DESIGN OF ENVIRONMENTAL PERFORMANCE MONITORING SYSTEMS IN THE SUPPLY CHAIN: THE ROLE OF INTEROPERABILITY

Complete Research

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Abstract

In response to the mounting request for sustainable supply chains, companies need to assess the environmental performance of their operations and products. Recent studies within the field of Information Systems (IS) argue that information systems can forge supply chain sustainability by monitoring a firm's environmental performance. The latter requires a specific type of Information Systems, namely environmental performance monitoring systems, hence our study focuses on such systems and addresses the challenge of designing them. That is, through a design science approach, we capture the industrial and informational requirements of environmental performance monitoring in the supply chain context and derive a conceptual architectural framework that is generic in the sense of including all the basic components that comprise such systems. To establish the applicability of our architectural framework, we instantiate it for two cases of environmental performance monitoring systems that are then deployed under different settings. We conclude by proposing a set of design propositions and discuss their validity and importance in relation to a firm's level of interoperability.

Keywords: Environmental Performance Monitoring Systems, Sustainable Supply Chain Management, Information Flows, Interoperability

1 Introduction

Firms in several industries nowadays implement various practices in order to develop more sustainable supply chains, under the pressure of stricter regulatory requirements, energy costs' inflation, increasing requests of supply chain partners and mounting environmental awareness of consumers. Monitoring environmental impacts at the different stages of a supply chain has been recognised as a main issue in the development of sustainable supply chains (Seuring and Müller, 2008). Such a monitoring forms the basis for controlling the environmental performance of supply chain processes, for making environmental-aware decisions regarding improvement measures and for tracking the progress in environmental performance. Thus, a growing number of firms deploy and monitor various environmental indicators (Olugu et al., 2011; Veleva et al., 2003) and even integrate carbon footprint monitoring in the management of their supply chain (Lee, 2011; Sundarakani, 2010). However, the level of implementation of environmental performance measurement still remains low.

In this context, environmental data are either completely absent or merely available at high aggregation levels (Melville and Whisnant, 2012), thus preventing firms from accurately evaluating internal and external performance in environmental terms. While economic and operational data are available in internal systems, various integration issues regarding information technology remain to be tackled before incorporating both environmental and non-environmental aspects (El-Gayar and Fritz, 2006;

Lee, 2003). Furthermore, in the realms of supply chain, efficient information sharing and collaboration among supply chain partners must be effectively developed to enable an end-to-end information flow (Banker et al., 2006). Therefore, information systems could enable environmental performance measurement by "collecting and analysing environmental and operational data sets, integrating environmental with other information flows, calculating and monitoring both the environmental and traditional performance indicators of processes and products, through analysis, reporting and business intelligence”. Let us hereafter refer to this type as “Environmental Performance Monitoring Systems".

More specifically, these systems should be able to capture energy and carbon related information from energy consumption measurement infrastructures, to integrate and interoperate with a company's existing enterprise systems (e.g., ERP), to interpret and integrate the data received from various sources and to exchange data with the enterprise systems of supply chain partners. Evidently, the level of a firm's interoperability critically affects the implementation of these systems (Dassisti et al., 2013; El-Gayar and Fritz, 2006) and possibly introduces additional obstacles, especially regarding data exchange across the supply chain. Despite the growing interest for this kind of systems, limited work has been done on their design and their actual implementation and deployment (Malhotra et al., 2013, Melville, 2013; Seidel et al., 2013), not to mention interoperability-related issues. Although previous studies imply general design principles for environmental reporting and monitoring tools (Hilpert et al.,2013; Hilpert et al, 2014; Seidel, 2013), these studies remain rather superficial in their design principles which remain non-explicitly related to contextual implementation settings, such as the level of interoperability or technological maturity, data availability-acquisition and integration, or even the organisational aspects motivating the use of such tools.

Hence, our work aims at advancing the successful design of an environmental performance monitoring system across the supply chain, by first elaborating on the effective integration of the various information flows needed to enable environmental performance measurement. Then, our work introduces the firm's interoperability level (Dassisti et al., 2013; El-Gayar and Fritz, 2006) as a critical aspect affecting the design of these systems. Interoperability is the ability of disparate and diverse organisations to interact towards mutually beneficial goals, via sharing information and knowledge on the business processes they support, by means of data exchange among their ICT infrastructure (Chen et al., 2008; IDABC, 2008). To proceed in this direction, one must address the following core questions:

- Which are the necessary components of an environmental performance monitoring system?
- How is the design of environmental performance monitoring systems affected by a firms' interoperability level?

The remainder of the paper is structured as follows. Section 2 offers a justification for the relevance of this work by drawing upon the pertinent literature. Section 3 describes the research methodology adopted and the case context of this study. Section 4 presents the industrial and information requirements regarding environmental performance monitoring systems. Section 5 presents our conceptual architectural framework that addresses the identified requirements, along with its instantiation at the two cases. Section 6 discusses the major findings from the field study of the proposed architecture and Section 7 concludes by discussing certain limitations and important implications for future research.

2 Environmental Performance Monitoring Systems

The topic of sustainable supply-chain management has received substantial attention over the last years by researchers and practitioners alike. The major challenges in the development of sustainable supply chains include the identification and measurement of impacts arising from both environmental and economical aspects (Seuring and Müller, 2008a) and the assessment, monitoring, analysis and evaluation of supply chain processes (Abbasi and Nilsson, 2012; Seuring and Müller;2008b). Measuring the environmental performance of supply chains remains non-trivial due to several reasons, including limited data availability (Veleva et al., 2003), complex integration of various data types (energy consumption, production, warehousing, etc.), non-effective data alignment across different partners

(Hervani et al., 2005), lack of standardized environmental performance measures (Hervani et al., 2005), inter-organizational dispute on performance management and measurement (Hervani et al., 2005), and insufficient capturing of non-traditional performance data by current enterprise systems (Hervani et al., 2005). Still, incorporating both environmental and non-environmental aspects is crucial for tackling the trade-offs among the distinct performance aspects (Björklund et al., 2012; Caplice and Sheffi, 1995; Keating et al., 2008; McIntyre et al., 1998, Shaw et al., 2010; Vanteddu et al., 2006, Zampou et al., 2014a).

Information systems can support firms to confront the main issues discussed above by enabling them to standardize, monitor, capture, and utilize (meta-) data (Björklund et al., 2012; Dao et al., 2011; Hervani et al., 2005; Melville, 2010; Watson et al., 2012). In addition, they could facilitate collaboration and information exchange by improving information flows among partners (Banker et al., 2006). Moreover, they could support and optimise both operational and strategic decisions by unifying traditional key performance indicators (KPIs), such as cost and service level with environmental KPIs and the energy profile of products and processes (Bunse et al., 2011; Watson et al., 2010). Last, they could also incorporate life-cycle analysis methods and process the data required for impact assessment at product level (Shaft et al., 2008; Melville, 2010).

Focusing on environmental management information systems, Teuteberg and Straßenburg (2009) review environmental management information systems (EMIS) and classify them into different types, each providing business functionalities of a different scope. Indicatively Hilpert, et al. (2013) propose a cost-efficient system of real-time data gathering for product carbon footprints in transportation processes and Zampou, et al. (2014b) identify those major functionalities that suffice to characterize an IS as 'energy-aware' in manufacturing and introduce a generic framework of a case-independent energy-aware IS. Our motivation stems particularly from a recent set of high-level requirements and design principles (Carlson et al., 2001; Hilpert, et al., 2014, Seidel et al., 2013), while our work contributes towards a design science approach that further specifies the functionalities to be integrated in these systems or the information that must be transmitted, processed, and stored (Brown, et al., 2005; Malhotra et al., 2013; Seidel et al., 2013).

Several issues must be tackled within such a design approach, the most prominent being the data management and the integration with other systems (El-Gayar and Fritz; 2006). Melville et. al., 2012 use real cases to identify unique data challenges that arise mainly from the nature of the required data (e.g. heterogeneous data, secondary data, unsystematic, highly distributed, heterogeneous, spatial and time relative). Analogous importance is attributed to the data acquisition and the related data granularity (El-Gayar and Fritz, 2006; Watson et al., 2010; Melville, 2012) and availability (El-Gayar and Fritz, 2006; Erlandsson and Tillman, 2009). Interestingly, data integration is critical (Carlson et al., 2001; Eun et al., 2009; Hilpert et al., 2011) as these systems are usually not integrated with enterprise systems, thus not feeding carbon footprint into relevant decision processes (Liu and Stallaert, 2010).

Therefore, interoperability appears as a catalyst for resolving the aforementioned issues on integration, hence affecting the development of the anticipated design approach for environmental monitoring systems. Its role on addressing sustainability goals has so far been highlighted in terms of tackling the complexity and diversity of the IT applications, reducing the heterogeneity, improving the quality of data stored (Dassisti et al., 2013; Hrebiceket al., 2007). We note that all three different levels of interoperability, i.e., technical, semantic and organizational (IDABC, 2008) become relevant in our approach, i.e., the technical facilitation of communication and data interchange, the data integration, aggregation and consistency (across heterogeneous information systems) in semantic terms, and the organisational alignment of business goals and processes to foster collaboration. Thus, it becomes noteworthy that, despite its growing attraction, interoperability is not formally investigated within the design of environmental performance monitoring systems.

3 Research Approach

We utilise the design-science paradigm (Gregor and Jones, 2007; Hevner et al., 2004; Peffers, 2007) to develop artifacts that apply and test theories and methods through an iterative process of development (Kuhn, 1996; Berente and Lyytinen, 2006). Hence our accomplishments include a) a critical analysis of existing solutions on environmental performance monitoring, b) the current industrial requirements regarding environmental performance monitoring in the supply chain, and, c) a conceptual architecture and two respective system prototypes (artifacts).

The industrial context of our research includes the sectors of 'Textile & Clothing' (TCI) and 'Fast Moving Consumer Goods' (FMCG) and involves manufactures, suppliers and retailers. A series of monthly workshops with industry experts, all addressing carbon footprint monitoring in the supply chain, led to an Industrial Interest Group (IIG) that clarified the main concerns regarding environmental performance, hence formulating the problem dimensions. These concerns, along with current practices, were confirmed via an industry survey among supply chain managers, sustainability managers and manufacturing representatives across Europe (ECR Europe, 2012).

Our study enjoys a broad scope regarding the environmental performance monitoring, ranging from the supplier of raw materials to the point of sales. However, environmental performance monitoring for manufacturing is recommended to be handled separately, as this allows for analysing the manufacturing specifics (The Consumer Good Forum, 2012). Thus, to set specific objectives and coherently advance the design and validation of our architectural framework, we worked separately for manufacturing issues, with two representative textile organisations interested in energy-efficiency (a leading textile manufacturer and an international clothing company) and for supply chain issues with two representative FMCG organisations interested in sustainability (a retailer and a major food manufacturer). These organisations contributed to the detailed requirements and specifications, to the design and development of the system and mainly to its validation through two iterations in real-world settings.

The textile manufacturer is one of the oldest textile industries. It is an Italian Medium Enterprise with 210 employees and a production of more than 700.000 meters of fabrics. It is currently interested in enhancing the energy efficiency in manufacturing and collaborative supply chain practices. Despite its interest, the firm currently collects energy data only for accounting purposes based on energy bills. Due to the absence of sensor enabling automatic energy monitoring, it uses the Energy Audits as a systematic procedure in order to gain a suitable knowledge of the energy consumption profile of an industrial activity/plant and to identify and quantify energy saving opportunities mainly from the viewpoint of costs and benefits. Let us call this manufacturer as 'Case A'.

Our 'Case B' is the clothing company with 735 employees in Germany alone and an annual turnover of 184 million Euro. Another 2000 people are employed in Eastern Europe for the manufacturing of garments. It has also 109 retail stores in 58 countries and more than 1500 additional upmarket fashion stores around the world. As its energy costs remain high, it is especially interested in reducing the energy consumption. In this case, extensive energy consumption data are available (by both energy audits and real-time sensor monitoring) but cannot be mapped to production orders and final products.

'Case C' is a major Greek retailer whose internal mechanisms portray an environmentally-aware enterprise. Its supply chain consists of a central warehouse and a total of 94 stores (53 supermarkets and 41 Cash & Carry). The central warehouse stores the products received from most suppliers (more than 600) and distributes them to the stores using its own fleet of vehicles. It has already deployed various environmental-friendly practices, like ambient sunlight for daytime lighting in buildings.

Last, 'Case D' is a multinational food manufacturer and one of the main suppliers in the FMCG sector, having an environmentally-aware profile. It has an extensive and complex supply chain network with presence in Europe (Italy: 5 mills, 9 production plants; rest of Europe: 3 mills, 6 production plants), America (1 mill, 2 production plants), Asia and Oceania. Its distribution network is vast, with partners in more than 100 countries. It has implemented several environmental practices over the years such as energy saving programs, installation of two co-generation plants, LCA methods and Environmental Product Declaration (EPD), business intelligence and sustainable packaging in its logistics.

Two iteration phases were followed in order to design and develop an Environmental Performance Monitoring System (artefact) in each case. The artefact and the required software (e.g., interfaces with existing systems) and hardware elements (e.g., energy sensors) were installed and demonstrated in all four companies. Moreover, a process for collecting, processing and validating the actual data was deployed. The activity of pilot testing the system in real-world settings was conducted in two phases, so that the first phase could give feedback to the second round of design and development. That round was strongly guided by the interoperability challenges imposed by the limited environmental data availability, the different data granularity levels, the poor data quality, the dependencies and coordination problems due to the need of aligning inputs from multiple partners, the technical integration issues and the absence of automation mechanisms; evidently, these challenges reveal specific features to be implemented in order to ensure the efficacy of such systems in a real-world context. Table 3.1 summarises the actual data and the systems that provide them in the four cases. During the pilot testing, the system was also evaluated in order to explain whether the non-functional requirements are met. Moreover, a further evaluation of the artefacts was conducted by selected employees working in our study Cases in order to gain feedback about the efficiency of the system. They interacted with the system by executed a set of pre-defined scenarios and then completed a questionnaire for evaluation purposes.

	Case A	**Case B**	**Case C**	**Case D**
Scope	Manufacturing	Manufacturing	Supply Chain	Supply Chain
Energy Consumption Data Availability	Limited data from energy audits	Limited data from energy audits	A building management system in one store (recording consumption every 5 secs) and energy bills for all other stores	Energy sensors that couldn't be integrated as they didn't have an interoperable API.
Fuel Consumption Data Availability	Not applicable	Not applicable	Actual vehicle refills are available in ERP	Not available as an external 3PL provider is used
Processes flow data	MES keeps information about production processes	A new ERP/PPD keeps data on production processes	Warehouse management systems keeps daily data on inventories and distributions processes	ERP stores suppliers' transactions (e.g., ordering). No data on distribution because of an external 3PL provider
Contextual flow data	Stored in ERP	Stored in ERP	Stored in ERP	Stored in ERP
Data exchange Mechanisms	N/A	N/A	They have already been installed for other cases.	No such mechanisms are installed

Table 3.1. Case settings Requirements of Environmental Performance Monitoring

3.1 Business Needs

Environmental performance monitoring should address all players in the supply chain (Ahi and Searcy, 2014), from the supplier that provides a firm with the raw materials down to the point-of-sales (Fig 4.1). Hence monitoring includes three main activities: manufacturing, warehousing and transport (The Consumer Goods Forum, 2012). Warehousing includes warehousing activities related to the storage and handling of raw and packaged materials for source or semi-finished or finished goods. Transport includes inbound and outbound activities across all transportation modes (e.g. road, rail, sea, inland waterways). Both warehousing and transport can be planned, controlled and executed in-house, as well as outsourced to a third party. Manufacturing activities include activities related to the production of raw materials, semi-finished or finished goods.

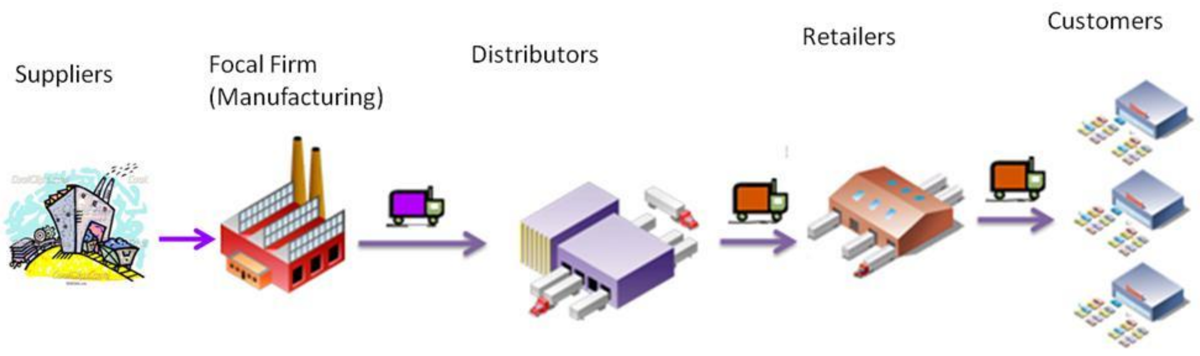

Figure 3.1: The scope of environmental performance monitoring

In our cases, the development of environmental performance monitoring is mainly motivated by energy and fuel cost reduction, by reporting carbon emissions for regulatory reasons and by the environmental concerns of consumers and supply chain partners. Therefore, environmental performance monitoring focuses on two sources of environmental impacts, namely energy and fuel consumption, and the respective carbon emissions. However, there is also the need of associating environmental aspects to traditional supply chain and manufacturing aspects, e.g. associating environmental performance indicators to warehousing capacity utilisation. Based on our extensive interaction with the Industrial Interest Group and the four organizations, we have been able to identify a set of key requirements related to environmental performance monitoring in the supply chain and also a set of key performance indicators (Appendix A). The list of key performance indicators is not exhaustive as the main objective was to implement a limited set of indicators in various more detailed levels of analysis.

Environmental performance monitoring in manufacturing

This type of environmental performance monitoring allows for monitoring, controlling and improving energy consumption in manufacturing processes while also supporting energy-based decisions. It requires the collection of energy data from various data sources (e.g., sensors, energy audits). For the data collection to take place, we should define the sensitised objects that refer to "a physical good that has the capability to sense and report data about its use" (Watson et al., 2010). Since production machines are responsible for the greatest part of energy consumption in manufacturing, they define the sensitised objects in our case. However, energy is also consumed by activities that are not involved directly in products' manufacturing. Hence, the energy consumed can be divided into direct and indirect (Seow and Rahimifard, 2011). Direct Energy (DE) refers to the actual energy used by various processes required for manufacturing the actual product, whereas Indirect Energy (IE) on the other hand refers to energy consumed by all other activities, e.g., lighting, cooling/heating and ventilation. The common current practice of energy monitoring involves the so-called 'energy vectors' (i.e., the expected energy consumption per machine and production order) that are produced through aggregated historical data and energy audits. Therefore, if actual energy consumption measurements are absent, the energy vectors are used in order to estimate energy consumption and support environmental performance monitoring. This type of environmental performance monitoring also supports the calculation of energy consumption at different levels of granularity and across different processes. The different levels are shown in Table 4.1

Environmental performance monitoring in warehousing and distribution

This type of environmental performance monitoring allows for monitoring, controlling and improving energy and fuel consumption and the respective carbon emissions in warehousing and transport processes and also extends monitoring beyond a company's boundaries to cover the whole supply chain. It analyses the existing ordering and distribution processes to support environmental-based decisions. It could also be used for supporting reporting objectives. It requires the collection of two types of environmental data: the energy consumption data related to the warehousing activities and the fuel consumption data related to the distribution activities. The sensitised objects in a supply chain are the warehouse power supplies and the vehicles used in distribution. Both energy and fuel consumption data are collected from different partners in the supply chain. Also, the energy and fuel consumption are translated into carbon emissions. This type of environmental performance monitoring supports the calculation of energy consumption at different levels of analysis as show in Table 4.1.

Manufacturing	**Supply Chain**
Machine	Store/warehouse section
Process step	Store/warehouse
Process	Vehicle
Production order	Distribution link
Department	Route
Facility	Supply chain networks
Article	Product category and product

Table 3.2 Environmental Performance Monitoring Level of Analysis

Based on the above, we conclude on a set of generic requirements, summarised in Table 4.2.

Requirements	**Explanation**	**Manu fac-turing**	**Sup-ply Chain**
Energy and fuel consumption data collection	The system should capture energy consumption from energy meters, handle the energy streams and support alerting mechanisms where applicable for enhancing environmental efficiency.	√	√
Operational data collection	The system needs to collect information about transactions (production processes, distribution process) and contextual information regarding the machines, processes, products, inventories deliveries, partnerships.	√	√
Energy consumption data collection from non-sensor resources	The system needs to support the management and utilisation of energy consumption flows non-recorded by sensors. Such flows include the information coming from energy audits, as translated into energy vectors or energy consumption bills or fuel refills.	√	√
Estimation of environmental impacts	The system should implement a business logic that will enable the calculation of carbon emissions and the allocation of environmental impacts on the more detailed level of analysis, e.g. process, product etc.	√	√
Workflow monitoring	The system needs to support the monitoring and the supervision of the various processes and calculate the required key performance indicators.	√	√
Environmental reporting	The system needs to present the required key performance indicators in various formats.	√	√
Supply chain design	The system needs to support the design of the various supply chain networks.		√
Information exchange	The system needs to support information sharing, information synchronisation and the collaboration with supply chain partners.		√

Table 3.3 Environmental Performance Monitoring System General Requirements

3.2 Information Flows and Data Requirements

The different levels of analysis presented above impose the need of collecting operational data from different existing systems (e.g., MES, APS, ERP) and integrating various types of information in order to interpret the energy according to the particularities of manufacturing or warehousing or distribution.

Therefore, during the user requirements capturing process, we have also identified the data required for covering the aforementioned requirements and identifying the potential sources for their retrieval. Although different activities in the supply chain scope have their own specificities and hence require different kinds of data, all data could be classified into the following information flows:

- Contextual information flow (CI): includes information on machines, processes, products, facilities, supply chain partnerships and supports the interpretability of the transactional information.
- Transactional information flow (TI): includes information on the transactions that take place in the supply chain such as production processes, ordering, distributions, inventory management.
- Environmental information flow (EC): includes information on energy consumption that is either measured by energy sensors or retrieved by existing Building Management Systems and fuel consumption information referring usually to vehicle fuel refills or to actual fuel consumption monitored through sensors and metering devices installed on vehicles.
- Product environmental information flow (PEIF): includes information on the environmental profile of the products, as provided by external sources, including the embodied carbon footprint of the products recorded by Life Cycle Inventories (LCI).

It easily follows that the information needed to support the requirements of Table 4.2 comes from different existing systems (such as ERP, warehouse management systems, energy sensors, building management systems, EMS, APS). More specifically, information related to machines and their mapping to processes is handled by applications such as MES and APS; product information is stored in applications such as PDM for manufacturing but also in ERP; business information related to the orders, articles and quantities to be produced, deliveries and inventories is processed by ERP or Supply Chain Executions Systems; energy and carbon emissions information is captured by sensors, Life Cycle Inventories-LCI etc. As the collection, the integration and the synchronisation of the various information flows is a major challenge for the design of such systems, a generic set of data-related requirements has been obtained and is summarised in Table 4.3.

Requirements	Explanation	Manufacturing	Supply Chain
Data validation	The system should validate and clean-up of the data received in order to be integrative.	√	√
Automated input interfaces	The system should have interfaces that that enable collecting environmental and operational data from existent business information systems automatically.	√	√
Quality indices about the data availability	The system should examine the data availability and provide the respective indices related to it.	√	√
Ensuring the same level of granularity	The system should check if the data received have the same level of granularity e.g. inventories from all warehouses and stores should be stored on a daily basis	√	√
Data transparency	The system should provide features that provide information about data type and origin as well as collection proofs regarding the environmental and operational data e.g. secondary environmental data are used for the estimations	√	√
Data sychronization and mapping	The system should map the entities and sychronize the data received from other resources e.g. map the codes for products from different suppliers	√	√

Table 3.4 Environmental Performance Monitoring System Data Related Requirements

Last but not least, an environmental performance monitoring system needs to meet some non-functional requirements (see Appendix B). The non-functional requirements have been collected from the input and the discussion with the business partners and were based on the Standard ISO/IEC model**,** which defines quality standards by identifying a set of features and attributes that a generic software needs to have.

4 Design of Environmental Performance Monitoring Systems

Let us now propose a set of mandatory components that cover the user requirements related to both manufacturing and supply chain by integrating the respective information flows. Here are the components and their primary functional objectives.

- The **Data Layer** refers to the main data interface that acts as a single receiver of all available data sources. As environmental performance monitoring is a data-intensive procedure, it requires transactional and contextual data from various sources. Therefore, a component that collects, validates, cleans-up and identifies the relations among them becomes crucial. This component consists of two separate sub-components that function independently of one another: the Energy Data Layer, and the Operational Data Layer. The former orchestrates the communication and synchronization with energy sensors and Building Managements Systems thus receiving and storing all energy consumption data, while the latter imports data from existing systems such as MES, ERP, WMS.
- The **Energy Sensor Monitoring** collects energy consumption data from the Energy Data Layer and implement a business logic for aggregating energy consumption at different levels of analysis and combining the energy data with the infrastructural information, e.g. it calculates the energy consumption per department of a manufacturing site.
- The **Non-sensor energy monitoring** utilizes all energy consumption flows non-recorded by sensors, e.g., the energy consumption recorded by energy bills. Such flows include the information coming from energy audits in the manufacturing cases, as translated into the energy vectors needed e.g for calculating indirect energy in the manufacturing case.
- The **Supply Chain Design** has the objective of designing the supply chain and providing all the required information regarding the supply chain objects of interest (e.g. node, product details, partners details, geographical information etc.). Since supporting environmental performance monitoring requires the structure of the supply chain and the scope of monitoring to be defined, this component supports the definition of the scope based on a user's existing supply chain settings.
- The **Transactions Flow Network Monitoring** refers to the monitoring and supervision of a set of processes, e.g. distribution, ordering or production. This component is responsible for (a) monitoring the daily activities (shipments, storage, production) and (b) supporting the calculation of the required KPI’s for the different levels of analysis. This component tracks all supply chain processes and initiates the procedure of estimating energy and carbon footprints. Also, it communicates with the collaboration platform to receive/ submit information from supply chain partners
- The **Energy Consumption and Carbon Footprint Estimator** includes the business logic for aggregating and disaggregating anticipated energy consumption, transforming them into carbon emissions and then estimating the carbon footprint, using allocation methodologies such as LCA. Specifically, it computes the carbon emissions of the activities (processes) of manufacturing, warehousing, distribution (emissions from warehouses, stores, transportation and packaging materials), at all levels listed in Table 4.1. Since the calculation and allocation of environmental impacts is a complex procedure, often based on various methodologies, this component allows the user to review and set the allocation parameters of that procedure. as the information regarding the distribution process were not available at the required level of detail.

- The **Report Generator** creates standard formatted reports that cover all the aspects of environmental performance monitoring in the supply chain (e.g. energy measurement, carbon footprint at different levels of analysis etc.). A dedicated reporting component is important in order for a user to perceive the system as one homogeneous entity and understand the systems' value.
- The **Collaboration Platform** refers to the component that is responsible for maintaining the collaborative relationships among the supply chain partners and facilitating data exchange. Most importantly, it provides data to other components from different partners. Although non-surprising, this component enables the supply-chain-wide scope of the overall architecture..

Notice that our framework could also include a component for sensors measuring actual fuel consumption or a component for non-sensor fuel consumption monitoring. However, based on our cases and the current state of the art, fuel consumption data are usually not available. Therefore, the estimations of fuel consumption and the respective carbon emissions are based on industrial vehicle-related fuel consumption averages, that are usually incorporated as parameters in the Energy Consumption and Carbon Footprint Estimator.

Then, we provide two exemplary instantiations of these systems, one for the two manufacturing cases and the other for the two supply chain cases, in order to highlight their similarities and their differences. Figure 5.1 depicts these instantiations.

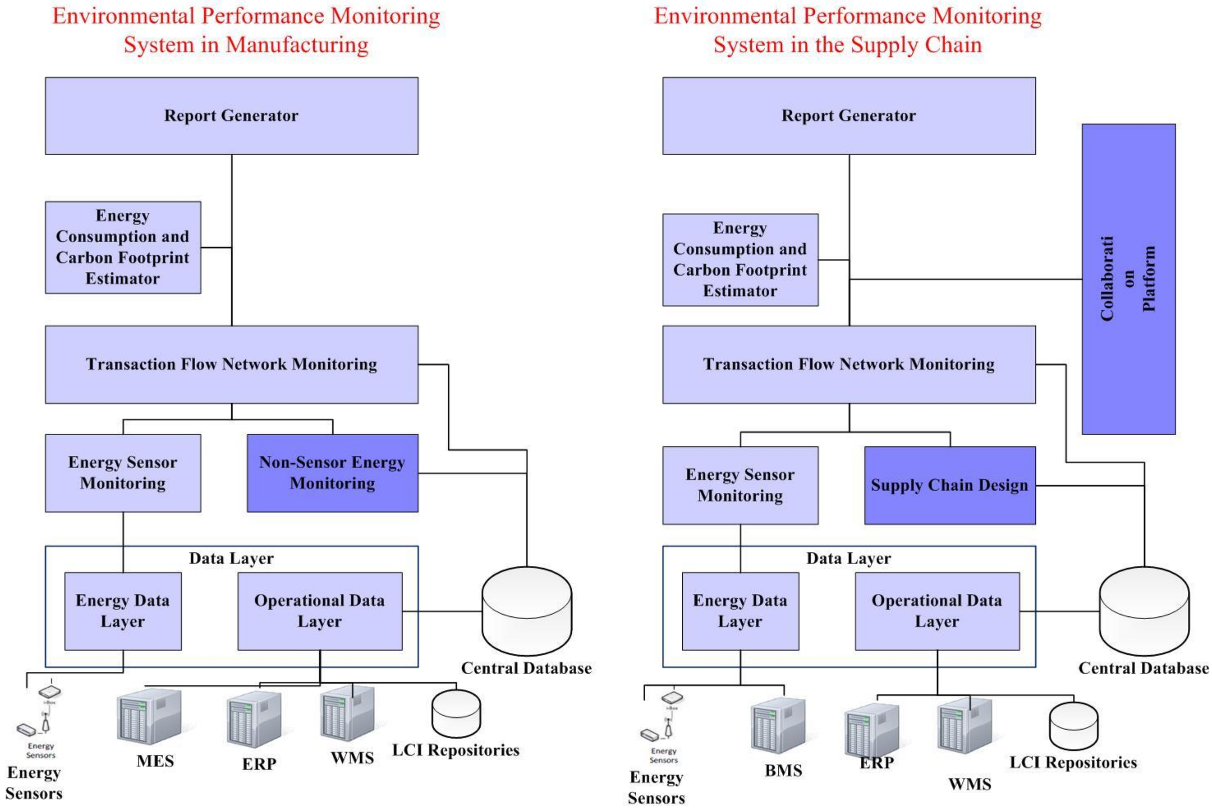

Figure 4.1.Environmental Performance Monitoring System Instantiations

5 Findings

In summary, the evaluation of the artefact during pilot testing of the system in real-world settings shows that no technical problems were encountered that could diminish the pilot user experience and reduce the overall quality of the system. Moreover, the system was perceived as user-friendly and reliable, offering easy access to information and supporting efficient monitoring of energy consumption and carbon emissions. Also, the employees that used the system endorsed the system's reliability and quick response to requests. The users further claim that the system provides information that was unavailable before and can support the reduction of carbon emissions by enforcing the decision making process. In Appendix B, we present in detail both the non-functional requirements and the evaluation outcomes.

Let us now compare the two instantiations in order to elucidate the design principles for environmental performance monitoring systems. First, we highlight the specificities of manufacturing and supply chain that drive specific design decisions. Then, we compare the two instantiations through the lens of the interoperability challenges that arise in the four cases examined; most such challenges are related with the acquisition and integration of information flows under the settings presented in Table 3.1.

As presented in Figure 5.1, the two instantiations share most of their components. Therefore, we may conclude that the high-level design principles formulated by each component remain the same in both manufacturing and supply chain cases, hence arising as sufficiently consistent across different contexts and cases. Any differentiation of these functionalities, as determined by the context settings, becomes apparent only after a more detailed consideration.

Indicatively, the operational data layer manages different kind of data in per case, thus yielding a different XML schema and data interface. Similarly, the energy and carbon allocation methodologies applied in each context is different since the allocation unit in textile manufacturing cases is one square meter of the produced article while in the two supply chain cases it is a unit of volume or weight of products distributed; calculating the indirect energy in manufacturing imposes another context-determined differentiation. As a result, the Energy and Carbon Footprint Estimator nests possibly different methodologies ensuring the reliability of the estimations, once adaptability to context specificities.

In addition, the need of handling semi-finished products and raw materials in manufacturing requires the development of a feature that maps and monitors the transformation of raw materials to semi-finished or finished products in the Transactions Flow Networking component of the manufacturing instantiation. Furthermore, measuring the environmental performance across the supply chain and also extending the scope of environmental performance monitoring outside a single firm's boundaries imposes the need for handling and designing different supply chain networks and managing the relationships with external partners. Therefore, the Supply Chain Design and Collaboration platform components are implemented for the supply chain instantiation.

Overall, the structural similarities of the two instantiations imply that the design proposed is, in the main, generic enough to cover the requirements of environmental performance monitoring, while also admitting context-driven differentiations without altering its main principles.

As described in Section 3, the two instantiations have been pilot-tested in the real settings of the four cases and the issues raised during the demonstration have been fetched back to the second round of design and development. At that point of our work, the limited (or absent) interoperability of existing infrastructures raised most of the non trivial challenges, related to limited environmental data availability, different data granularity levels, poor data quality and data inconsistencies, dependencies and coordination problems due to misaligned inputs from supply chain partners, technical integration issues and absence of automation mechanisms Therefore, the revisions of our second design round may well be attributed to several interoperability aspects.

Hence, we opt for discussing the differences in the design, as related to two main aspects of interoperability, namely technical and semantic interoperability, in relation to the four cases listed in Table 3.1.

Technical interoperability

In our study, we consider that the level of technical interoperability imposes the effort required for the integration with existing technological heterogeneous infrastructures (e.g. energy sensors, ERP, WMS) in order to receive the different information flows.

In cases A, B, and D, an energy-sensor infrastructure was implemented, as the energy consumption data were either unavailable or non-extractable from existing systems due to integration problems. Despite the fact that energy sensors measure the energy consumption every 15 seconds, keeping such detailed information was neither necessary nor performance-wise efficient. Therefore, a feature that processes and aggregates the energy consumption data at the specified time granularity level was implemented in the Energy Sensor Monitoring component. Moreover, this component should also ensure that the required energy consumption data is available for several other components. Hence, a control mechanism responsible for identifying any energy data loss (e.g. due to communication problems) was set up to send the respective notifications and allow data retrieval from the energy meters' local memory. In Case C, where a BMS was already installed, interfaces with the existing systems were developed and the data layer processed the data received through these interfaces. However, the sensitised objects in the external systems differed from the specified ones in the developed system instantiation cases (e.g. energy consumption is measured in a group of machines instead of a machine) and they should be translated in the specified granularity level. Therefore, an extra feature that translated the energy consumption data to the specified granularity level (both time and sensitised objects) should be developed in the Data Layer in the Energy Sensor Monitoring component.

Cases A and B represent a large category of companies where only secondary energy consumption data or actual data do not cover all cases and should be supplemented by secondary ones. In these two cases, energy consumption data collected through energy audit processes should be taken into account. As these data were kept in spreadsheet-like applications, a new component, the Non-Sensor Energy Monitoring, was designed for covering this. In general, this component will tackle the absence of actual sensor measurements and will be responsible for handling secondary energy data.

In the two supply chain cases where this was applicable (cases C and D), the fuel consumption data didn't cover the initial data requirements. Hence, the absence of the required fuel consumption data led us to dismiss the alternative of receiving daily data. In case C only the vehicle fuel refills were available impeding the mapping between the routes travelled and the actual fuel consumption. So, a set of parameters that specify the average fuel consumption per vehicle and per type of route were calculated based on the actual data. In case D, the actual fuel consumption was not available as the distribution processes were supported by an external third party logistics provider. Therefore, industrial average values regarding fuel consumption were used for estimating environmental impacts. Both parameters were incorporated in the Energy Consumption and Carbon Footprint Estimator. Moreover, a business logic that chose the appropriate environmental impacts estimation parameters based on the fuel consumption data availability was developed.

Regarding product environmental information that comes from external sources, such as LCI repositories, the integration is a challenging process as most of them do not give APIs. Moreover, the availability of information is limited and does not often cover the actual requirements. Therefore, the need of evaluating the trade-off between the integration effort required and the quality of information is raised. In this study's cases, the integration with LCI repositories wasn't implemented as we concluded that limited data requirements were covered and the effort of integration was relatively high.

Semantic interoperability

Even though the lack of technical interoperability raised various issues during the implementation, addressing the semantic interoperability challenges was the most critical. The level of semantic interoperability imposes the effort required in order to synchronise data/information across heterogeneous information systems (energy sensors) and different type of information flows. As the semantic interoperability challenges mainly result from the acquisition and integration of information flows, most of them were addressed by the Data Layer Component. Indicatively, we refer to aligning the data granularity levels (e.g. we have daily deliveries but we have fuel consumptions on 3-4 days period), ensuring the semantic consistency of data (e.g. in manufacturing setting the start time data field described the starting of a production process and not the starting of a production process in the machine) and tackling dependencies and coordination issues (e.g. product codes are different in the various systems).

In case C, a WMS has been recently installed. Therefore, the data were following the data specification document and no extra features needed to be implemented for ensuring the data granularity alignment. On the other hand, in case D for example, the information regarding a vehicle's specific route was not available and only the initial and final delivery points were known. Therefore, a set of assumptions regarding the sequence of delivery points or a logic for extracting this information from other data was deployed (i.e. deliveries and delivery batches from invoice and route datasets). A similar logic was also developed in case A, where the detailed batch flow in the various machines wasn't available. Moreover, in Case D, where the data were stored in internal and external systems, there was a need for translating external codes (e.g. product codes, article codes) to internal systems codes, in order to ensure the consistency of the data received and enable the integration of the various information flows. All the above features were part of the operational data layer component.

6 Concluding Remarks

Prior research has primarily considered the importance of environmental performance on addressing sustainability goals in the supply chain and has identified the significant role of information systems for enabling its monitoring. It has further anticipated a new class of information systems: the environmental performance monitoring systems. However, there are limited studies that systematically investigate the respective design of these systems. By using a design science approach, this paper contributes to bridging this gap by capturing the industrial requirements of environmental performance monitoring in the supply chain and by suggesting a set of relevant information flows (contextual, transactional, environmental, product environmental) together with a conceptual architecture encapsulating them. Following the design science paradigm, a prototype has been developed and pilot-tested in four companies in the textile and FMCG sectors. By observing the implementation process and analysing the outcomes, we have been able to elucidate our design approach and make a set of design propositions that may help both practitioners and researchers in building such a system.

This study has several limitations that in turn imply opportunities for further research. As in all case-study-based research designs, one important limitation lies in the narrow empirical basis that may well assume case-specific conditions rather than general concepts. Although our study curtails this limitation by validating the outcomes of system implementation within four different cases and with other industrial experts, the occurrence of further empirical evidence could shed further light on the design propositions.

Our study suffers also from limited impact assessment of an environmental performance monitoring system in both financial and environmental terms, which could well be the topic of future work. This work could also examine data granularity levels to investigate how different such levels influence the value of information and affect the impact of environmental performance monitoring systems. Exploring other contextual factors, such as the motives behind the use of such systems, and these factors' role in system's design, is another fruitful topic for future research.

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Appendix A - Environmental Key Performance Indicators

Indicator	**Type**	**Level of Analysis**	**Measuring Unit**
Total Energy consumption	E	Machine, Process step, Process, Production order, Facility, Department ,Article	KWh
Total Indirect Energy Consumption	E	Machine, Process step, Process, Production order, Facility, Department, Article	KWh
Total CO2e emissions	E	Machine, Process step, Process, Production order, Facility, Department, Article	kg
Total Energy Costs	O	Machine, Process step, Process, Production order, Facility, Department, Article	Euro
Number of products produced	O	Machine, Process step, Process, Production order, Facility, Article	items, pallets, tone, kg
Machine Idle Time	O	Machine, Process step, Process, Production order, Facility	mins
Makespan	O	Machine, Process step, Process, Production order, Facility	mins
Energy efficiency	I	Machine, Process step, Process, Production order, Facility, Department, Article	KWh/reference unit of the level of analysis
CO^2 efficiency	I	Machine, Process step, Process, Production order, Facility, Department, Article	Kg/reference unit of the level of analysis

Table 1. Key Performance Indicators in Manufacturing

Indicator	**Type**	**Level of Analysis**	**Measuring Unit**
Total Energy consumption	E	Store/warehouse section, Store/warehouse, Product category, Product	KWh
Total CO2e emissions	E	In all levels of analysis	kg
Average number of products stored	O	Store/warehouse section, Store/warehouse, Product Category/Product	items, pallets, tone, kg
Total number of products sold	O	Store section, Store	items, pallets, tone, kg
Total number of outbound products	O	Warehouse section, Warehouse	items, pallets, tone, kg
Area	O	Store/warehouse section, Store/warehouse	m2
Service level	O	Store/warehouse	-
Inventory rotation	O	Product Category/Product	-
Energy efficiency	I	Store/warehouse section, Store/warehouse	KWh/m2
Space_CO2e efficiency	I	Store/warehouse section, Store/warehouse	Kg CO2e/m2
Inventory_CO2e efficiency	I	Store/warehouse section,	kg CO2e / item

		Store/warehouse, Product Category/Product	stored, kg CO2e / pallet stored, kg CO2e / tone, kg CO2e / kg stored
Node_CO2e effectiveness	I	Store/warehouse section, Store/warehouse, Product Category/Product	Kg CO2e / item sold, Kg CO2e / tone sold, Kg CO2e / kg sold)

Table 1. Key Performance Indicators in Warehousing

Indicator	**Type**	**Level of Analysis**	**Measuring Unit**
Total fuel consumption	E	Vehicle, Distribution link, Route, Supply Chain Network	litre
Total CO2 emissions	E	Vehicle, Distribution link, Route, Supply Chain Network, Product category / Product	kg
Distance travelled	O	Vehicle, Distribution link, Route, Supply Chain Network	km
#Products Distributed	O	Vehicle, Distribution link, Route, Supply Chain Network	items, pallets, tone, kg
Vehicle fill rate	O	Vehicle, Distribution link, Route Supply Chain Network	-
Transport_CO2_efficiency	I	Distribution link, Route Supply Chain Network, Product category / Product	kg CO2e / itemskm, kg CO2e / palletskm, kg CO2e / tonnekm, kg CO2e / kgkm
Transport_CO2_ effectiveness	I	Distribution link, Route Supply Chain Network, Product category / Product	kg CO2e /items, kg CO2e / pallets, kg CO2e / tonne, kg CO2e / kg
CO2_effectiveness	I	Supply Chain Network, Product category / Product	

Table 3. Key Performance Indicators in Distribution

Appendix B - Non-Functional Requirements

This section presents the non-functional requirements. Table 1 shows all the non-functional requirements that were analyzed before the pilot execution, as part of the pilot preparation task. These qualities have no actual quantitative measures (e.g. metrics) to be taken into consideration, since these are mostly qualities whose fulfilment is based on the decisions made during the design phase of the integrated system and its respective components. Table 2 shows the results of the analysis made in the non-functional requirements that a quantitative measurement can be applied. These qualities were measured in two different ways: through a stress test process, when the pilot systems were live and available and through constant monitoring, using log files and proper user feedback.

Non-Functional Requirement	**No.**	**Description**	**Fulfilled?**	**Analysis/Comments**
Deployment	NFR.1	Distributed components shall be communicate with a compliant W3C architecture (e.g. Message Oriented model, Service Oriented model or Resource oriented model)	Yes	All components have been designed to communicate using RESTful web services, that fulfil the W3C constrain mentioned by NFR.3
Interoperability	NFR.2	Individual components should be able to exchange information and use the information exchanged.	Yes	All components have been designed to exchange information with at least one other component (either directly or through the common database), and to use the information exchanged.
	NFR.3	The system should inform the partners about the minimum information resources required in order to produce accurate and meaningful measures.	Yes	All components of the system have been implemented so that they provide this kind of information to the partners.
Security/Privacy	NFR.4	The system should ensure authentication, authorization and integrity to protect from unauthorized exposure of information	Yes	The users of the system are required to log in, before being able to access any of the system components and services.
	NFR.5	The system should conformed with specific European market regulations and Fair Trade Acts.	Yes	This is guaranteed by the design of the different components of the system, as these are depicted in the overall architecture.
Scalability	NFR.6	The system should be able to scale up horizontally and vertically by increasing hardware resources	Yes	All components have been designed, so that they can scale up as more hardware resources are provided to them.
	NFR.7	The system should be able to manage multiple suppliers and retailers and other roles that participates in the supply chain context (e.g. 3PL)	Yes	Both the database and the components of the system have been designed to be able to handle more than one partner (each one with a possibly different role) that participates in the supply chain context.

Table 1.Non-functional requirements measured before the pilot execution

Non-Functional Requirement	**No.**	**Description**	**Fulfilled?**	**Metric**	**Value**	**Process / Comments**
Availability	NFR.8	No downtime is expected for activities like database, upgrades and backups	Yes	Number of times system was unreachable	0	This is guaranteed by the host that provides the pilot environment. During the piloting there were no downtimes of the system
Fault Tolerance	NFR.9	The system should continue operating properly and recover without loss of data in the event of failure of individual components.	Yes	Number of times the system failed because of an error	0	This is ensured by the loosely-coupled architecture of the system. Even if a component created faulty behaviour, the rest of the system could continue functioning. No problems were encountered during the pilots
Performance	NFR.10	Every component of the system should support more than 250 of simple queries per minute	Yes	Requests per second	200+	This was measured by a custom Java application that executes 5 simple queries per second (e.g. retrieve all functional nodes), and another one that makes 200 HTTP requests per second to different components (i.e. pages) of the system.
Response Time	NFR.11	No more than 10 seconds for typical queries and 30 seconds for custom queries considering that the central database is being queried	Yes	Response Time in ms	<3 sec	This was measured by a custom Java application that executes 10 typical queries (e.g. retrieve all functional nodes) and custom queries (e.g. retrieve all products in a functional node) per second, measures the response time for each one of them, and calculates an average value. The actual database load during piloting was

						less than the stress tests conducted above.
	NFR.12	Every component of the system should periodically report to the Administrator its average and maximum response time regarding the Interfaces it controls.	Yes	Data Availability	No misses	All components are required to log their response times. All the data was recorded successfully at their appropriate log files.
Robustness	NFR.13	The system components should be able to recognize invalid data provided through an interface and response back with an informative message	Yes	Graceful handling of errors / Total number of errors	20/20	All components are required to display informative error messages. In our trials, all known error and error handling code has been tested successfully. During piloting, no unhandled errors were reported (like system crashes, stack traces etc).

Table 2.Non-functional requirements measured during the pilot execution