirements and Justificatory Knowledge

We identified four key aspects of ECM that guided the formulation of the design requirements:

- **Data capture and integration.** Collecting the required types of data from heterogenous sources and various systems is challenging because the traditional IS used in supply chain management, such as ERP, WMS, MES, and routing systems, do not typically capture environmental data like energy or fuel consumption. The current state is characterized by a lack of automated reporting of key energy data, as energy consumption data could be collected either by energy sensors or from building management systems (BMS) and fuel consumption monitoring systems. In the current state, ECMS also must be integrated into existing systems to retrieve supply chain data.
- **Data quality and availability.** ECM is a data-intensive process, and companies cannot easily meet the data requirements by means of their existing infrastructures. Even when data is available, it may not cover the level of detail required to enable ECM. For example, we may miss data regarding energy consumption at the machine level. Poor data quality, such as incorrect inventory levels, is another obstacle.
- **Energy and carbon performance metrics: definition and selection.** Selecting the appropriate energy and carbon performance metrics is a challenge because of the lack of established measurement frameworks and a holistic approach to measuring energy and carbon consumption. Defining metrics ensures the comparability of the results. For example, if the manufacturer of a product relies on industry averages to calculate its carbon emissions, and the manufacturer of another product in the same product category relies on actual measurements of carbon emissions, their respective metrics may not be comparable.

- **Collaboration and information-sharing.** Expanding ECM beyond a firm's boundaries poses additional challenges related to collaboration, information-sharing, and coordination. Standardizing the rules for data collection and collaboration facilitates data exchange throughout the supply chain and the implementation of measurement of energy and carbon consumption.

Existing studies support these four key elements, as highlighted in reviews that address fifteen years of work on SSC management and its measurement (Ansari & Kant, 2017; Janssen et al., 2015; Tuni et al., 2018). An ECMS should be able to address these aspects of ECM by supporting firms in their efforts to standardize, monitor, capture, use, and interpret data and to diffuse information. In alignment with what has already been suggested, data storage, validation, analytics, and reporting are key components of ECMS (Melville et al., 2017). We propose a set of essential, rather than exhaustive, design requirements, as shown in Table 3.

Table 3: ECMS Design Requirements

Design Requirement	Description
DR1. Data collection and storage	Collecting energy-consumption, fuel-consumption, operational, and delivery data
DR2. Integration of data flows	Integrating energy-consumption information from, for example, energy-monitoring systems, into supply chain and product information from MRP, ERP, and WMS; integrating emission factors from governmental or institutional sources
DR3. Data validation	Validating and cleansing data
DR4. Supply chain monitoring and interorganizational coordination	Monitoring and supervising the various supply chain processes, supporting information-sharing, and coordinating various supply chain partners
DR5. Environmental performance/impact estimation	Calculating energy consumption and carbon emissions and allocating the environmental impacts at various levels of analysis, such as the process and warehouse levels
DR6. Environmental reporting	Reporting the required KPIs in various formats and visualizations to comply with environmental standards and reporting initiatives

The "integration of data flows" requirement (DR2) constitutes the core of an ECMS design. ECM is information-intensive, and an ECMS must present information in forms that address the varying specificities of scope and factors like time, product, and physical unit (e.g., store, warehouse, vehicle, route, production order, machine). The design of ECMS requires combining various data sources and information flows. Objects like machines and vehicles that can sense and report energy data are sources of energy information that must be clearly defined and combined (Watson et al., 2010; Zampou et al., 2014b).

4.3 Constructs and Principles of Form and Function

We build our design theory on two types of constructs:[4] *information flows* of the categories of data required for ECM, and *system components* for collecting, processing, and disseminating such data. Information-sharing and coordination in the supply chain require transactional information to coordinate the physical demand and supply chain, contextual information to ensure that the different organizations interpret data in the same way, and inter-organizational product information to facilitate cross-company coordination (Legner & Schemm, 2008). Building on this conceptualization, we suggest four information flows (Table 4). The energy information flow and the product-environmental information flow are new types of flows, derived from the need to collect and analyze energy-consumption- and fuel-consumption-related data in the context of ECM and to calculate the total carbon emissions that are associated with a product during its life cycle.

We propose the energy information flow as a distinct information flow to highlight the difference between ECMS and existing supply chain management information flows, as Legner and Schemm (2008) suggest, and we highlight the need to collect energy-consumption and fuel-consumption data in addition to traditional supply chain data like inventories and routes. The energy- and fuel-consumption data are not stored in the

[4] By "constructs" we refer to the abstract building blocks that required to formulate the principles of form and function—hence, the overall design theory. Here, these constructs represent information flows and system components, so we use "component" to refer to what ECMS instantiations are composed of and "construct" to refer to the abstract underlying idea that is also considered in our formulation of design principles.

traditional supply chain management systems, although in some cases they may be imposed by energy bills or fuel-consumption invoices in a company's ERP—so they should be treated differently, either by collecting them from different sources or by calculating them.

The product environmental information flow addresses consumers' demand for sustainable products and the need for manufacturers and suppliers to provide their products' environmental profiles. ECMS support the calculation of these environmental profiles, but hidden carbon emissions may be inherited from, for example, raw material production. Therefore, the product environmental information flow and respective data can be provided by, for example, suppliers of raw materials life cycle inventories (LCIs). We also categorize the product environmental information flow as a distinct information flow to highlight the need to treat it differently, either by collecting this data from other sources or by calculating the data.

We define the data entities each of these information flows comprise. The data related to the energy information flow does not have to relate only to environmental objectives but can also relate to improvements in traditional operations or cost reductions and even trade-offs between environmental and cost-reduction targets.

Table 4: Constructs: ECM Information Flows

Information Flow	**Description**
Transactional information flow	Transactions that take place in the supply chain, such as ordering, distribution, inventory management, and production
Contextual information flow	Products, facilities, processes, and supply chain partnerships that support the interpretability of transactional information
Energy information flow	Energy consumption in warehouses that is either measured by energy sensors or retrieved from existing BMS Fuel consumption, referring to vehicle fuel refills or to actual fuel consumption monitored through metering devices installed on vehicles, and possibly data from governmental agencies or standardization initiatives (e.g., emission factors)
Product environmental information flow	Environmental profile of products, including products' embodied carbon footprints as recorded by other supply chain partners or LCIs

Table 5 lists definitions for each of the system components, their primary functional objectives, and their association with the design requirements. Our design builds on the idea of combining data sources and elaborating on the effective integration of the information flows.

Table 5: Constructs: ECMS System Components

System Components	Description	DRs
Data Collection	System components for collecting, validating, cleansing, and identifying the relations among all the data received from various sources. The Data collection component consists of two separate sub-components that function independently: the energy data layer and the operational data layer. The first handles the communication and synchronization with energy sensors and BMS. The second imports data from ERP, WMS, and other corporate systems. Thus, this component handles all information flows for monitoring activities.	DR1, DR3
Energy Monitoring	The system's mechanism for aggregating and reporting energy-consumption data at different levels of analysis, such as energy consumption per node/section. It addresses the mandate for such reporting by retrieving energy-consumption data from the energy data layer and uses all energy-consumption flows that are not recorded by sensors provided by the operational data layer, such as energy bills and energy audits. Overall, this component supports sensor energy-monitoring and non-sensor energy-monitoring. It handles the energy information flow and the contextual information flow by associating energy power meters or energy consumption to specific machines, processes, and infrastructures.	DR2, DR5
Supply Chain Coordination	System components for coordinating the supply chain, maintaining the collaborative relationships between supply chain partners, and facilitating data exchanges. They provide all the required information regarding the objects of interest, such as nodes, products, and partner details. Moreover, they support modelling of the supply chain structure to maintain and disseminate semantic information regarding an organization's underlying structure (e.g., facilities, departments), the production arrangement (e.g., processes, process steps), warehousing, the composition of a product, and so on. It also coordinates the collection of external data and handles the contextual information flow.	DR4
ECMS Workflow Engine	System components for monitoring the daily supply chain processes (e.g., warehousing, ordering, distribution, production) and for supporting estimation of the energy consumption and carbon footprint indicators. The workflow engine also handles information from other supply chain partners, so it handles all flows. It is the key component in materializing the ECM daily calculations, so it also includes the application programming interfaces (APIs) of standardization bodies and initiatives regarding emission factors and environmental profiling of processes.	DR2, DR5
Reporting	The system component that facilitates the creation of formatted standard reports that cover the various aspects of ECM in the supply chain and compliance with standards like ISO 14000 series and GRI.	DR6

Figure 5 visualizes the architecture based on the five system components—data collection, energy monitoring, supply chain coordination, ECMS workflow engine, and reporting—and their interrelationships in terms of information flows. The architecture supports data collection, integrates the various information flows and calculates the respective KPIs (energy monitoring, supply chain coordination, and ECMS workflow engine), and visualizes the ECMS outcomes (reporting).

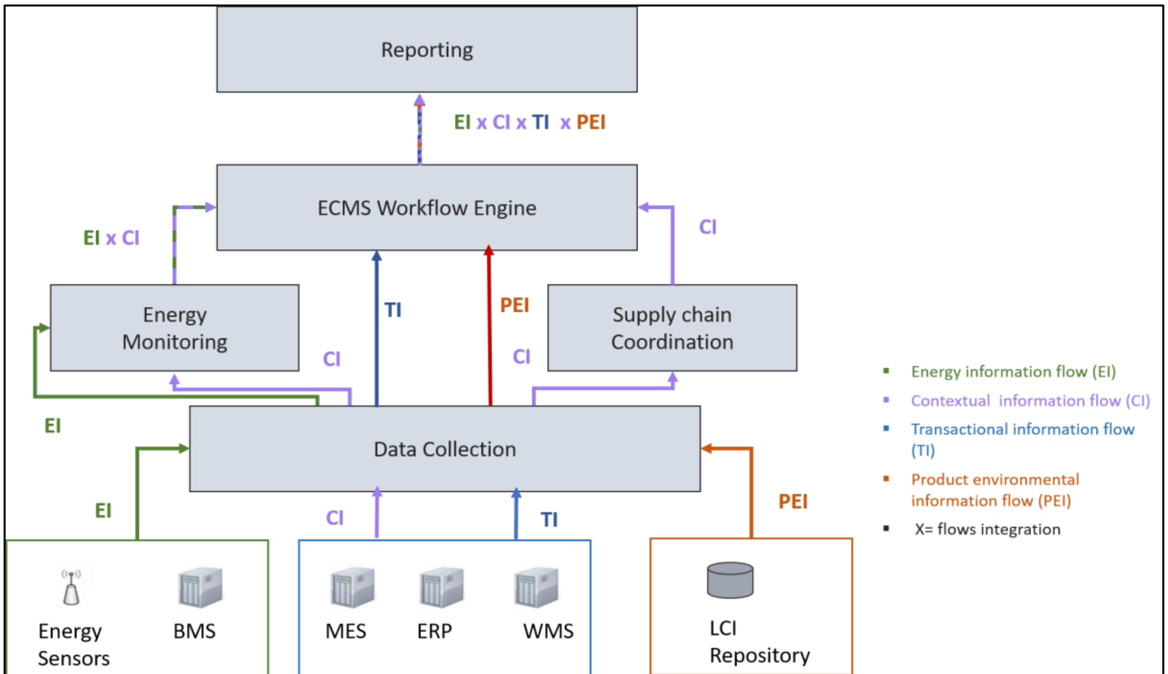

Figure 5. ECMS Constructs: System Components and Information Flows

The **data collection** system component collects the various types of data from existing systems and infrastructures, such as ERP, WMS, BMS, LCI repositories, and energy sensors, and handles all information flows. ECMS should collect data from heterogenous data sources; firms in the manufacturing industry must often supplement energy data with additional energy-consumption data, such as data collected through energy audit processes. The **energy monitoring** system component processes the energy information flow and assigns energy consumption to low-level supply chain processes (contextual information flow) to derive KPIs like energy consumption per sensor, per machine, and per section. Because secondary energy-consumption data like that collected through energy audit processes is kept in spreadsheet-like applications, this system component also supports non-sensor energy-monitoring**.** Applying ECM across the supply chain and extending its scope outside a single firm's boundaries requires handling and designing different supply chain networks and managing the relationships with external partners, which demands a system component that models supply chain processes and allows various participants to access shared data and shared functionality. Therefore, the **supply chain coordination** system component handles the contextual information flows, while an **ECMS workflow engine** system component materializes ECM in the appropriate purpose and scope and calculates the various KPIs by handling all four information flows. The **reporting** system component presents the KPIs calculation results derived by the ECMS workflow engine component.

We use these system components to formulate principles of form and function. Table 6 presents the design principles, i.e. the design theory's principles of form and function—each of which is related to a key system component—drawing on the "anatomy of a design principle" that Gregor et al. (2020) suggest. Structurally similar formulations of the relationship between material features of information technologies and their outcomes can be found in, for instance, Seidel et al. (2018).

Table 6: ECMS Design Principles[5]

Key Component	**Design Principles**
Data Collection	DP1.1. Provide features for collecting and cleansing energy and operational data so the system affords the ability to process energy and operational data.
Energy Monitoring	DP2.1. Provide features for assigning sensors to specific machines and processes; for collecting, processing and storing energy sensor consumption data; and for calculating energy values per time interval so the system affords the ability to monitor energy sensors. DP2.2. Provide features for identifying, collecting, and processing energy secondary data so the system affords the ability to monitor non-sensor energy.
Supply Chain Coordination	DP3.1. Provide features that enable data exchange among supply chain partners by using data privacy and security protocols and applying standards for information-sharing so the system affords the ability to coordinate across the supply chain.

[5] We made editorial changes to align the terminology we use in the formulation of our design principles, so Table 6 shows a simplified version of the original principles.

	DP3.2. Provide features for modeling organizations' structure, production and supply chain processes and supporting their decomposition into the required levels of analysis so the system affords the ability to coordinate across the supply chain.
ECMS Workflow Engine	DP4.1. Provide features for combining data from various sources of the daily operational activities across the supply chain (e.g., shipments, inventories, production), including emission factors and relevant data from governmental databases, so the system affords the ability to monitor the supply chain end-to-end and coordinate information flows. DP4.2. Provide features for calculating KPIs at various levels of analysis so the system affords the ability to monitor the supply chain end-to-end and to coordinate information flows.
Reporting	DP5.1. Provide features for reporting on the organizational, supply chain, and production process structures so the system affords the ability to inform users about the scope of ECM. DP5.2. Provide features for reporting on the ECMS purpose and scope, hierarchies, and KPIs and complying with environmental standards and reporting initiatives so the system affords the ability to inform end users about measurements of ECM

4.4 ECMS Expository Instantiation

We developed four instantiations of the ECMS, two covering the manufacturing dimension and two the warehousing, distribution, and supply chain dimensions. Figure 6 shows a screenshot of the manufacturing instantiation that calculates energy consumption at the level of production processes. Figure 7 displays the energy consumption trend and KPIs like CO_2, products distributed, and transport efficiency of various distribution networks as an example of the instantiation developed for the warehousing and distribution companies, C and D.

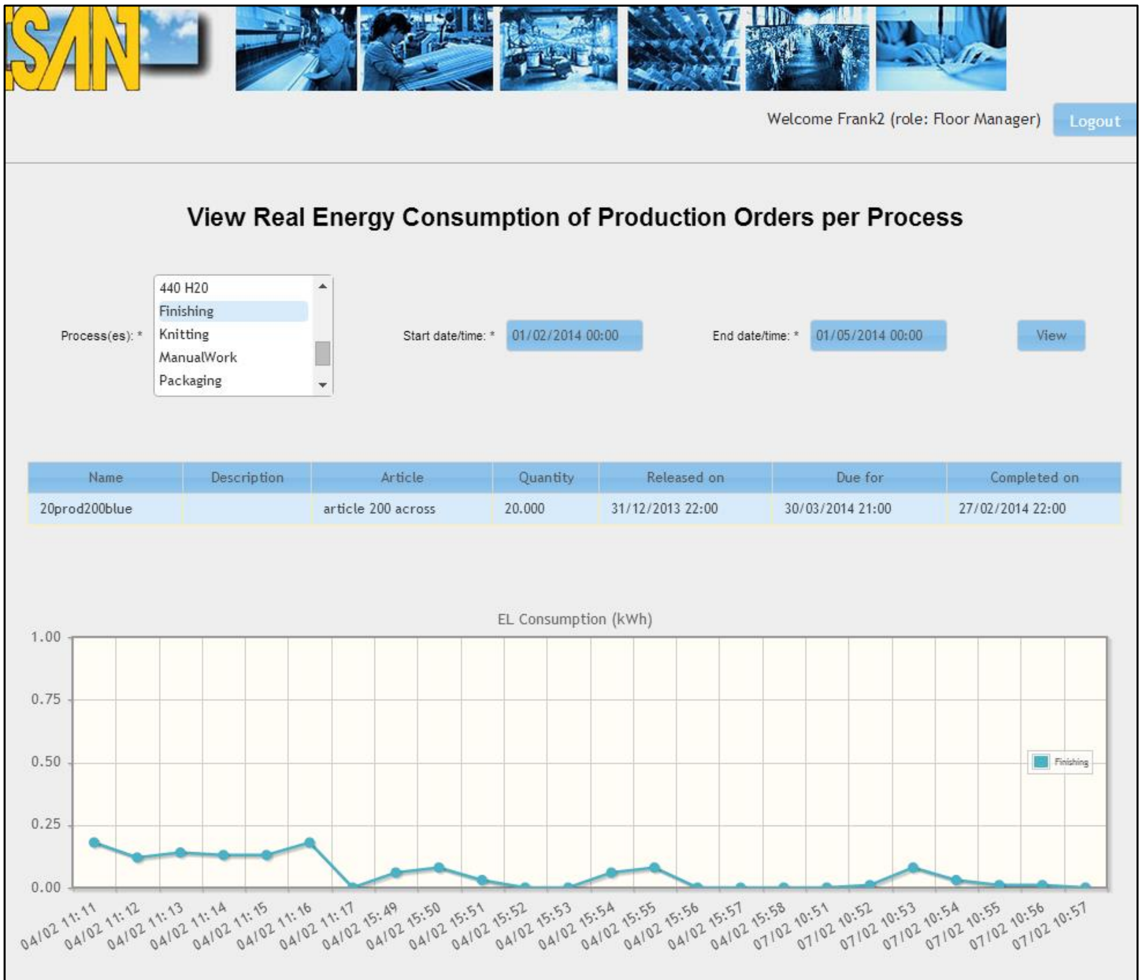

Figure 6. ECMS Manufacturing Instantiation

The instantiations implement the key constructs of our theory and differ only in details related to the different implementation and deployment contexts. For example, the data collection system component manages various kinds of data for each case, thus yielding different XML schemas and data interfaces. Similarly, the energy measurement and carbon allocation methodologies differ because the allocation unit in textile manufacturing is one square meter of the produced article, while in the two FMCG companies it is a unit of volume or weight of distributed products. Calculating the indirect energy in manufacturing imposes another context-related differentiation. All principles except DP2.2 and DP3.1 were implemented in all instantiations; DP2.2 was implemented only for manufacturing, where secondary energy data from energy audits had to be collected, and DP3.1 was required only in the warehousing and distribution instantiations.

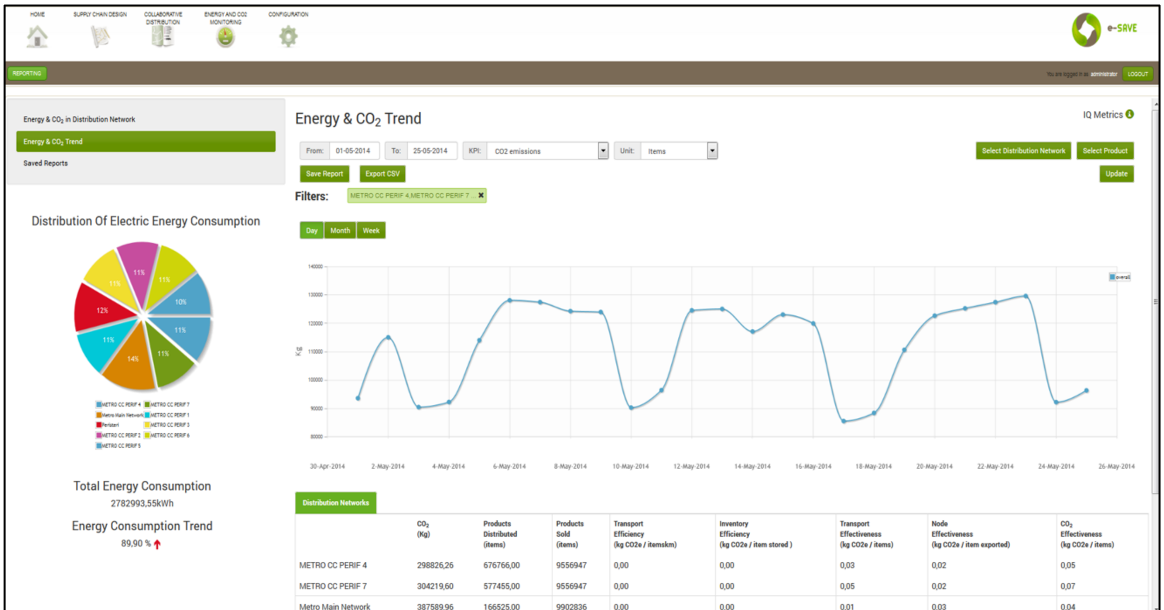

Figure 7. ECMS Warehousing and Distribution Case Instantiation

Overall, the structural similarities of the four instantiations suggest that the proposed design is sufficiently generic to cover the requirements of a broad range of ECMS. However, the four organizations also provided challenges related to data quality and availability, data capture and integration, energy and carbon performance metrics, and collaboration and information-sharing that we considered in the specific implementations (Table 7). We adapted the generic blueprint to the idiosyncratic requirements of each case while remaining faithful to the general abstract design principles. Thus, we translated the design principles into concrete focal features of the artifact features by focusing on the features we needed to instantiate the design theory (Lukyanenko & Parsons, 2020).

Table 7: Settings at the Instantiation per Organization

Organization	Energy Consumption Data Availability	Fuel Consumption Data Availability	Transactional and Contextual Data Availability	Data Exchange Mechanisms

A	Limited data from energy audits and a small number of sensors	Not applicable	MES keeps daily data about production processes, and ERP stores orders data	Not applicable
B	Data from energy audits and real-time sensor-monitoring	Not Applicable	ERP and MES keeps data on production processes and ordering	Not applicable
C	Real- time energy-monitoring via BMS at one store and monthly energy bills for all other stores	Actual vehicle refills available in ERP	WMS keeps daily data on warehousing transactions like orders and inventories), and distribution processes data are kept in ERP	Already installed for other cases
D	Energy sensors with no interoperable APIs that could not be integrated into ECMS	Not available because an external 3PL provider is used	ERP stores data about warehousing transactions like ordering; no data on distribution because an external 3PL provider is used	No such mechanisms installed

Several interfaces were developed to capture or retrieve energy and fuel data from already installed systems like energy-capturing infrastructure, BMS, or legacy systems. Moreover, energy sensors were installed in three of Organization C's stores to capture actual energy consumption and in Organization A to monitor the energy consumption of selected machines. The transactional and contextual data specified were extracted as a consolidated daily batch from MRP, MES, ERP, and WMS systems.

5 Implementation, Demonstration, and Evaluation

This phase focused on validating and refining the initially formulated design theory through two rounds of demonstration and evaluation. The first round of this phase identified design and implementation challenges while the second round had the objective of validating the extent to which our theory helps to implement ECMS that support energy- and carbon-consumption measurements and facilitate environmentally aware decision-making and practicing. We highlight how we refined the constructs and design principles between the two rounds, mainly by introducing a new construct—the carbon footprint estimator—and a set of new principles and also provide proof-of-value evidence about ECMS.

5.1 Settings for Artifact Demonstration and Evaluation

We deployed, demonstrated, and evaluated the ECMS theory and artifacts at the four organizations' sites to cover the key dimensions of ECMS (Figure 2). We obtained daily transactional data from the respective MRP, MES, ERP, and WMS systems and uploaded them to the ECMS for a period of twelve months in the first round and five months in the second. We retrieved contextual information like, product categories and production processes once during the initialization phase and again when updates were required.

ECM for manufacturing: For Organization A, we focused on the processes of weaving, dyeing, and finishing, which use the most energy-consuming machines. Energy audits were used as a systematic procedure to clarify the processes' energy-consumption profiles, and energy sensors were installed to monitor the machines' energy consumption. We also examined machines like the steam boiler and compressed air, air-filtering, and lighting machines to measure the indirect energy consumption. We measured each department's consumption of indirect energy over a period and multiplied it by the working time of that department. Then we could accumulate the direct and indirect energy per product into a single value. For Organization B, extensive data on energy consumption were available from both energy audits and real-time sensor monitoring, but these were used only to analyze the energy consumption that accrued over months or years, so it was not feasible to map them to individual products.

ECM for warehousing: This configuration captured the energy consumption and carbon emissions of individual nodes in a supply chain. For Organization C, we selected the retailer's central warehouse and three stores as representing different environmental profiles—a store with old infrastructure, a one with conventional infrastructure, and one with new, environmentally friendly infrastructure. Energy sensors were installed in various nodes and processes.

ECM for distribution activities: We selected two distribution networks: the retailer's distribution network that connects the central warehouse to all of the stores served by the retailer's own fleet (Organization C) and the supplier's distribution network that connects the central warehouse to every delivery point served by a third-party logistics company (Organization D). In Organization C, the retailer could provide all required transactional and contextual data; even though actual fuel consumption was not available, the vehicle fuel refills were, allowing the average fuel consumption per vehicle and route to be estimated. In Organization D, actual fuel consumption data was not available, so we used the industrial average of fuel consumption.

ECM across the supply chain: We also captured the energy information and carbon information across the supply chain, from the suppliers' warehouses to the retail stores (Organizations C and D). Synchronizing contextual information like the volume and weight of products or boxes was critical to our ability to calculate carbon emissions per product.

5.2 Round 1: Reflection and Refinements on the Components of Design Theory

Here we discuss the four key categories of the findings that surfaced during this round and that led to a revised set of constructs and design principles. We also elaborate on the key findings per category and provide examples.

First, in the category of **data quality and availability,** we identified limited environmental data availability, poor data quality, and data inconsistencies at all four sites. For example, organizations A and D kept mainly aggregated information about energy consumption per month based on their electricity bills, while B manually recorded it via physical audits. The fuel consumption data availability in organizations C and D was even more limited. Transactional information related to inventories and deliveries were of poor quality. For example, we identified negative inventory values in organization C and inaccurate packaging details in terms of product weight, along with a lack of delivery routes in C and D. The manufacturing organizations, A and B, could not meet the requirement for detailed time-dependent information regarding production processes. Moreover, we found inconsistencies and difficulties in transforming data into comparable terms, as organizations A and B used varying measurement units, such as meters for fabrics and items for garments. C and D usually expressed vehicle capacity in terms of number of pallets and stores' transportation requests in terms of product items and their quantities.

With regard to the category of **data capture and integration**, we identified in integration issues with existing systems, limited automation of data-retrieval mechanisms, varying data-granularity levels, complexity in integrating the information flows at all four sites. We also found in organizations C and D dependencies and coordination problems related to aligning the inputs from supply chain partners and in organizations A and B issues with tracking the workflow because of time-dependent data, and the presence of semi-finished products in manufacturing. Integration with existing WMS (A and B), BMS (C), and energy sensors (B and D) was a demanding process that required the development of interfaces and mechanisms to retrieve energy and operational data continuously and to receive the energy-consumption and fuel-consumption data that were previously recorded at intervals other than daily by spreadsheet-like solutions in A and D. Organizations kept these data at various granularity levels. For example, in A and B, energy sensors were sometimes linked with a group of machines instead of individual machines, so they did not support the direct allocation of energy consumption to process steps and articles.

In the category of **energy and carbon performance metrics definition and selection**, we found a lack of standardized and comparable energy, carbon, traditional, and integrated performance indicators*.* An extended list that included energy-performance indicators covering both direct and indirect energy, carbon-related performance indicators, integrated indicators that incorporated both environmental and operational aspects, and indicators that referred to both processes and products was required in all cases. Comparability of the various carbon performance indicators across the supply chain in C and D was another major challenge because of diversity in the calculation methods the various partners used.

Finally, concerns related to **collaboration and information-sharing** included partners' reluctance to share the extended set of required data because of their concern that suppliers could use their environmental information as part of their selection process. Therefore, establishing clear collaboration rules related to information-sharing was an important implementation issue. Previous collaboration, mutual trust, and established information-sharing processes were important facilitators of ECMS implementation in C and D.

These challenges and insights allowed us to reflect on the emergent design theory and to derive refinements. The demonstration's findings related mainly to data and technical issues, so we did not revise our design theory's purpose or scope or the design requirements.

Revised Constructs

Our demonstration highlighted the complexity of estimating carbon emissions, so we introduced a new construct called the **carbon footprint estimator** to represent the system components that encapsulate the logic behind the respective calculations and that decouple them from the ECMS workflow engine. This construct incorporates the business logic for aggregating and disaggregating energy consumption at various levels of analysis, transforms this data into carbon emissions, and then estimates the total carbon footprint. It nests methodologies like the LCA and standards like the GHG Protocol (2011) and translates the energy-consumption estimations and carbon-emission calculations specified in the KPIs.

The carbon footprint estimator system component computes the carbon emissions of the activities involved in manufacturing, warehousing, and distribution across a supply chain at different levels; allocates these activities' carbon emissions to products; and provides carbon emissions, emission factors, and environmental parameters to other components when needed. Selecting the appropriate emission factors from LCI databases like the ecoinvent database (ecoinvent, 2019) or from the International Reference Life Cycle Data System (European Commission, 2018) is a prerequisite for calculating carbon footprints. One can add "custom" emission factors that LCA specialists have derived as configuration parameters or calculate them using actual data like emission coefficients based on a particular vehicle's fuel consumption over a particular period, rather than coefficients of average emissions.

In summary, the carbon footprint estimator system component implements an LCA methodology and reports the carbon emissions according to the GHG protocol scope 3 standard (GHGProtocol, 2011) as follows:

1. Scope 1 emissions: direct emissions from owned or controlled sources, such as emissions that occur physically at the warehouse or store
2. Scope 2 emissions: indirect emissions from the generation of purchased energy the company consumes or emissions associated with the warehouse's infrastructure and equipment and the packaging materials used
3. Scope 3 emissions: all other indirect emissions that occur in a company's value chain, including both upstream and downstream activities, such as the emissions of a vehicle owned by a third-party logistics company when transportation is outsourced

The carbon footprint estimator can compute the carbon emissions daily or on request from the ECMS Workflow Engine by using energy- and fuel-consumption data and details about manufacturing, warehousing, or transportation activities. For example, it computes distribution activities' carbon emissions per route using the type of vehicle, the fuel consumption and/or load weight per route, and the length of the route. In the case of warehousing, it estimates carbon emissions from the list of dates/section IDs, electricity consumption per section per day, the type of section, the section area, and the section volume.

Once the computation of carbon emissions from activities has been completed, the carbon footprint estimator can allocate these emissions to certain products, which requires allocation parameters like volume and mass and is time-dependent. For example, if a product has been in a certain location (e.g., in a refrigerator) during a certain period, the carbon footprint estimator can allocate to the product part of the refrigerator related emissions during that period because they can be directly related to the product's conservation. Thus, the total emissions of a refrigerator during a well-defined time period can be uniformly allocated to all the products it contained during the same period.

To conclude, an independent system component must incorporate the carbon estimation and allocation logic to give the user the ability to set its parameters. This component receives all information flows as input from the ECMS Workflow Engine component that is responsible for coordinating the ECM calculations, and conducts the carbon estimations and allocations. The ECMS Workflow Engine then aggregates the KPIs at the level of analysis requested. For example, it could calculate the sum of three stores' carbon emissions for a week and feed their comparisons into the Reporting component. Figure 8 presents our revised architecture.

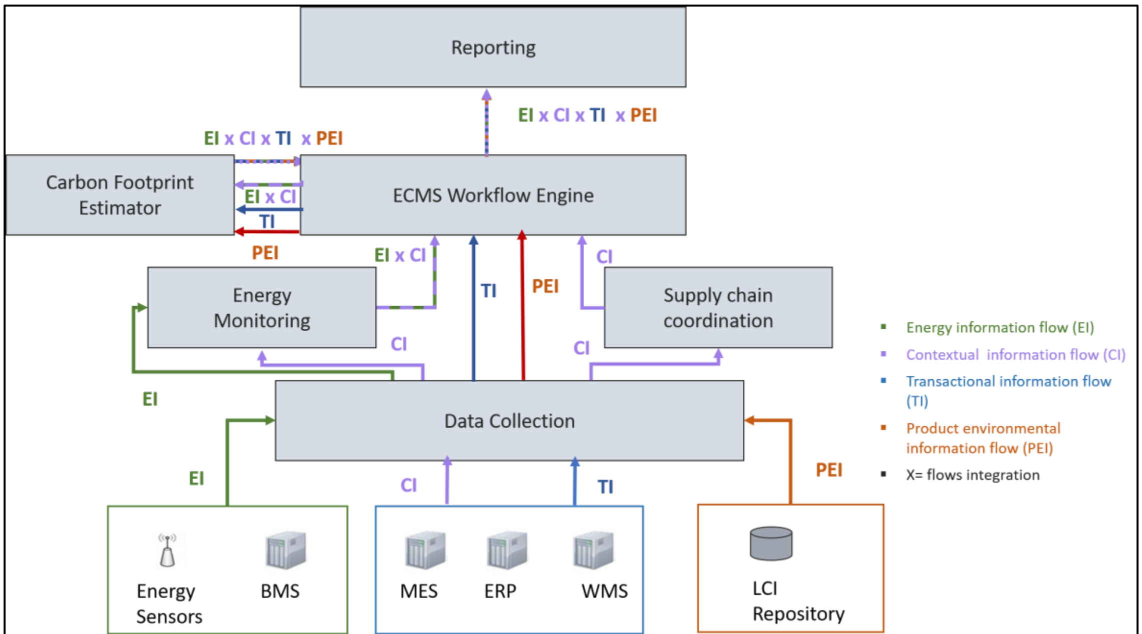

Figure 8. ECMS Constructs: System Components and Information Flows (revised)

Revised Design Principles

Principles related to the data collection component. Because of environmental data's limited availability, ECMS require mechanisms with which to derive this data, either by using existing transactional data, such as calculating fuel consumption based on invoices, or by using industrial averages related to vehicle fuel consumption. Based on these findings, we derived the new DP1.2 design principle as follows:

> DP1.2 **(**new) Provide features for generating missing environmental data so the system affords the ability to process energy data given a company's levels of data availability and quality.

To address poor data quality and data inconsistencies, we employed a data-cleansing process and corrected product weights (C and D) in collaboration with the end users. We estimated missing weights or volumes of product categories using secondary data from other sources. To derive the actual delivery route in cases where only deliveries, but not the actual routes, were available, we created pseudo-routes using the distances between delivery points (D). For A and B, where we could not retrieve article step sequences and times from the existing systems, we developed time profiles of the different articles, process steps and processes. To express two metrics in compatible terms, we constructed dedicated approaches to translate, for instance, the required products into the number of fully loaded pallets. Based on these findings, we derived the new DP1.3 design principle as follows:

> DP1.3. (new) Provide features for generating missing operational and transactional data and transforming existing data into a compatible format so the system affords the ability to process operational and transactional data given a company's levels of data quality and inconsistency.

Principles related to the energy-monitoring component. We based DP2.2, which is related to non-sensor energy-monitoring on the requirements elicited from the manufacturing organizations. However, this design principle is also relevant to the warehousing and distribution organizations, where ECMS must use energy-consumption bills or the fuel refills kept in invoices to calculate energy consumption. In general, the component must compensate for the absence of actual sensor measurements and handle secondary energy and fuel consumption data. Therefore, we revised DP2.2 to include secondary fuel consumption data, rather than only the energy-related data:

> DP2.2 (revised). Provide features that can identify, collect, and process the secondary energy-consumption and **fuel-consumption** data so the system affords the ability to monitor non-sensor energy and fuel, **given a company's levels of data availability**.

Principles related to the supply chain coordination component. Respondents relayed concerns about disclosing environmental information that supply chain partners can use during negotiations, particularly information about bad environmental performance, which we addressed by defining a minimum set of required data and by sharing aggregated high-level KPIs (C and D). Moreover, the ECMS provides various levels of collaboration that allow supply chain partners to engage gradually with ECM and to differentiate the information shared. To address collaboration issues and information-sharing concerns, we revised DP3.1 as follows:

> DP3.1 (revised). Provide features that enable data exchange among supply chain partners by using data privacy and security protocols **that consider various levels of information exchange,** and apply standards for information-sharing so the system affords the ability to coordinate across the supply chain.

Suppliers and retailers (C and D) used their own internal codes to describe the contextual data flow among products, partners, facilities, and vehicles. For example, even when a product had the same barcode across its lifecycle, suppliers and retailers used an internal product code. To align various internal product codes or differences in measurement units, we devised a new design principle:

> DP3.3. (new) Provide features for aligning master data like supply chain partners' various product identification codes so the system affords the ability to trace and coordinate the data across the supply chain.

Principles related to the ECMS workflow engine component. Even when the required data were available and of good quality, organizations usually kept them at differing levels of granularity. For example, C and D kept transactional data like inventories and shipments on a daily basis, while all four companies kept energy-consumption data either at a highly aggregated level (e.g., monthly) or at a too-detailed level, as energy sensors could record energy consumption in real time. Therefore, we had to consider granularity levels as a basic parameter in our ECMS design. We concluded that, in C and D, collecting and aggregating information at a daily level was adequate to ensure both applicability and meaningfulness of results, whereas A and B required the exact time-stamp of all transactional data. Collecting and monitoring information at a detailed time level in A and B increased complexity and made the applicability of an ECMS even more challenging. As a result, we base the required granularity level on the trade-off between complexity and the level of informational detail.

To address the issue of varying levels of data granularity levels, we suggest the following DP:

> DP4.3. (new) Provide features like mechanisms for aggregating energy-consumption data at a daily granularity level that transform multiple kinds of data into the same granularity level so the system affords the ability to monitor the supply chain end-to-end and coordinate information flows.

Principles related to the reporting component. In addition to the ECM results, at least one end-user in each of the four organizations expressed the need to know the data availability levels—their type and origin—along with the data quality, data granularity, the business logic for calculating the carbon emissions, and the standards applied for calculating the various KPIs, to be able to interpret this data. Therefore, we formulated DP5.3 as follows:

> DP5.3. (new) Provide features for reporting data availability, data quality, data granularity, the ECM calculation and allocation logic, and the standard applied so the system affords the ability to inform end users in a transparent, accurate, and comparable way.

Principles related to the carbon footprint estimator component (new). Ensuring the comparability of the results necessitates integrating information flows, which requires a shared granularity level, a complete and accurate dataset, and availability of all required data. For example, in C and D, we could not compare the carbon emissions of two routes when the routes used different allocation parameters, such as weight, volume, and item. To address the complexity of combining different types of information flows, the ECMS deployed an adaptable logic, allocating the carbon emissions at different levels of analysis and ensuring uniform granularity at all four sites. This logic initially examines data availability and informs the definition of its parameters based on a set of availability measures, such as industry standards for fuel consumption per vehicle type if actual fuel consumption is not available.

DP6.1. (new) Provide features for calculating the ECM KPIs at various levels of analysis using the data granularity level, data accuracy, data availability, and emission factors so the system affords the ability to estimate energy consumption and the carbon footprint.

In specifying and defining the KPIs to be monitored, common standards can be used to ensure the comparability of different energy and carbon indicators and to address diversity in the carbon calculation and allocation methods used. However, common standards were often missing at the four sites, and end-users stated that they had to select the standard to be applied to calculating the KPIs. For example, we employed the GhG Protocol (2011) and, for C and D, we also adopted the Sustainability Measures for Logistical Activities (Consumer Goods Forum, 2012), as they calculate aspects of the environment and the operations daily.

DP6.2. (new) Provide features for implementing various assessment methodologies, carbon management standards, and related KPIs so the system affords the ability to estimate energy consumption and the carbon footprint—given the lack of standardized indicators of energy consumption and carbon emissions and traditional performance indicators—and compliance with reporting standards or initiatives, including governmental guidelines.

5.3 Round 2: Reflection on the Utility of ECMS Design Theory

In the second round, our design theory components converged well, so we added no constructs or principles. Instead, we focused on evaluating the extent to which the ECMS design theory, if instantiated, helps to integrate information flows, ECM, and environmentally aware decision-making and practicing. This round allowed us to evaluate our design theory and the associated artifact through proof-of-concept and proof-of-value research (Nunamaker et al., 2015).

The final set of system components and principles appears in Table 8.

Table 8: Final ECMS System Components and Design Principles

Key Component	Design Principles

Data Collection	DP1.1. Provide features for collecting and cleansing energy and operational data so the system affords the ability to process energy and operational data. DP1.2 Provide features for generating missing environmental data so the system affords the ability to process energy data given a company's levels of data availability and quality. DP1.3. Provide features for generating missing operational and transactional data and transforming existing data into a compatible format so the system affords the ability to process operational and transactional data given a company's levels of data quality and inconsistency.
Energy Monitoring	DP2.1. Provide features for assigning sensors to specific machines and processes; for collecting, processing and storing energy sensor consumption data; and for calculating energy values per time interval so the system affords the ability to monitor energy sensors. DP2.2. Provide features for identifying, collecting, and processing the secondary energy-consumption and fuel-consumption data so the system affords the ability to monitor non-sensor energy and fuel, given a company's levels of data availability.
Supply Chain Coordination	DP3.1. Provide features that enable data exchange among supply chain partners by using data privacy and security protocols that consider various levels of information exchange, and apply standards for information-sharing so the system affords the ability to coordinate across the supply chain. DP3.2. Provide features for modeling organizations' structure, production and supply chain processes and supporting their decomposition into the required levels of analysis so the system affords the ability to coordinate across the supply chain. DP3.3. Provide features for aligning master data like supply chain partners' various product identification codes so the system affords the ability to trace and coordinate the data across the supply chain.
ECMS Workflow Engine	DP4.1. Provide features for combining data from various sources of the daily operational activities across the supply chain (e.g., shipments, inventories, production), including emission factors and relevant data from governmental databases so the system affords the ability to monitor the supply chain end-to-end and coordinate information flows. DP4.2. Provide features for calculating KPIs at various levels of analysis so the system affords the ability to monitor the supply chain end-to-end and to coordinate information flows. DP4.3. Provide features like mechanisms for aggregating energy-consumption data at a daily granularity level that transform multiple kinds of data into the same granularity level so the system affords the ability to monitor the supply chain end-to-end and coordinate information flows.
Reporting	DP5.1. Provide features for reporting on the organizational, supply chain, and production process structures so the system affords the ability to inform users about the scope of ECM. DP5.2. Provide features for reporting on the ECMS purpose and scope, hierarchies, and KPIs and complying with environmental standards

	and reporting initiatives so the system affords the ability to inform end users about measurements of ECM. DP5.3. Provide features for reporting data availability, data quality, data granularity, the ECM calculation and allocation logic, and the standard applied so the system affords the ability to inform end users in a transparent, accurate, and comparable way.
Carbon Footprint Estimator (new)	DP6.1. Provide features for calculating the ECM KPIs at various levels of analysis using the data granularity level, data accuracy, data availability, and emission factors so the system affords the ability to estimate energy consumption and the carbon footprint. DP6.2. Provide features for implementing various assessment methodologies, carbon management standards, and related KPIs so the system affords the ability to estimate energy consumption and the carbon footprint—given the lack of standardized indicators of energy consumption and carbon emissions and traditional performance indicators—and compliance with reporting standards or initiatives, including governmental guidelines.

In this round, we presented the results of specific scenarios in workshops with at least one end user per organization. The group of end users, in collaboration with the research team, specified the scenarios based on the ECMS' purpose and scope dimensions that we also used to define the demonstration settings. Rather than an exhaustive list of scenarios, we wanted to evaluate an instantiation of a designed artifact to establish its utility in achieving its stated purpose (Venable et al., 2012), thus offering key proof-of-concept examples (Nunamaker et al., 2015). The end-users assessed the ECMS' utility in these scenarios, which are described in Appendix A. The second evaluation round also gave us an opportunity to collect evidence about the value of ECMS, thus moving toward a "proof-of-value" evaluation of the artifact. Next, we present the outcomes, structured according to overall feedback, energy and carbon measurement, environmentally aware decision-making and practicing, aspects of implementation and future enhancements, and further exploitation.

Overall feedback

Overall, the end users in organizations A, B, C, and D agreed that the developed artifact met the initial requirements and addressed first-round challenges like data heterogeneity, integration quality, and completeness. For example, an end user from D stated that

> combining information flows and trusting the ECMS results are key to the system's success and must be safeguarded with appropriate validation processes. I am happy to see that the new design principles addressed the challenges raised in the first round.

All users perceived the deployed ECMS as user-friendly and reliable, as offering easy access to information, and as supporting efficient monitoring of energy consumption and carbon emissions. The systems provided information that was previously unavailable and that the respondents considered to be timely, accurate, easy to understand, and relevant to key organizational decision-makers. The respondents from organizations C and D expressed that environmentally aware decisions could be positively affected by the higher quality of the information.

Respondents identified the combination of energy- and carbon-related KPIs with KPIs related to production (A and B), sales or supply chain operations (C, D) as the key strengths of ECMS in terms of optimizing performance and enhancing decision-making. A respondent from organization D also highlighted that,

> by enabling ECMS automatic energy data capture, energy and carbon calculations were based on our actual, daily data rather than yearly estimations, and the opportunities to quantify our impacts could now be materialized. Thus, ECMS provided credible results that are based on my own data and not on generic industry data provided by a third party.

Moreover, they recognized the unified data layer and data collection component as significant contributions of the ECMS since they allowed them to collect their supply chain partners' data (D).

Energy and carbon measurement

Energy consumption in organization A was highly dispersed and understood only through monitoring. The weaving department contained many small machineries with linear energy consumption, whereas the finishing mill used few large machineries with varying non-linear and heavy energy consumption on average. These latter machines were idle 36 percent of the time, which was reduced to 22 percent after the company used the ECMS results in their production scheduling processes. The ability to observe the energy consumption per machine, per process step, or for an entire textile process revealed both the machines' energy profiles and the commonalities and differences among the types of products. That is, the organizations perceived different levels of aggregation as critical.

For organization B, identifying the most energy-consuming machines was valuable because these machines affect peak electricity consumption, which incurs high penalties if it is excessive. Reducing these peaks led to a significant cost reduction. Moreover, the energy consumption during standby, cooling, or heating was shown to be substantial, even sometimes during the weekend, when limited production took place, so detailed monitoring may lead to considerable reductions. Energy monitoring also helped to improve production schedules, mainly in terms of energy-consuming machines' reduced consumption while on standby; up to 16 percent of energy use could be saved by shutting down such machines at appropriate intervals.

The new analyses also showed that indirect consumption, such as by water depuration systems, warehouses, and administration in organizations A and B, was significant, and non-production departments in organization B used about half of the electrical energy. Organizations must consider all departments, not only the production departments, when the goal is to reduce electricity consumption.

Energy costs are a major cost driver in organization C's stores, so C invested in energy-efficiency infrastructures in their new and renovated stores over the years. After the ECMS presented the energy consumption and carbon footprint of three representative stores, the supply chain manager realized that

> the environmental impact of our green store is one third of the environmental impact of our older, less energy-efficient store and around half of a conventional store.

ECMS also provided organization C with the ability to measure the energy consumption and environmental carbon footprint of the various sections in its stores, considering their temperature requirements for products like cheese and cold cuts, frozen foods, fruits and vegetables, meat, and other refrigerated food. Thus, according to an end user at organization C,

> ECMS enabled us to monitor energy consumption per section and product category, which allowed a more efficient and fair distribution of the carbon footprint on product categories. However, we must be careful when using this information to avoid stigmatizing any product categories.

An end user in organization D observed that

> we need to be able to detect monthly where we lose energy, but our current system is not so sophisticated, as it is based mainly on energy-consumption bills. ECMS and the smart meters provided us with better information about our energy consumption.

ECMS was also valuable in measuring the impact of alternative modes of distribution and networks, such as direct store delivery vs. centralized delivery based on a product's carbon footprint. By understanding the energy- and carbon-measurement logic incorporated in ECMS and the estimations related to product categories and product levels, the end users in D could get information for more products, calculate their environmental product declarations, and even experiment by changing product-related attributes like packaging units.

Environmentally aware decision-making and practicing

In organization A, implementing ECMS obliged the operators to engage in a critical discussion about all aspects of energy consumption, from a single machinery analysis to renegotiating the purchasing contract. All functions were involved, from production to maintenance, from scheduling to accounting. This discussion led to potential cost reductions from renegotiating energy contracts; reducing the time required to produce (i.e., the ‘makespan’), which reduced indirect consumption and, to a large extent, fixed consumption; and reducing machines’ idle time. All of these outcomes reduced the energy consumption directly related to production.

Organization B decided to reduce the number of people who worked during the weekend to the absolute minimum to avoid using non-productive infrastructures like ventilation. However, energy-aware behavior by employees was also important. For example, reducing the number of employees over the weekends would reach its full potential for energy reduction if employees were aware that using a ventilation system for only one person would consume excessive energy and jeopardize the energy-reduction efforts. Moreover, working with ECMS had the potential to have a strong potential economic impact by eliminating shifts with low utilization of machines, as long as delivery dates are not violated, reducing the number of times total consumption exceeded the peak agreed with the electricity provider, and shutting down energy-consuming machines when they are in standby.

By measuring the energy consumption and carbon footprints of stores with different profiles, managers in C could quantify the impact of investments on energy-efficient infrastructures and plan their future investments, such as replacing refrigerators. D also highlighted the necessity of having the ECMS results:

> We need ECMS because CO_2 is also directly connected with costs. If we reduce CO_2, we can reduce our costs as well. All this information may be used in negotiations with clients—or customers may request it—to show them the improvements in some environmental aspects of our company. We are talking about certifications. It’s absolutely necessary to prove that we are improving ourselves and that we have environmental plans to reduce our CO2.

Organizations C and D contended that ECMS could strengthen the collaboration between supply chain partners and that joint environmental decisions could be positively affected by information of higher quality and granularity and enhanced visibility of the supply chain. For example, the possibility to compare different distribution networks passing through—or not passing through—the retailer's central warehouse enabled organization C and D to initiate a discussion on addressing the environmental challenges jointly.

Customers' requests for details about carbon footprints at the product level have raised issues related to competition between companies, so the need for accurate and comparable measures to enhance the quality of benchmarking increases. ECMS addressed the complexity of these calculations in organizations C and D so they could pass this information to their end consumers.

Overall, the end users in A, B, C, and D believed that ECMS is aligned with their environmental strategies and could support their sustainability practices overall. For example, A and B want to develop an energy efficient production process that would alleviate peaks in energy consumption peaks and use the available machines more efficiently, C wants to measure the environmental impact of its activities and develop energy-efficient stores and warehouses, while D wants to improve the environmental profile of its product and to address environmental challenges in collaboration with retailers.

Finally, ECMS can help not only big companies but also small and medium-sized enterprises to capture their emissions, identify their origin, and reduce them based on measurements of CO_2. They can compare their advancements per individual service and at various operational levels. Ideally, such an approach is compatible with financial accounting, as it allows users to integrate and compare figures, to see the effects of monitoring and to make better business decisions and trade-offs daily by using a common approach. Methodologies that are simple, practical, and less complex are the key (D).

Aspects of implementation, future enhancements

The transition to ECMS was non-trivial for the organizations in our study, as most employees were used to their legacy systems, and contextual help and customization were important. The instantiation was efficient, but the shift that was required for the all four organizations to understand its use and value was non-trivial, as were the integration and the data-interfaces required. After the two rounds of demonstration and evaluation, it was clear that the full potential could be unlocked only by redesigning some processes, such as production planning and scheduling for A and B.

In the demonstration phase, ECMS was not fully integrated with the organizations' existing systems, so considerable additional manual effort was required to collect data that were not easily available. This level of integration was acceptable in the context of prototype development, but integration is critical for the further operational use of ECMS. However, one of the respondents stated that,

> because of its business value, commercial platforms or ERP systems could also adapt the functionalities ECMS supports,

thus eliminating any future integration effort.

Addressing data issues remains a prerequisite for enhancing the ECMS implementation. For example, validating non-linear-energy-consumption models for organization B requires more detailed data over a longer time horizon to avoid miscalculations. As the combination of information flows requires strict data specifications, the organizations required more detailed exception-handling to return precise information with malformed data, inconsistent requests, or bad configuration parameters. Moreover, the environmentally aware decision-making process could be improved by adding new, more meaningful KPIs to the reports using the CFE component and including cost parameters. ECMS should also include an extended element to consider at least an organizations' cost, as cost data for supply chain partners are confidential. However, as one of the respondents claimed,

> It would be good to have the cost next to the CO_2, but our focus is not on the cost. Reducing CO_2 in transportation usually also reduces the cost (D).

User-friendliness and system usability were other aspects of the implementation on which the users commented, but developing polished interfaces and providing multilingual context-sensitive help was beyond the four pilots' scope. Therefore, the respondents considered the artifact instantiation to be acceptable for a system demonstration but also expressed that it should be improved before being released as a permanent deployment (A, B, C, D).

Future exploitation

A simple comparison of the energy used and saved was not the only KPI that the end users considered in validating the ECMS' potential impact. The new information provided and the environmentally aware decision-making enabled end users to decide to

> systematically invest further in the realization of the ECMS (A and B).

Organization C assessed the energy consumption per warehouse and per storage section, as well as across its distribution network. Electric power bills and fuel consumed in handling internal deliveries from warehouse to stores were among the organization's highest running expenses. Organizations C and D anticipate acquiring competitive advantage in terms of green collaborative supply chain processes, collaborative distribution processes, and distribution optimization, and ECMS could support reporting and negotiation with several of their customers and suppliers.

As for organization D, a representative stated,

> We want to adopt an ECMS in our company; this is not an academic and research game for us but an endeavor to understand how systems like that can provide us with energy and carbon footprint information, support our sustainability strategies, and enrich our decision-making processes with environmental aspects…. I would base my environmental reporting

on the ECMS reports, which are much more accurate than the rough estimates I currently do monthly. Both regulations and consumers' attitudes suggest that. In the future, the information and capabilities provided by ECMS will not be only useful but mandatory.

We can also attribute the positive feedback and outcome of the second evaluation round to the research approach followed to design and develop the artifact. We engaged end users throughout this process so they could communicate their needs and requirements during multiple rounds and interactions with the research team and fully understand the design and implementation challenges of ECMS. Against this backdrop, in the second round, they focused on the information value gained and how ECMS can support the measurement of energy consumption and carbon consumption, along with environmentally aware decision-making and practicing. They recognized this potential and its future exploitation. However, all of the organizations also recognized the requirement to develop the ECMS artifact further, mainly by increasing integration with existing systems and polishing interfaces, for it to be exploitable as a product for deployment and productive use.

6 Discussion and Implications

Contribution to the Green IS Literature

Our design theory contributes to the ongoing discourse on developing prescriptive knowledge about IS that support environmental sustainability (Malhotra et al., 2013; Seidel et al., 2013) and their impact when implemented in the field. Previous studies translate explanatory and predictive theory into green IS design knowledge (e.g., Recker, 2016; Seidel et al., 2018; Watts & Wyner, 2011), but most consider green IS at an aggregate level (e.g., Chowdhury, 2012; Melville, 2010). Therefore, to explain how they address pertinent environmental problems (Corbett, 2013) we must unpack the black box of green IS by studying the design and implementation of ECMS as a key type of green IS.

While our focus is on ECMS, our study also provides some key insights into green IS in general. While green IS are typically defined by a focus on their ends in terms of enabling environmentally sustainable processes and outcomes (Recker 2016; Watson et al., 2010), we extend this perspective by attending to the means that help to accomplish these ends: environmental information flows coupled with key material features for ECM and environmentally sensitive decision-making and practicing.

Against this background, we explore the specific types of data and associated information flows that are salient to the development of ECMS because it is this environmental data that is often not available in an appropriate form. Therefore, it is not used for environmentally sensitive decision-making and practicing although it is this data that one must have to attend to economic, social, and environmental KPIs simultaneously.

We also explicate this means-end relationship by attending to key material features in the form of two types of constructs in our design theory: energy information flows and system components for monitoring energy and estimating the carbon footprint. We highlight how these environmentally specific components, in conjunction with more generic components for data collection and reporting, constitute a green IS. This insight highlights how we can reinterpret IS—arguably the greatest drivers of productivity in the past decade (Watson et al., 2010)—in light of sustainability , then combine them with environmentally specific functional building blocks to form IS that facilitate simultaneous economic and environmental outcomes.

We involved industry practitioners in all phases of design and development to obtain the requirements and justificatory knowledge that informed our design and, thus, the constructs (system components and information flows) and design principles we derived. Deep engagement with industry practitioners provided the foundation for developing prescriptive knowledge (Buhl et al., 2012; Mathiassen & Nielsen, 2008; Seidel et al., 2017). We also actively engaged with scholars and practitioners from other fields, such as management, computer science, engineering, environmental science, supply chain, retailing, and manufacturing—an approach that researchers found was conducive to green IS research (vom Brocke et al., 2012).

Contribution to the literature on ECMS in the Supply Chain

We contribute to the discourse on the use of IS in the development of ECM in the supply chain (Björklund et al., 2012; Maestrini et al., 2017; Qorri et al., 2018). Our ECMS design addresses the ECM requirements through six system components—data collection, energy monitoring, supply chain coordination, ECMS workflow engine, the carbon footprint estimator, and reporting—that integrate and coordinate four types of information flows: transactional, contextual, energy, and product-environmental. Our study identified the carbon footprint estimator as a key component of ECMS. Defining the design principles related to this component and integrating them in our architecture were key steps in consolidating the emergent ECMS design theory. By collecting evidence from four organizations in different industries, we broaden our understanding of ECMS in the supply chain. Our components reached their final form and content only after two rounds of building, demonstrating, and evaluating an expository instantiation with these four organizations.

This design theory contributes also to the broader category of EMIS—and ECMS in particular. While a considerable body of knowledge is related to the design of systems from which we can extract design requirements and design principles, these works focus on implementing artifacts that address specific problems, rather than on formulating an abstract IS design theory, as our study does.

We also contribute to the currently limited knowledge about the impact and 'proof of value' of ECMS/EMIS, along with their implementation challenges, such as integration with legacy systems, data acquisition and quality, varying levels of data granularity, and integration of energy-related information into process or operational data. The data-related challenges of ECMS arise mainly from data that is heterogeneous, secondary, and time-dependent, thus diminishing the information's reliability and accuracy (Melville & Whisnant, 2012). ECMS' data capture and integration capabilities impact its data quality (Melville & Whisnant, 2014), so we need design principles that address data quality, transparency for stakeholders, and increased accuracy (Melville et al., 2017). Thus, system implementation was not our primary focus but part of our proof-of-concept and proof-of-value approach. We identified the implementation challenges of ECMS by running four practical demonstrations and attending to how they affected ECMS design.

By providing empirical evidence about the challenges of ECM in the supply chain, we address the call for more empirical studies on the development of performance measurement in SSCs (Ahi & Searcy, 2015; Björklund et al., 2012). More specifically, we offer insights related to the different ECM dimensions of manufacturing, warehousing, distribution, and overall supply chain, along with the KPIs per dimension, the necessary information flows (contextual, transactional, energy, and product environmental), and the factors that affect the development of ECM that must be considered.

Considering recent trends, the Planetary Boundary (PB) framework receives considerable attention as an environmental sustainability reference and has diffused into policy-making (Galaz et al., 2012), as well as into industrial organizations (Bjørn et al., 2017; Steffen et al., 2015). It provides a framework for managing environmental resources at the global level and a way to move beyond assessing anthropogenic systems in terms of eco-efficiency to assessing its impacts in relation to the actual state of the environment. However, most of the environmental impacts human activities cause operate through local effects, so many studies investigate how life-cycle impact assessment methods can assess environmental impacts at the local level to operationalize the framework (Bjørn et al., 2015; Ryberg et al., 2016; Sala et al., 2020).

This view provides a space in which to position ECMS' role and outcomes in the global context. Sala et al. (2020) match the seventeen LCA impact categories (e.g., climate change, resource use) with the planet's ten boundaries. The carbon emissions or CO_2 equivalents that ECMS can calculate are the main metrics associated with the LCA impact categories related to climate change. In this view, ECMS can provide outcomes that can link to three key elements of the PB framework—climate change, ocean acidification, and biodiversity integrity—and support addressing these problems. However, future studies should explore how IS could support the calculation of other supply chain KPIs and materialize the PB framework in a more holistic way.

Practical and Managerial Implications

The ECMS design theory suggested here and the artifact we developed can inform software engineers in their efforts to design IS for ECM in the context of supply chains. Our results highlight the core principles of ECMS design, thereby emphasizing a compact set of material features and functionalities than ECMS must offer.

For software vendors, our architecture exhibits a coherent decomposition of the system's components and their interactions. Modularity can improve the systems' reusability and integration, although the various ECMS components may require context-dependent implementation and deployment. Modularity further opens ECMS implementation to the involvement of stakeholders who have expertise in various fields, including energy sensor management, ECM, and supply chain management.

For managers and practitioners across the supply chain, our work captures the essential requirements related to ECM, presents an ECMS that addresses these requirements, and offers proof-of-concept, along with main implementation challenges and proof-of-value. Such knowledge can assist professionals in assessing the current state of their ECMS implementation and in adopting, implementing, and continuously improving ECMS. This practical value is supported by decomposing the general idea of

ECMS into key components and by formulating prescriptive knowledge in terms of design principles related to these components. While some companies have energy-reporting systems in place, others may be more competent in terms of estimating carbon emissions. Our suggested ECMS design theory can help these companies to develop their expertise, processes, and systems toward full-fledged ECM in the supply chain.

7 Conclusion

Our study derives prescriptive knowledge in terms of an IS design theory for ECMS in supply chains. By applying a DSR approach, we formulated an ECMS design theory, developed an expository instantiation based on the design, evaluated and refined the ECMS design theory and the expository instantiation, and provided proof-of-value evidence in two rounds of building, demonstration, and evaluation in four organizations.

Our key limitation lies in the study's restricted empirical basis and, hence, the risk of focusing on specific conditions instead of general concepts. We sought to minimize this risk by grounding our conceptual design on previous studies and by validating the outcomes with industrial experts beyond those involved in implementing the system. The iterative process, stage of reflection and formalization of learning, and the overall action research approach we used supported a sound methodological effort to address this limitation.

Further research could investigate whether industry-specific characteristics significantly affect the role and design of ECMS, especially related to the actual and measurable impact of ECM in financial and environmental terms. We consider our consolidated design principles and probably the constructs themselves a starting point for similar work.

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Katerina Pramatari is Associate Professor at the Department of Management Science and Technology of the Athens University of Economics and Business and scientific coordinator of the ELTRUN/SCORE research group. She has received various academic distinctions and scholarships and has published more than 100 papers in scientific journals, peer-reviewed academic conferences and book chapters, amongst them in Journal of Retailing, European Journal of Information Systems, Journal of Strategic Information Systems, Journal of Information Technology, Decision Support Systems etc. She is also heavily involved in the Technology Transfer domain as a VC partner and in various activities fostering youth entrepreneurship.

Ioannis Mourtos is Associate Professor at the Department of Management Science and Technology of the Athens University of Economics and Business and scientific coordinator of the ELTRUN research group. He is conducting both theoretical and applied work with a primary focus on Mathematical Programming and Combinatorial Optimization. In terms of polyhedral analysis, he has worked on multi-index assignment, stable matchings, matroid parity and max-cut. In terms of computing, he is mainly interested in Integer Programming, Constraint Programming, as well as their integration. His interests in more applied fields are interdisciplinary and include applications of optimization in manufacturing and transport, along with decision support and the design of related information systems. He is particularly focused on energy-aware information systems and how these encompass the use of elaborate modelling and computing methods to optimize relevant sustainability metrics. He has a broad and diverse publication record, serving also as an ad-hoc reviewer for several well-known journals. He enjoys an extensive network of international collaborations and has served as scientific coordinator of EU-wide research projects.

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