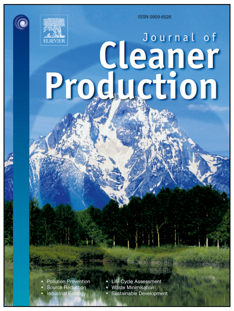

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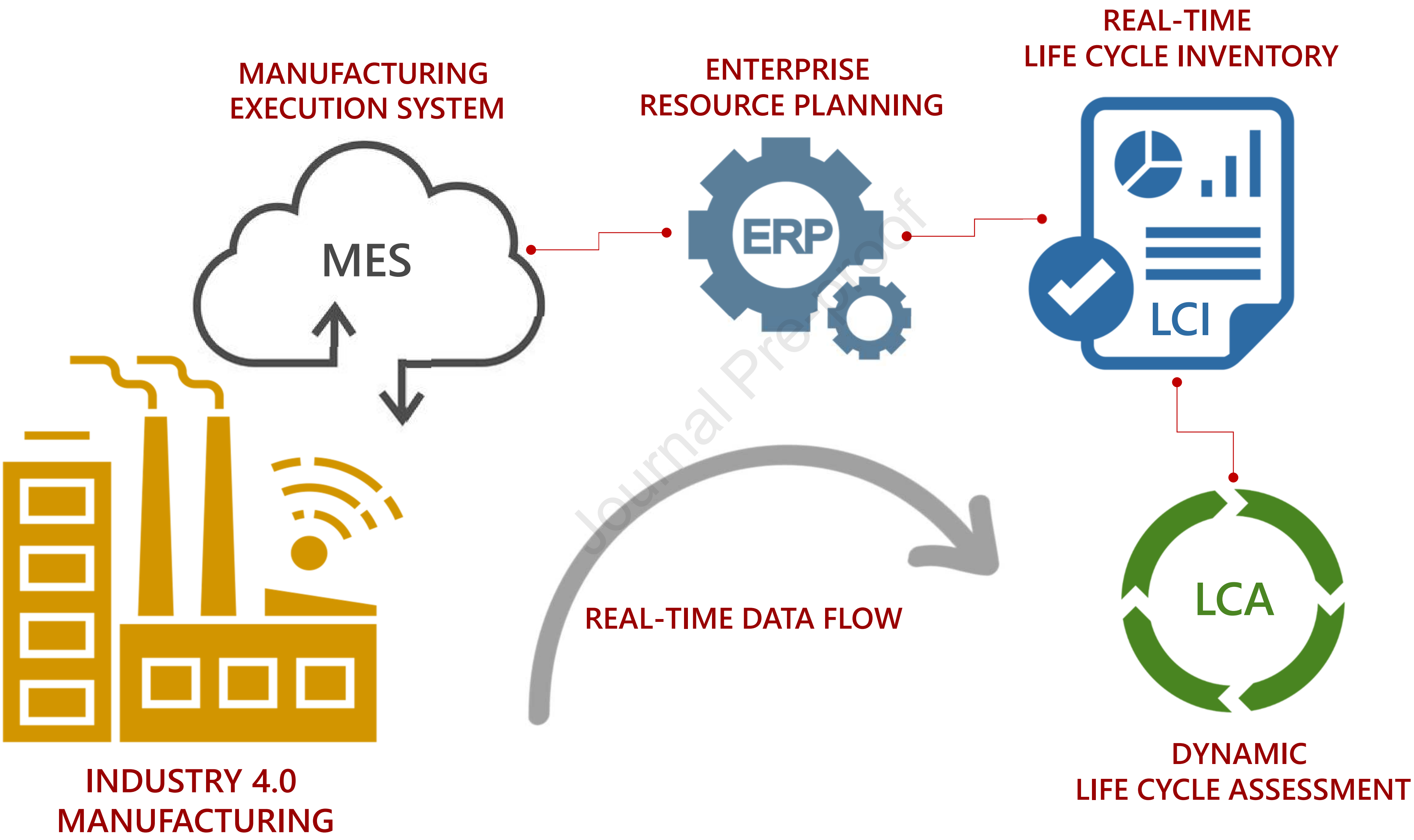
MANUFACTURING
EXECUTION SYSTEM
MES
ENTERPRISE
RESOURCE PLANNING
ERP
REAL-TIME
LIFE CYCLE INVENTORY
LCI
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LIFE CYCLE ASSESSMENT

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Highlights

- A digitized Life Cycle Inventory is proposed for Life Cycle Assessment studies.
- Industry 4.0 and IoT technologies offer real-time manufacturing environmental data.
- Enterprise Resource Planning and Business Intelligence are used for real-time LCI.
- The real-time LCI based on ERP has been integrated with a customized LCA tool.
- A Dynamic LCA based on real-time LCI, has been tested in a ceramic tile factory.
- Dynamic LCA provides real-time environmental assessment of tiles manufacturing.
- Dynamic LCA data has been successfully validated with a static commercial tool.

Abstract

With the advent of Industry 4.0, new technologies have been made available to companies in order to monitor, integrate and trace processes through integrated digital systems; thanks to a combination of sensors and control systems, manufacturing information are collected and processed so that a detailed database helpful for the monitoring and continuous improvement of the production plant can be built. The potentiality of this comprehensive data collection may be exploited also from an environmental point of view, with the aim to enhance the sustainability of processes; in fact, a large part of this data provides the basis for the Life Cycle Inventory (LCI), the most energy and time-consuming phase of the Life Cycle Assessment (LCA) which in this way could become quicker and dynamic. Based on a case study related to an Italian ceramic tile manufacturer, the aim of this paper is to describe the architecture and the application of the Dynamic LCA system that integrates the Enterprise Resource Planning (ERP) system with a customized LCA tool through a Business Intelligence (BI) software. The model was tested on different levels of validation in order to verify first the proper functioning of the IT architecture and then the environmental impact results provided, both in a static and dynamic way. The validation processes were successful, and the Dynamic LCA system has proved to be a valuable tool for the evaluation and monitoring of environmental impacts related to the production process.

Keywords: Life Cycle Assessment (LCA), Life Cycle Inventory (LCI), Enterprise Resource Planning (ERP), Industry 4.0, Business Intelligence (BI).

1 Introduction

The Life Cycle Inventory (LCI) (Islam et al. 2016) is the second of the four phases of the Life Cycle Assessment (LCA) methodology regulated by the ISO 14040 and ISO 14044 series of international technical standards (Klöpffer 2012):

1. Goal and Scope Definition,
2. Life Cycle Inventory,
3. Life Cycle Impact Assessment,
4. Life Cycle Interpretation.

The LCI consists of the identification and quantification of the input and output flows from the system under analysis throughout its life in order to establish a database of environmental loads (Ciroth et al. 2020). To this end, therefore, the consumption of resources (raw materials, water, recycled products), energy (thermal and electrical) and air, water and soil emissions are identified and quantified thus arriving at a real environmental balance sheet (Cuenca-Moyano et al. 2017). The LCI is the most delicate and challenging phase of an LCA study because it leads to the construction of an analogical model of reality that should represent, as accurately as possible, all the exchanges between the individual phases belonging to the production process (Patouillard et al. 2019). This inventory of environmental loads shall be made by collecting input and output data for each process phase within the system boundaries and determining where each phase starts and ends (Righi et al. 2018). The origin of the data can be of two types (Bhochhibhoya at al. 2017; Landi et al. 2020): primary sources (when the data are obtained directly at the production sites and associated to the related process units) and secondary sources (when the data come from databases, literature, estimates). In order to ensure the reliability of the inventory, primary sources should be used for those parts of the system concerned which are directly related to the product/service, whereas databases for the parts of the system concerned may only be used indirectly (Sanchez Moore et al. 2019). Like each phase of the LCA study, the process for conducting an LCI is iterative (Mehmeti et al. 2018). In fact, as data is collected and the system is better known, new data requirements or limitations can be identified. This may involve a change in data collection procedures so that the goals of the study are still met. Normally for an LCA study of a product manufacturing process, primary production data referring to the reference year of the study and specific to the production reality shall be used. For example: Japanese life cycle database from 1990 to 2010 (Dente et al. 2020); production data for the year 2015 (Gediga et al. 2019); time horizon of 100 years (Yoshida et al. 2018), 2012 as the study reference year (Ripa et al. 2017); 2013 as the study reference year (Comodi et al. 2016); the incoming and outgoing flows from the system have been referred to the year 2011(Buratti et al. 2015).

In the absence of primary production data, it is possible to refer to average production data or literature data. It is therefore clear that the collection of primary data in complex manufacturing processes, consisting of several phases that exchange semi-finished products even in a non-sequential way, can be a very long and difficult operation that can also lead to errors and/or force simplifications (Bailey et al. 2020; Baruffaldi et al. 2019). It can also occur when, within the same operational context, the quality of the primary data differs according to the process phases (Renteria Gamiz et al. 2019). For example, for some equipment the supplier can provide data on energy consumption in operation and in other cases not, which means that a manual measurement must be carried out. It is consequently evident the role exercised by the analyst who carries out the LCA study: he will have to discretionally decide the cut-off criteria, i.e. the principles of exclusion of inputs that are not significant for the analysed system (De Feo and Ferrara 2017; Filimonau 2016). This discretion of the analyst could influence the final result of the environmental impact assessment (Yung et al. 2018) and make the comparative purpose of environmental performance between alternative products ineffective. This comparability is one of the aims of the Environmental Product Declaration (EPD) which is based on an LCA analysis (Strazza et al. 2016).

The complexity of the LCI (Schlegl et al. 2019) is one of the factors that makes LCA studies difficult to carry out within the business because it requires specialists capable of conducting the analysis, a strong collaborative attitude of management and a factory staff able to conduct the collection of primary data in an effective manner (Linhares and Pereira 2017). This is also one of the reasons why environmental monitoring through the LCA has not spread to the quality systems of companies, especially for less structured companies such as SMEs (Heidrich and Tiwary 2013). So environmental assessment, due to the objective difficulties of data collection, is not only economically but also time consuming and therefore it is carried out only occasionally by companies, in particular when there is a need to obtain environmental certifications. It is therefore clear that the environmental assessment, unlike manufacturing performance indicators, has not yet taken on the features of systematicity and periodicity to be fully included in the quality management systems of production companies. The aspect of the frequency with which an environmental impact assessment should be carried out on a case-by-case basis is not sufficiently addressed in the scientific literature. This proves that the analyses are mainly performed to meet a specific need at a specific time, such as a research objective (in the academic field) or the achievement of an environmental certification (in the business field). Meinrenken, Anthony and Lackner (2013) stressed some key concepts when applying the LCA method to the real world:

i. The complexity of inventory analysis and data structure can discourage widespread use of LCA, not fully exploiting its benefits.
ii. This complexity also manifests itself in the difficulty of finding primary data, which is the reason the LCA offers the possibility to use secondary data from databases to arrive at approximate environmental assessment results.
iii. Within the very large amount of inventory inputs (primary and secondary) in the real world, only some of these are crucial for the environmental impact of a phase of the monitored life cycle.
iv. Over-simplified approaches to address this complexity may fail to identify important aspects of the LCA and thus produce misleading information on sustainability.
v. Thanks to Enterprise Resource Planning Systems (ERP), many companies already have most of the primary inventory data required to perform LCA.
vi. By using real data flows from ERPs, the complexity, limitations and inconsistencies of common data in LCA inventory data can be overcome.

In the scientific literature there are some seminal researches that, in a pioneering form, have foreseen a connection between ERP systems and LCA tools. Simplified LCA tools have been developed in recent years with the aim of reducing the time and resources required in LCI and LCIA phases. These tools, besides being easier to use, are more adequate to support the integration of environmental variables in the business management processes and to promote eco-labelling initiatives (Arzoumanidis et al. 2013). In contrast, the simplified LCA tools are often not able to incorporate the methodological differences between companies and industrial segments. Januschkowetz and Hendrickson (2001) experiment how the LCI of an automotive supplier's electrical product can be run using the SAP W3 ERP system. The authors demonstrate that environmental data can be integrated into ERP systems, making it easier to record and spend time on inventory analysis. In this research, the variable time related to data maintenance emerges only data, which is used regularly, will be consistently maintained and updated. The automatically performed Life Cycle Assessment (LCA) was conducted by Moon et al. (2003) for a steel company. The researchers developed an LCA software package and a database server to connect it to company database systems including ERP. The paper demonstrates that the automatic method, based on monthly on-line data calculations, is superior to manual data collection in terms of time and cost savings (man-month) and data reliability. Brooks et al. (2012) argue that organizations also need an integrated Sustainability Information System solution (Sustainability IS) to collect, integrate, automate and monitor sustainability information and therefore introduce the concept of Sustainable Enterprise Resource Planning (S-ERP). Based on Chofreh et al. (2014), S-ERP systems are a holistic solution that can help organizations to collect, process and deliver comprehensive sustainability data, integrating all sustainability information and processes across business functions. The authors themselves describe S-ERPs as systems that are still under development. In line with this conclusion are De Soete et al. (2014) who, through a study of a pharmaceutical synthesis, have highlighted the possibility of simplifying the LCA by using primary data that are normally sent to the PLCs (Programmable Logic Controllers) through process equipment control sensors. However, these data collected in production lines and important for environmental sustainability measures, seem to be of little value for existing ERP applications. To solve this limitation De Soete (2016) proposes to build a custom ERP application for LCA in order to match primary process data with Life Cycle Inventory databases and life cycle impact assessment tools. With a view to customizing the ERP, Hasan et al. (2017) identify a set of 63 sustainability performance indicators, 12 of which are related to environmental performance, to be integrated into the ERP system to make the most of its informational potential. A framework for the operational implementation of an S-ERP system is proposed by Chofreh et al. (2018). It provides a holistic perspective to guide decision makers towards sustainable organisations and integrated organisations in a sustainable way.

Nowadays in the manufacturing context the low frequency of LCA analysis is a paradox because with the advent of the so-called Fourth Industrial Revolution or Industry 4.0 (Frank et al. 2019), multiple tools have been made available, also for SMEs (Dassisti et al. 2019), to monitor Key Performance Indicators (KPIs) of the manufacturing phases (Perini et al. 2017), including those to collect data on material flows and energy and water consumption (Jena et al. 2020). Usually the digitization of manufacturing companies takes place through the implementation of a MES (Manufacturing Execution System) (Yue et al. 2019), a software that, interfacing with planning systems (ERP) (Borangiu et al. 2019) and control systems (PLC) (Chen et al. 2017), collects and processes strategic information to help management to control and improve the production of a plant. Factory 4.0 is a digitized system capable of collecting and processing all the information coming from the machinery at every stage of the process, generating useful knowledge that allows decisions to be made (Chofreh et al. 2020). Thanks to these digital systems, it is possible to have a real-time monitoring of the factory, with a better integration of data and processes as well as the exchange of live information between the organizational level of the company and the organizational level of manufacturing (Morgan and O'Donnell 2018). With the digital transformation of Industry 4.0, innovation has been driven by technology, the next step pioneered by Rauch (2020), will be that of innovation driven by data and artificial intelligence to give rise to a so-called Industry 4.0+. Thanks to the integration of Business Intelligence with the most innovative Artificial Intelligence technologies, the processing, analysis and use of data collected in real time becomes an even faster and more effective process for manufacturing companies (Soni et al., 2020).

Therefore, some critical issues emerge:

1. impossibility to use the life cycle assessment tools (LCA) for rapid corrective actions on the process and the product, because the impact assessments are based on data from historical series, therefore with impact already occurred;
2. difficulties in collecting and processing data to carry out impact assessments using traditional techniques;
3. the need for specialized personnel for the use of commercial software for environmental impact assessment.

Starting from these premises, this paper intends to address the following research questions (RQs):

1. RQ1: *Can IoT technologies and manufacturing models from Industry 4.0, facilitate LCI for LCA studies*?
2. RQ2: *Is it possible to dynamize LCA analysis by exploiting the potential of production data collected by ERP*?
3. RQ3: *Can digital manufacturing technologies enable real-time LCA analysis*?

The rest of the paper is organized as follows. Section 2 outlines the framework of research approach followed in study. Section 3 describes the methodology and the results of the static Life Cycle Assessment. Section 3 illustrates the construction of the digital system to make the LCA dynamic, showing the results achieved. Section 4 concludes by summarising and discussing the contribution of this study and its implications.

2 Research framework

This study aims to answer previous research questions by developing an environmental assessment framework that leverages Industry 4.0's digital technologies to automate inventory analysis. Thanks to the digitization of the LCI, the LCA analysis can be carried out in real time and no longer based on historical data alone.

2.1 Case study

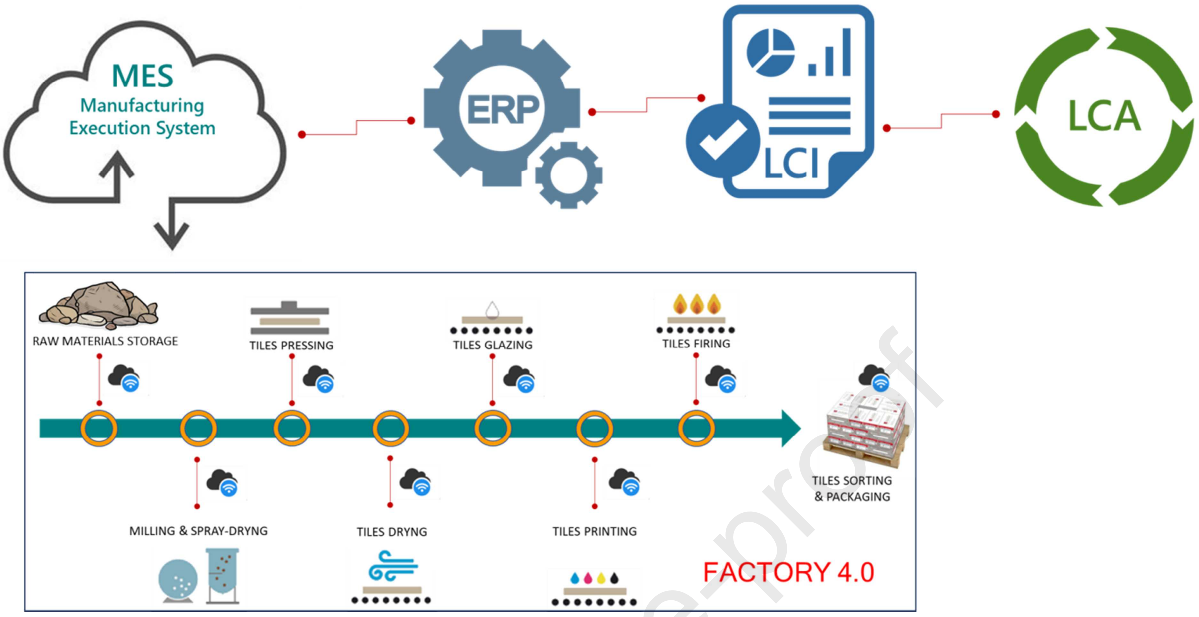
The development of the automated environmental assessment framework (or Dynamic LCA system) was carried out within the Italian ceramic industry, a sector organised in the form of an industrial district located in the Emilia Romagna Region across the provinces of Modena and Reggio Emilia, that produces ceramic tiles for the building industry. It is internationally known as the Sassuolo district, taking the name of the town from which, it developed from the second half of the 20th century (Settembre-Blundo et al. 2019). Today, the Sassuolo district has more than 90 companies that employ more than 19 thousand people and produces 416 million square meters of tiles, equal to 81% of national production (Confindustria Ceramica 2019). This sector has distinguished itself in recent years for the large investments that the companies in the district have made to adopt digital technologies and robotics, transforming a low-tech industry into a concentrate of mechatronics (Garcia-Muiña et al. 2018). Environmental sustainability represents another of the distinctive features of the Italian ceramic industry, which differentiates it from its international competitors (Ferrari et al. 2019). There are many initiatives undertaken over the years at the district level. In addition to certification activities and sustainability policies developed by individual companies, collective projects and initiatives have been implemented. Since 2012 the Emilia Romagna Region has signed an agreement with the association of ceramic tile manufacturers (Confindustria Ceramica) for the processing of environmentally relevant data, which is still in force today. The agreement commits the Region to transmit data on environmental parameters and emissions in its possession each year; Confindustria Ceramica reworks them and produces the sector's Environmental Report on the performance of its member companies (Bonvicini et al. 2018). The availability of data resulting from this agreement also made it possible to prepare the Environmental Product Declaration (EPD) for the Italian ceramic industry sector (Confindustria Ceramica 2016). Due to the high number of companies involved, this sector EPD, is an example of best practice worldwide in the construction industry.

In order to carry out the experimental part of the research, a company was selected as a case study in the Sassuolo district, which is among the Top 10 of Italian ceramic producers and among the Top 5 for economic performance. The company also has fully digitized factories according to Industry 4.0 criteria, and since 2012 has started the systematic implementation of an ERP that now governs all operational processes in an integrated and modular way. Thanks to the ERP, it was also possible to create a single central database without duplication and redundancy of data, for the efficient traceability of documents and transactions. In order to estimate the digital maturity level of the chosen company as a case study, the IMPULS (2015) assessment tool, developed by the foundation of the VDMA (German Engineering Association) and conducted by IW Consulting (a subsidiary of the Cologne Institute for Economic Research) and the Department of Industrial Management of the University of Aachen, was used. The tool allows to analyze the manufacturing company on six dimensions (strategy and organization, smart factory, smart operations, smart products, data driven services, employees), each of which is assigned a score calculated through a maturity index. The final score is the weighted average of the values obtained for the six factors, then the tool assigns the result to one of six possible levels: 0. Outsider, 1. Beginner, 2. Intermediate, 3. Experienced, 4. Expert, 5. Top Performer. The assessment placed the company, selected as a case study, at level 5 Top Performer, thus justifying the choice for the validation of the digital LCA framework.

2.2 Ontological model

The design of the Dynamic LCA system started from the construction of an ontological model (Muñoz et al. 2013) able to abstract and conceptually organize the knowledge in the field of environmental assessment and production management, combining procedures and concepts already known and already available, in a new operational combination to be verified and validated. The first element of the ontological model is the Conceptual Pattern shown in Figure 1. At the base of this scheme is the "*Factory*" unit. The ceramic process consists of a set of sub-processes and phases, even independent of each other, which, starting from the raw materials, create semi-finished products that will be reworked in the following phases (Morales et al. 2017). The process starts with the storage of raw materials coming directly from the mines (clays, feldspars and sand), which are mixed in a batch and sent to a mill for grinding in water. At the end of the operation a solid (66 wt%) - liquid (33 wt%) suspension called ceramic body slurry is obtained. Special pumps take the slip and put it in the spray drier where the high pressure nebulizes the ceramic body, while in countercurrent a jet of hot air is injected that makes the grinding water evaporate producing a fine and homogeneous powder, ready to be pressed. The pressing of the spray-dried body powders takes place with hydraulic presses at a pressure of 450-500 kg/cm^2. This operation gives the product the desired shape and the right compactness and resistance.

Figure 1 Conceptual Pattern of the Dynamic LCA system (Source: our elaboration on the ceramic process scheme proposed by Morales et al., 2017)



Subsequently, using rapid hot air dryers, residual humidity is removed from the ceramic body to prepare the manufactured product for the subsequent phases of glazing and decoration through digital printing of the inks. Tiles are fired in continuous roller kilns, where high temperatures are reached (from 1200°C to 1230°C). Along the path inside the kiln (which can reach a length of 100-120 m) the tiles are first heated up to the maximum firing temperature and, after a specified stay at this temperature, are progressively cooled down. During firing the product undergoes reactions and chemical-physical transformations necessary to obtain a mechanically resistant structure. The last stage of the production process is the sorting and packaging, which has three objectives: the elimination of defective parts, the division into first and second quality and the grouping into homogeneous lots by tone.

The combination of traditional production technologies, such as those described above, with innovative ones such as sensors and tools for monitoring and analyzing production data, can turn the plant into a smart factory (Garcia-Muiña et al. 2018). Intelligent and interconnected sensors and PLCs, inserted in the production lines, collect data that are potentially useful not only for production control but also for LCI. However, this data can be transformed into knowledge through an MES system that improves data and provides useful information to make the right decisions at the right time. With a view to implementing the LCI, MES software is an essential tool because it represents the convergence point for various data sources, as it can be directly connected to production equipment and can also record information entered manually by the operators. Furthermore, in order to fulfil their mission, MES systems must integrate with the company's ERP, thus acting as a communication link between the decision-making and production levels. Thanks to this link, the ERP can become the most effective tool to accurately and quickly perform the LCI preparatory to LCA. This 4.0 factory architecture for dynamic data collection, combined with the LCA tool, properly customized for the specific industrial system, forms the Dynamic LCA system.

From a methodological point of view, the approach proposed by Lemke and Łatuszyńska (2013) for the verification and validation of a modeling process was followed. On this basis, an ontological model has been drawn, as represented in Figure 2. It is a formal representation of the conceptualization of a domain of information that is reusable and shareable in other realities. The proposed ontological model consists of the following elements:

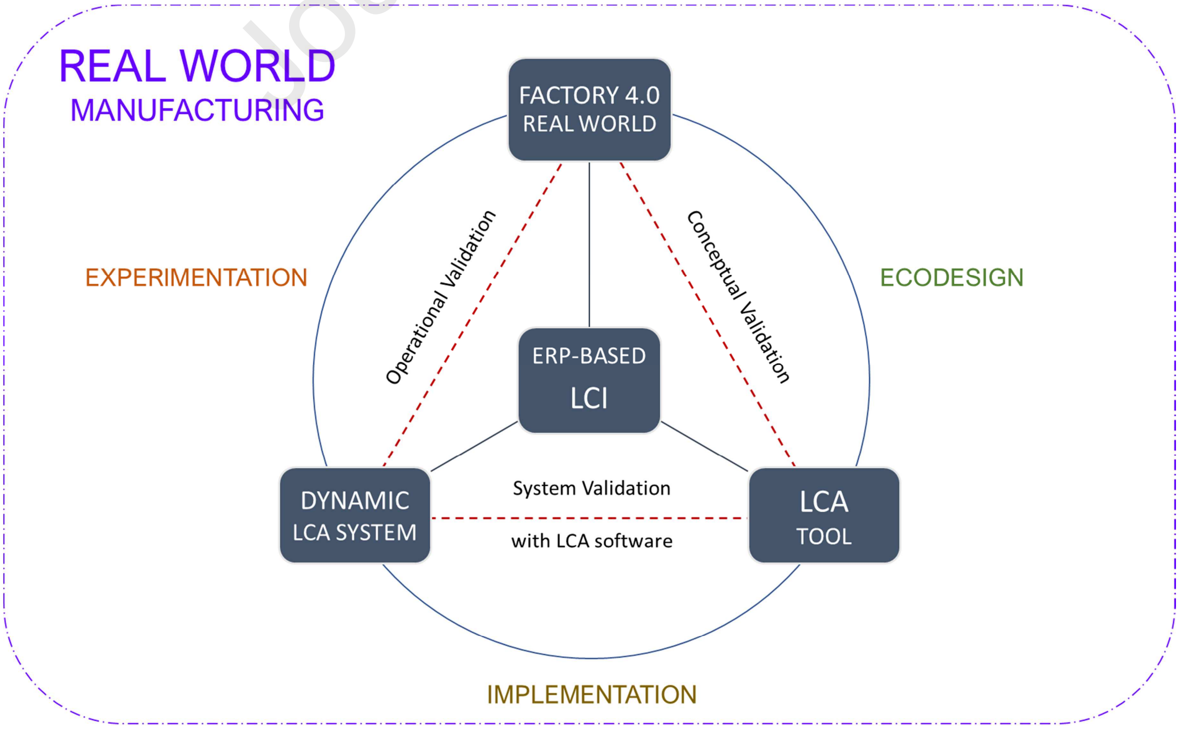
- *reference domain*: real world of manufacturing;

- *concepts*: elements that have the similar properties [LCA tool, Dynamic LCA system, ERP-Based LCI and Factory 4.0 as Real World];
- *hierarchy between concepts*: with top-down approach from general to particular [(1) LCA tool, (2) Dynamic LCA system, (3) ERP-Based LCI, (4) Factory 4.0 as Real World];
- *relations between concepts*: conceptual validation, eco-design, system validation, experimentation, operational validation, implementation.

The purpose of the ontological model is to lay the logical basis to dynamize LCI operations, and the four elements described above will serve, from an operational point of view, to integrate ERP and LCA in order to automate the collection of quantitative data.

Following the Ontological Model in Figure 2, both the Conceptual Pattern shown in Figure 1 and the Dynamic LCA system realized in an operational environment have been validated by comparison with the results obtained from SimaPro software and throughout a triple validation (conceptual, system and operational), described in detail in Section 4. The LCA tool is the basis for the operational development of the Dynamic LCA system, both of which are based on the LCI developed from the data available in the ERP. The LCA Tool was built by designing a custom calculation code for the specific process, based on a spreadsheet. For the customization of the LCA spreadsheet, the starting point were the results of a detailed LCA study reported in Section 3.1, traditionally conducted through the SimaPro 8.5.2.2 software (PRé, 2020). For the design of the Dynamic LCA system, the first step was the triple validation: one conceptual (on the right in the triangle of Figure 2) one related to the system (at the basis of the triangle) and the other operational (on the left in the triangle), to answer the question whether the ontological model as a whole adequately represents the real world of the factory and whether it is able to provide robust and reliable impact assessment results. In particular, the conceptual validation was carried out using the model as an eco-design tool to study three different production scenarios in which the raw material supply system was changed, in order to verify its predictive capabilities. The system validation was conducted to demonstrate the validity of the Dynamic LCA system in terms of both proper functioning of the IT architecture and accuracy of the results, in accordance with those obtained with the LCA commercial software; the operational validation was carried out to effectively ensure the dynamic response of the system in a real-time monitoring.

Figure 2 Ontological Model for Dynamic LCA system (Source: our elaboration on the verification and validation scheme proposed by Lemke and Łatuszyńska 2013)



3 Methodology

The Life Cycle Assessment at the basis of the present study has been conducted according to the ISO 14040 and ISO 14044 standards, adopting a cradle to grave approach; the case study and the results are described in the following section.

3.1 Detailed LCA study

In order to establish how to dynamize the inventory analysis by integrating it into the company ERP, a detailed LCA study was conducted adopting the current approach of using historical data, i.e. when the environmental damage has already occurred. This retrospective approach has already been used in many LCA case studies in the most recent scientific literature. Buyle et al. (2019) assume that trends in historical data are representative of future situations; other authors have used data collected in laboratory-scale (Delgove et al. 2019); Buyle et al. (2018) used data provided by other studies; Milovanoff et al. (2018) assessed the environmental performance over a period of time (2012-2014); Nemecek et al. (2016) and Askham (2011) based their studies on retrospective data.

The objective of this study was to assess the environmental impacts of the company's production of glazed porcelain stoneware tiles (Ferrari et al. 2019) in the 2017 reference year. The functional unit was the annual production of tiles and the boundaries of the system cover the entire life cycle, from the extraction of raw materials to the end of life. The production cycle was analyzed and divided into its specific phases in order to better identify and describe each manufacturing step; the process diagram used as a basis for manual data collection in the production departments, is shown in Figure 3. Subsequently, a comprehensive mass balance was performed to quantify all inputs and outputs in terms of material and energy for each manufacturing phase. Most of the data used are primary data; in particular, data related to the quantity of tiles produced, the mass of the ceramic body, water and energy consumption, emissions and waste were provided by the company. In the absence of primary data, they were estimated or taken from literature. The Ecoinvent 3.4 database (Wernet et al. 2016) was taken as reference especially for background processes referred to raw materials, transports, energies; the processes not included in the database were created ad hoc, such as end-of-life processes or machineries (Steubing et al. 2016). Some of the most relevant life cycle inventory data related to the analyzed system and referred to 1 m^2 of porcelain stoneware tile. are reported in Table 1.

Figure 3 Flow chart related to the life cycle of the tiles

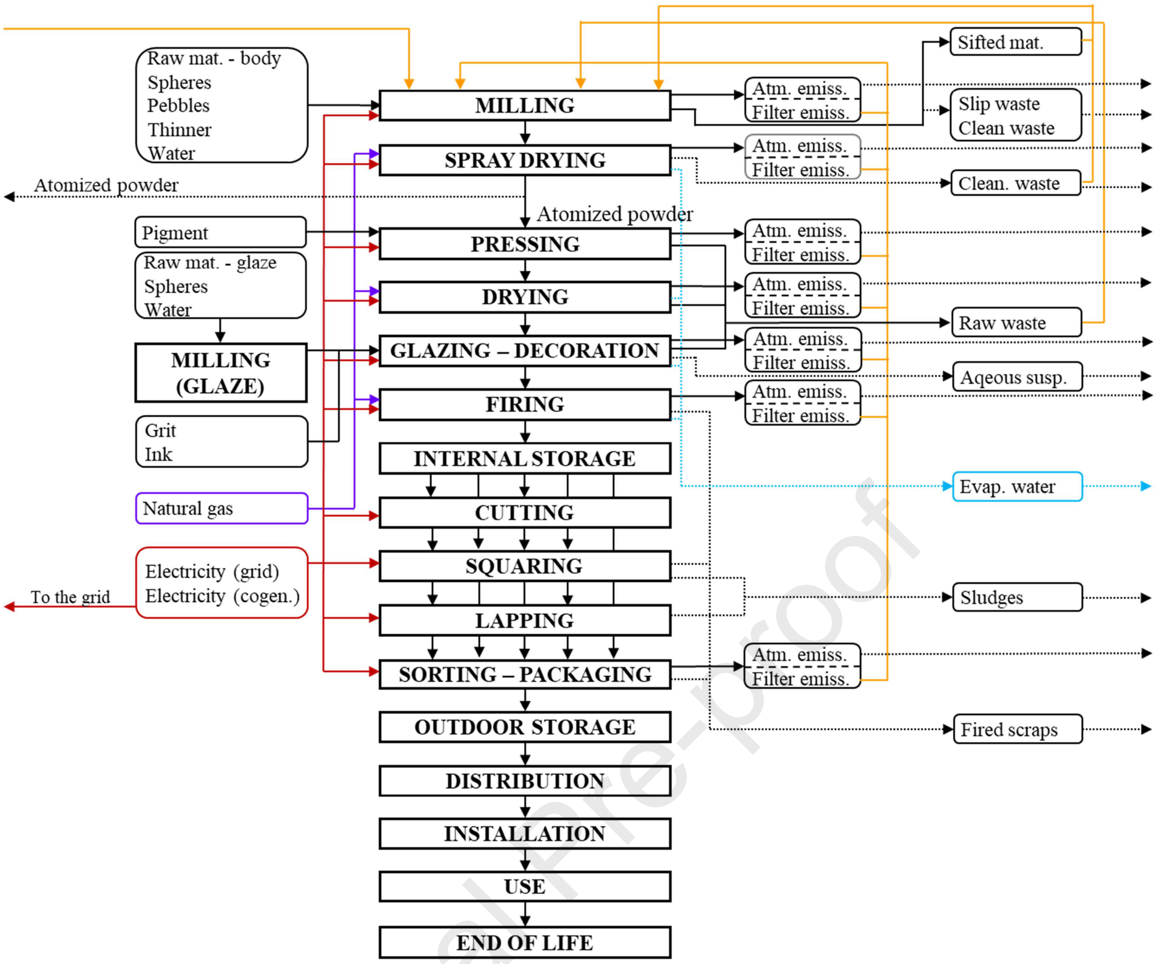


Table 1 Inventory data related to the production of 1m^2 of glazed porcelain stoneware tiles

CATEGORY	COMPONENT	VALUE	UNIT
Materials I/O (slip)	Extra-EU Clay	18-30	%
	Extra-EU Na-feldspar	20-35	%
	EU Clay	5-15	%
	National K-feldspar	5-10	%
	National Sand	5-10	%
	Water	20-30	%
	Fluidizer	0-2	%
	TOTAL	*100*	*%*
Materials I/O (glazing and decoration)	Glaze and engobe	45-55	%
	Grit	0.5-1.5	%
	Ink	0.5-1.5	%
	Water	45-55	%
	TOTAL	*100*	*%*
Energies	Electricity from grid	2.04	%
	Electricity from cogeneration	11.61	%
	Thermal energy	86.35	%
	TOTAL	*100*	*%*
Atmospheric emissions	Particulates	68.52	%
	Lead	0.07	%
	Fluorine	1.13	%
	Volatile Organic Compounds	3.80	%

	Aldehydes	3.33	%
	Nitrogen oxides	16.04	%
	Carbon oxides	7.12	%
	TOTAL	*100*	*%*
Transports	Extra-EU Clay (road+sea)	40.13	tkm/m^2
	Extra-EU Na-feldspar (road+sea)	38.21	tkm/m^2
	EU Clay (road+rail)	4.045	tkm/m^2
	National K-feldspar (road+sea)	1.437	tkm/m^2
	National Sand (road+sea)	3.852	tkm/m^2
Ceramic waste/scraps	Raw waste reused (from internal proc.)	0.59	% on raw mat.
	Raw waste reused (from external proc.)	0.93	
	Fired scraps	0.78	

The entire process was modelled by using SimaPro 8.5.2.2 (PRé, 2020); the system is based on the "*Allocation at the point of substitution (APOS)*" model that follows the attributional approach in which burdens are attributed proportionally to the specific processes (Saade et al. 2019). The assessment method used for the environmental analysis is IMPACT 2002+ (Jolliet et al. 2003); this method proposes two different approaches for the environmental assessment that look at different stages along the cause-effect chain. The mid-point approach considers the impacts earlier in the cause-effect in terms of impact categories while the end-point approach refers to the final effects in terms of damage categories such as Human Health, Ecosystem Quality, Climate Change and Resources. In addition, it is possible to express the results with a single aggregated score, useful especially for the comparison. In order to make the method more comprehensive and representative of the studied system, it has been modified by the research group, by adding for example further categories that take into account the impact of indoor and local emissions (Pini et al. 2014).

The results of the LCA analysis related to 1 m^2 of glazed porcelain stoneware tile are reported in Table 2 in terms of Single Score, both for each process step and in aggregate form by identifying three macrophases: sourcing, manufacturing, distribution-installation-use-end of life, in a cradle-to-grave life cycle perspective. It should be noted that the negative value related to "Δ energy" is due to the fact that, in a first analysis, the electricity consumption has been overestimated by considering the rated power of the machineries; this negative value corrects the electricity consumption according to the IPPC (Integrated Pollution Prevention and Control). The results of the Single Score analysis highlight that the total damage is 5.56×10^{-3} Pt for 1 m^2 of glazed porcelain stoneware tile. In particular:

- the sourcing of raw materials for the ceramic body is the most impactful phase (25.5 %) followed by installation (14.8%), tiles distribution (13.4%), firing (12.3%), use (8.4%) and spray-drying (5.9%). The other processes account for less than 5%;
- the most relevant contribution in terms of damage category is due to Human Health (34.5%), especially for nitrogen oxides emitted in air during the transport by barge of the raw materials for the ceramic body. Resources damage category is in second place (30.9%) mainly due to the consumption of natural gas during firing, followed by Climate Change damage category (25.4%) especially for the carbon dioxide emissions in air caused by the transport by barge of the raw materials. For Ecosystem Quality (7.16%), the emissions due to transports for the distribution of the tiles are mainly responsible for the damage while for both Human Health Local (2.15%) and Indoor (<1%) categories, the emissions of aromatic hydrocarbons during firing (respectively at a local and indoor scale) mostly contribute to the damage.

It can be concluded that the supply of the raw materials for the ceramic body is responsible for the main impacts, due to both distances and means of transport; therefore, in order to reduce the environmental burdens, a careful selection of the raw materials and a promotion of the use of local ones can play a very important role. Moreover, among the manufacturing processes within the gates of the company, the firing and spray-drying are the most harmful stages. Single Score results are displayed in Figure 4. The results obtained are representative of the company's reference production of glazed porcelain stoneware tiles and form the basis for the development of the customised LCA tool.

Table 2 Single Score results related to the life cycle of 1 m^2 of porcelain stoneware tiles

SOURCING

Stages	Human Health [Pt]	Ecosystem Quality [Pt]	Climate Change [Pt]	Resources [Pt]	Human Health Indoor [Pt]	Human Health Local [Pt]	Total Damage [Pt]
Body raw materials	6.32E-04	9.49E-05	3.45E-04	3.44E-04	8.14E-14	5.08E-07	1.42E-03
Glazes raw materials	1.03E-04	1.41E-05	5.47E-05	5.64E-05	-	-	2.29E-04
Total Sourcing	7.36E-04	1.09E-04	4.00E-04	4.01E-04	8.14E-14	5.08E-07	1.65E-03

MANUFACTURING

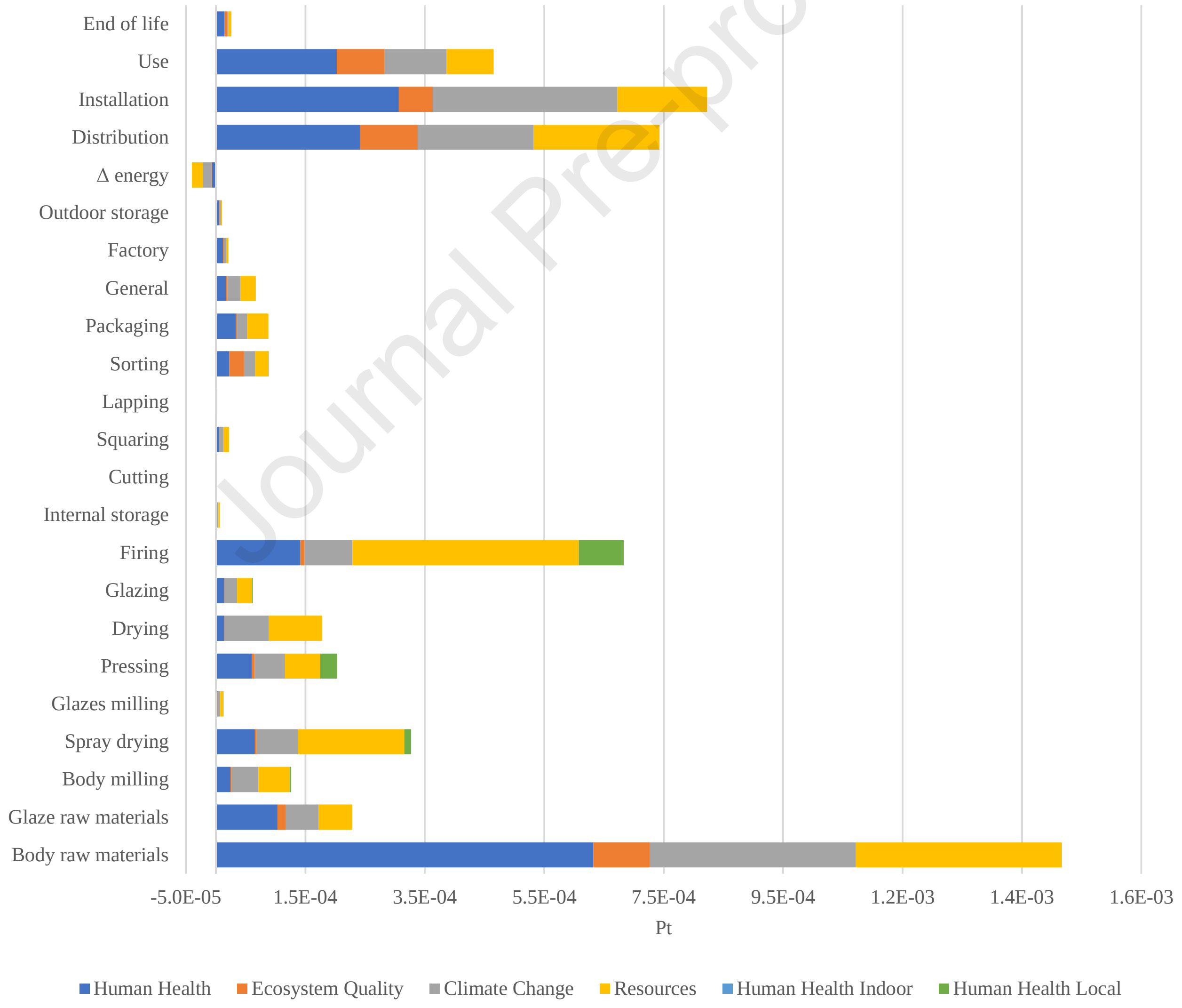
Stages	Human Health [Pt]	Ecosystem Quality [Pt]	Climate Change [Pt]	Resources [Pt]	Human Health Indoor [Pt]	Human Health Local [Pt]	Total Damage [Pt]
Body milling	2.47E-05	1.97E-06	4.49E-05	5.24E-05	3.02E-13	1.88E-06	1.26E-04
Spray-drying	6.52E-05	3.35E-06	6.89E-05	1.78E-04	1.91E-12	1.19E-05	3.27E-04
Glazes milling	2.74E-06	2.51E-07	4.38E-06	5.17E-06	1.09E-13	6.83E-07	1.32E-05
Tiles pressing	6.05E-05	4.43E-06	5.08E-05	5.91E-05	4.55E-12	2.84E-05	2.03E-04
Tiles drying	1.42E-05	9.04E-07	7.34E-05	8.93E-05	-	-	1.78E-04
Tiles glazing	1.38E-05	1.23E-06	2.08E-05	2.45E-05	2.17E-13	1.35E-06	6.18E-05
Tiles firing	1.41E-04	7.01E-06	8.04E-05	3.79E-04	1.20E-11	7.48E-05	6.83E-04
Internal storage	1.83E-06	1.80E-07	2.34E-06	2.71E-06	-	-	7.06E-06
Tiles cutting	1.97E-07	1.97E-08	2.04E-07	2.36E-07	-	-	6.56E-07
Tiles squaring	4.78E-06	5.46E-07	7.80E-06	9.17E-06	-	-	2.23E-05
Tiles lapping	3.69E-07	4.19E-08	7.33E-07	8.66E-07	-	-	2.01E-06
Tiles sorting	2.28E-05	2.48E-05	1.83E-05	2.22E-05	1.07E-15	1.34E-08	8.81E-05
Tiles packaging	3.38E-05	1.76E-06	1.70E-05	3.57E-05	-	-	8.83E-05
General	1.72E-05	2.55E-06	2.15E-05	2.57E-05	-	-	6.70E-05
Factory (building and land)	1.18E-05	1.84E-06	4.36E-06	3.33E-06	-	-	2.13E-05
Outdoor storage	6.02E-06	2.73E-07	2.06E-06	2.08E-06	-	-	1.04E-05
Δ energy	-5.92E-06	-5.61E-07	-1.53E-05	-1.82E-05	-	-	-4.00E-05
Total Manufacturing	4.16E-04	5.06E-05	4.03E-04	8.71E-04	1.91E-11	1.19E-04	1.86E-03

DISTRIBUTION, INSTALLATION, USE AND END OF LIFE

Stages	Human Health [Pt]	Ecosystem Quality [Pt]	Climate Change [Pt]	Resources [Pt]	Human Health Indoor [Pt]	Human Health Local [Pt]	Total Damage [Pt]

Tiles distribution	2.42E-04	9.60E-05	1.94E-04	2.11E-04	-	-	7.43E-04
Tiles installation	3.06E-04	5.72E-05	3.09E-04	1.50E-04	-	-	8.23E-04
Tiles use	2.02E-04	8.02E-05	1.04E-04	7.92E-05	-	-	4.65E-04
End of life	1.44E-05	5.22E-06	1.62E-06	5.17E-06	-	-	2.64E-05
Total Distribution. installation. use and end of life	7.65E-04	2.39E-04	6.08E-04	4.46E-04	-	-	2.06E-03
TOTAL	**1.92E-03**	**3.98E-04**	**1.41E-03**	**1.72E-03**	**1.92E-11**	**1.20E-04**	**5.56E-03**

Figure 4 Single Score results related to the life cycle of 1 m^2 of porcelain stoneware tiles



3.2 Design of a customized LCA tool

The starting point for the design of a customized LCA tool was a detailed analysis and selection of the most relevant process variables conducted thanks to a mutual collaboration between the company and LCA practitioners. First of all, following the same structure shown in Figure 3, a spreadsheet was developed, maintaining the separation between each life cycle phase in order to both facilitate the selection of the most relevant variables for every stage and keep the highest level of detail. The selection of the variables is the most complex but also interesting step of the process and different aspects should be kept in mind when deciding how many and which variables to consider. In fact, while the number and the type of variables should be such that the company can effectively collect and measure them all to make the spreadsheet applicable and useful, a wider range of variables can provide more scenarios with a higher level of detail. Therefore, it is important to strike a balance between the accuracy of the study and the usability of the tool, without losing information. In addition, it should be noted that, if the spreadsheet is designed with the highest level of detail achievable, it is possible at a later stage to decide to aggregate some variables or to fix them, if it is not interesting to modify them. The initial high level of detail allows for subsequent simplifications. Once the variables were selected, the system modelled within the software was reported in an Excel spreadsheet so that the environmental results obtainable from this tool depend on the value of the variables; if the value of a variable changes with respect to the original one considered in the software assessment (i.e. the amount of a raw material), the relative damage changes proportionally, according to the following equation:

$$Damage_{var_1^{S1}} = \frac{Damage_{var_1^{S0}}}{Value_{var_1^{S0}}} * Value_{var_1^{S1}}$$

where:

$Damage_{var_1^{S1}}$: environmental damage related to variable 1 in the modified scenario (S1);

$Damage_{var_1^{S0}}$: environmental damage related to variable 1 in the original scenario (S0);

$Value_{var_1^{S0}}$: value related to variable 1 in the original scenario (S0);

$Value_{var_1^{S1}}$: value related to variable 1 in the modified scenario (S1).

The LCA spreadsheet provides the environmental results both in terms of damage categories and of single score to allow a better comparison of processes. It should be pointed out that the development of a spreadsheet requires deep expertise in the field of life cycle assessment and the involvement of LCA experts for its design and customization. Moreover, the assistance of LCA practitioners is of paramount importance for ensuring a proper use of the tool by the company and indispensable especially in case of some changes in the process, such as the implementation of new production technologies or materials that cannot be foreseen during the design phase. With this customized LCA tool, starting from a static assessment performed with the software, it is possible to conduct LCA analyses by modifying, for example, the variables of interest from the perspective of an eco-design approach; furthermore, if the variables are constantly collected during the manufacturing activities, this LCA tool is also useful to dynamically monitor the sustainability aspects of production.

3.3 Design of an ERP-based LCI module

The customized LCA tool collects all the selected variables referred to the inventory analysis of the analyzed system modifiable according to the parameters on which the environmental assessment is based. The aim is to automate LCI through digital technologies, using the company's ERP as a primary raw data source. To support the transition to the Industry 4.0 paradigm (Bytniewski et al. 2020), the company decided to replace its old management system (AS400) with an ERP integrated information system (SAP). AS/400 launched in 1988 by IBM was an integrated system consisting of a hardware (AS/400), an operating system (OS/400) and equipped with many basic functions including a database. A traditional management software is used to manage and collect information from a suite of business applications (accounting, production, sales, salaries) in stand-alone configuration (Pati and Veluri, 2017). An ERP is instead a component of the management software that aims to integrate organizational and information flows. The applications, therefore, share the same technical architecture and especially the same database and data definitions. Information in a single place and format means that organizations no longer need to collect data from multiple systems and to translate them into a single format and meaning (Costa et al. 2016). This integrated application architecture and the sharing of the same database is of fundamental importance for a more effective use of IoT technologies and for the implementation of Industry 4.0 models in manufacturing realities thanks to the bi-directional dialogue between machine and production management activated (Rojko 2017).

The ERP database therefore contains most of the primary raw data to carry out the LCI and LCA. The system performs the analysis of business costs based on both analytical and industrial accounting referring to the logic of cost centers (Koupaei et al. 2016). Each cost is classified within a specific company area, which in the factory usually corresponds to a production department. In the specific case the cost centers representing the main stages of the ceramic process, are:

Raw materials (1); Plant general (2); Body milling and spray drying preparation (3); Glazes preparation (4); Pressing, drying, glazing and decoration (5); Firing (6); Cutting, squaring and lapping (7); Quality check and packing (8); AGVs and Parking (9).

The next step was the integration of the customized LCA tool based on the process illustrated in Figure 3, with the logical structure of the cost centers on which the ERP database is based. The integration scheme, represented in Table 3, indicates that there is no exact one-to-one correspondence between the elementary manufacturing units that were used for the LCI, and the ERP cost centers. In some cases, an aggregation (units 1, 2, 3, 5, 7, 8 and 9) is required when switching to the cost center logic. It is possible to conclude that the transition from the current retrospective way of realizing the LCI to the dynamic and digitized one must apply a criterion to group and reduce the elementary units for data collection, from 19 to 9.

In addition, some of the data available on the ERP and used for the LCI are listed in Table 4, in terms of data categories.

Table 3 Data categories available on the ERP and LCI elementary units

N°	ERP COST CENTERS	LCI ELEMENTARY UNITS
1	Raw materials	Raw materials - ceramic body
		Raw materials - glaze
2	Plant general	General
		Factory
		Δ energy
3	Body milling + Spray drying preparation	Body milling
		Spray drying
4	Glazes preparation	Glaze milling
5	Pressing + Drying + Glazing + Decoration	Pressing
		Drying
		Glazing (including decoration)
6	Firing	Firing
7	Cutting + Squaring + Lapping	Cutting
		Squaring
		Lapping
8	Quality check + Packing	Sorting
		Packing
9	AGVs - Parking	Internal Storage
		Outdoor Storage

Table 4 LCI data available on the ERP for the LCI, in terms of data categories

1. PLANTS EQUIPMENTS		N° LINE	USE	LIFE CYCLE	TOTAL MASS
Production steps for the spray-dried body	Industrial cogeneration	*n°*	*h/time*	*hours*	*ton*
	Spray-dried body preparation	*n°*	*h/time*	*hours*	*ton*

powder	Spray-dried body colouring	*n°*	*h/time*	*hours*	*ton*
Production steps for the ceramic tiles	Tiles pressing and drying	*n°*	*h/time*	*hours*	*ton*
	Glazes and inks preparation	*n°*	*h/time*	*hours*	*ton*
	Glazing lines	*n°*	*h/time*	*hours*	*ton*
	Digital printers	*n°*	*h/time*	*hours*	*ton*
	Kilns	*n°*	*h/time*	*hours*	*ton*
	Cutting, grinding and lapping	*n°*	*h/time*	*hours*	*ton*
	Sorting lines	*n°*	*h/time*	*hours*	*ton*
	AGVs (Automatic Guided Vehicles)	*n°*	*h/time*	*hours*	*ton*

2. OUTPUT PRODUCTION	**QUANTITY**
Spray-dried body powder	*ton*
Cogenerate electric energy	*kWh*
Ceramic tiles: total	m^2
Ceramic tiles: rectified	m^2
Ceramic tiles: rectified + polished	m^2
Ceramic tiles: cut + rectified + polished	m^2

3. OUTPUT FOR SALE	**QUANTITY**
Spray-dried body powder	*ton*
Cogenerate electric energy	*kWh*

4. MATERIALS & AUXILIARIES		**QUANTITY**	**TRANSPORT**		
			LORRY	**TRAIN**	**BARGE**
Ceramic body raw material	Clays	*ton*	*km*	*km*	*km*
	Feldspar	*ton*	*km*	*km*	*km*
	Sands	*ton*	*km*	*km*	*km*
	Milling water (aqueduct)	*ton*	*km*	*km*	*km*
	Milling water (from recycling)	*ton*	*km*	*km*	*km*
	Pigments	*ton*	*km*	*km*	*km*
	Fluidifier	*ton*	*km*	*km*	*km*
	Raw waste	*ton*	*km*	*km*	*km*
Decoration raw material	Ceramic glazes	*ton*	*km*	*km*	*km*
	Ceramic engobes	*ton*	*km*	*km*	*km*
	Digital inks	*ton*	*km*	*km*	*km*
	Milling water (aqueduct)	*ton*	*km*	*km*	*km*
Grinding media	Alumina spheres	*ton*	*km*	*km*	*km*
	Pebbles	*ton*	*km*	*km*	*km*

5. ENERGY SOURCES		**ELECTRICITY**	**NATURAL GAS**
Production steps for the spray-dried body powder	Industrial cogeneration	-	Nm^3
	Spray-dried body preparation	*kWh*	Nm^3
	Spray-dried body colouring	*kWh*	-
Production steps for the ceramic tiles	Tiles pressing and drying	*kWh*	Nm^3
	Glazes and inks preparation	*kWh*	-
	Glazing lines	*kWh*	-
	Digital printers	*kWh*	-

	Kilns	*kWh*	*Nm^3*
	Cutting, squaring and lapping	*kWh*	-
	Sorting & packaging lines	*kWh*	-
	AGVs (Automatic Guided Vehicles)	*kWh*	-

6. WASTE		***QUANTITY***
Production waste	Raw waste	*ton*
	Fired scraps	*ton*
	Filter sludge	*ton*
	Water waste	*ton*
	Metal waste	*ton*
	Paper waste	*ton*
	Plastic waste	*ton*
	Wood waste	*ton*
	Lubricating oil	*ton*
	Powders waste	*ton*

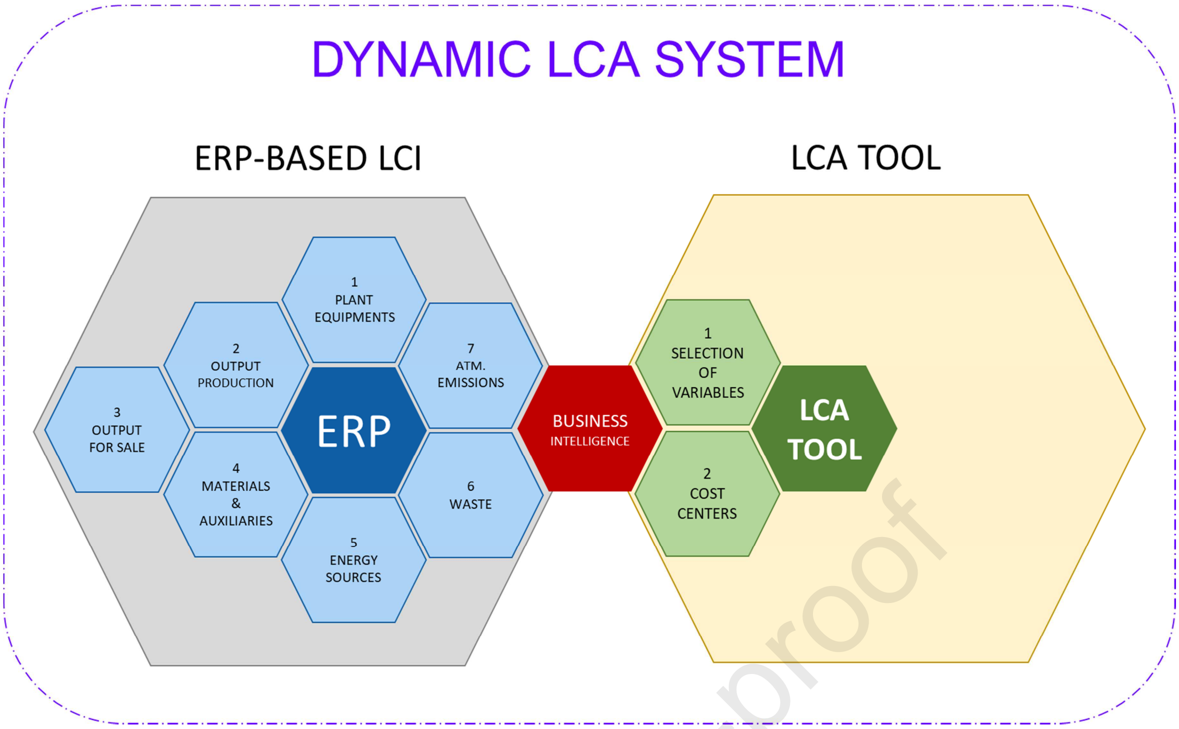
7. ATMOSPHERIC EMISSIONS		
FILTERS	**FLOW RATE**	**CONCENTRATION**
Particulates	*Nm^3/h*	*mg/Nm^3*
Lead	*Nm^3/h*	*mg/Nm^3*
Fluorine	*Nm^3/h*	*mg/Nm^3*
Volatile Organic Comp. (VOCs)	*Nm^3/h*	*mg/Nm^3*
Aldehydes	*Nm^3/h*	*mg/Nm^3*
Nitrogen oxides	*Nm^3/h*	*mg/Nm^3*
Carbon oxides	*Nm^3/h*	*mg/Nm^3*

3.4 Connection of ERP-based LCI module with the customized LCA tool

The connection between the customized LCA tool and the ERP-based LCI module, was made with Business Intelligence (BI) software. In general, Business Intelligence systems deal with the analysis and processing of data coming from different sources, in order to transform them into significant information for the organizations (Bordeleau et al. 2020). In addition, Business Intelligence also performs the task, not only to process the data, but also to take care of their representation to facilitate their understanding by the entire company team so that they can be used as a decision-making tool. ERP platform and Business Intelligence system are strongly complementary elements that together can give a strong support to optimize internal processes and improve business results (Zabukovšek et al. 2020). In this scenario, the ERP operates classically as a transactional system that holds a large amount of data on process and financial performance. This data serves as input to the Business Intelligence functions that transform it into useful information for making both tactical and strategic decisions.

In this research the technological node to be unravelled was the integration of the data source (ERP system) with the environmental assessment tool (LCA tool). In fact, a continuous data flow between the first and the second must be ensured, which is organized in such a way as to convey the data used for LCA analysis. To this end, the Business Artificial Intelligence software associated with the SAP™ ERP, SAP BusinessObjects™, has been used as an integration mode (Friedl and Pedell 2020). Business Objects acts as a live connector between the objects defined within SAP universes and the environmental impact calculation system based on an Excel spreadsheet, providing interactive and secure access to data stored in SAP without the need to extract, copy or move data manually. The connection layout, representing the Dynamic LCA system, is shown in Figure 5.

Figure 5 Business intelligence-based connection system between ERP-LCI and LCA tool to build Dynamic LCA system



4.Results

4.1 Conceptual validation by eco-design

According to Sargent (2015) the conceptual validation of the LCA tool is aimed at determining that the assumptions underlying the model are correct and that it can represent reality. In order to verify the model's ability to represent reality, the eco-design approach was used to define two alternative production scenarios to the current one. Eco-design is the way to incorporate environmental criteria in the design and development of a product, seeking to take preventive measures with the aim of reducing environmental impacts at different stages of its life cycle, from production to disposal (Navajas et al. 2017). In this way, the environmental factor is considered as another requirement of the product and with the same importance as other factors such as cost, safety or quality. The most effective eco-design methodology is the life cycle assessment (LCA), however its complexity (and cost) due to the need to acquire a lot of primary data on materials, technologies and processes related to all phases of the life cycle, hinders a wider adoption of this approach. In response to this criticality, the present study wanted to experiment the LCA tool, not only as a tool for monitoring the production process, but also as a way to apply the Life Cycle Thinking principle in product innovation (McAloone and Pigosso, 2018)

The detailed LCA analysis discussed in Section 3.1, showed that the main cause of the environmental impact during the whole life cycle of the ceramic product is due to the ceramic body raw material supply system (25.5%), in particular caused by transport. Therefore, from an eco-design perspective, the main objective was to significantly reduce the quantity of raw materials imported from extra-EU countries for which transport is an environmental criticality. Table 5 shows the formulations of the considered ceramic bodies. The composition B 0 is representative of a typical porcelain stoneware body currently produced (Dondi et al. 2014) where the raw materials imported from extra-EU countries (which represent 70% of the total) have the function of giving the ceramic body a high plasticity (illitic-caolinitic clay) and good meltability (sodium feldspar). The remaining part of the body is made up of illitic-caolinitic clay from Germany, potash feldspar and feldspar sand, both of national origin. With respect to the criteria of environmental sustainability, which penalizes factors such as the distance from the source of supply (e.g. non-EU) and the type of transport, raw materials, considered of lesser impact, have been indicated as "eco-raw materials", in order to proceed with the formulation of new compositions. In fact, two alternative compositions have been formulated to improve the environmental performance of the ceramic product. The B 1 composition foresees a significant reduction of extra-EU clay (20%) to the advantage of European clay from Germany (20%), in addition to the introduction of a national kaolinitic clay (15%). Similarly, extra -EU sodium feldspar has also been reduced (30%), partially replacing it with national potassium feldspar (10%). The B 2 composition, on the other hand, has undergone a radical change: extra-EU clay has been eliminated and replaced by European clay (29%) and national clay (30%), while extra-EU sodium feldspar (20%) has been partially replaced by national potassium feldspar (11%). In addition, national sand has been replaced by another type, again national, but coming from a mining process of recycling waste from other mining operations (10%). With this operation, the quantity of eco-raw materials increased from 30% (composition B 0) to 80% (composition B 3).

Table 5 Composition of the ceramic bodies studied

BODY COMPOSITION		B0	B1	B2
RAW MATERIALS	Extra-EU clay	30%	20%	0%
	Extra-EU Na-feldspar	40%	30%	20%
ECO-RAW MATERIALS	EU Clay	10%	20%	29%
	National Clay	0%	15%	30%
	National K-feldspar	10%	10%	11%
	National Sand	10%	5%	0%
	Recycled National Sand	0%	0%	10%
TOTAL ECO-RAW MATERIALS		30%	50%	80%

The LCA tool has therefore been tested to predict the environmental properties of the three different body compositions described above, assuming that the conditions of manufacture, installation and use of the finished product will not change. The only variables modified were therefore those related to the distance of the raw material sources from the production unit and the transport system: ship, train and truck. The results of the comparative LCA analysis, reported in Table 6 clearly show that the employment of eco-raw materials significantly reduce the environmental impact. For the sourcing phase, the total environmental damage decreases from 1.65×10^{-3} Pt (Points) for the B 0 composition to 1.40×10^{-3} Pt for the B 1 composition to 1.08×10^{-3} Pt for the B 2 composition. Climate change damage category evaluates the impact on the climate change in terms of kilograms of carbon dioxide equivalent (kg CO_2 eq), using carbon dioxide as a reference substance. The results, listed in Table 6, shows how a well-considered selection of raw materials from mines close to the tile manufacturing plant and more environmentally friendly transport systems significantly improve CO_2 emissions into the atmosphere. In fact, it goes from 3.96 kg CO_2 eq B 0 composition to 2.56 kg CO_2 eq for B 2 one (considering only the sourcing phase). Therefore, this eco-design test shows that the LCA tool is suitable to predict different design scenarios that anticipate the environmental performance of the finished product in real world.

Table 6 Total damage in terms of single score and Climate change results related to the sourcing of a 1 m^2 of ceramic tile for the three body compositions

SOURCING	TOTAL DAMAGE [Pt]	CLIMATE CHANGE [kg CO_2 eq]
B 0	1.65×10^{-3}	3.96
B 1	1.40×10^{-3}	3.33
B 2	1.08×10^{-3}	2.56

4.2 System validation

The phase of the system validation is finalized to verify if the model analyzed conceptually, corresponds to what was in the intentions for the description of the real world (Adamczak et al. 2018). In this case the validation was performed considering a double level of verification; the preliminary goal was to test the responsiveness of the Dynamic LCA system in term of proper functioning which means verifying whether the IT architecture was able to provide the LCI data, thanks to the Business Intelligence systems, and to correctly connect the ERP platform with the LCA tool. Afterwards, the results obtained by the Dynamic LCA system were compared with the results provided by SimaPro (PRé code 8.5.2.2) in order to ensure that no calculation errors inherent in the tool occurred. For the system validation, the Dynamic LCA system was tested with reference to the annual production of ceramic tiles (2017 reference year) with the aim to compare the results with those obtained by the software and showed in Section 3.3. During this validation, in practical terms, the ERP platform provided the LCI data related to the selected period of production thanks to a database query, then the Business Intelligent systems collected all the information and transferred them to the LCA tool which finally showed the environmental impact assessment results.

The test brought satisfactory results as the Dynamic LCA system was able to access the LCI data from the ERP platform and connect them correctly to the LCA tool; moreover, the obtained results matched those provided by the SimaPro calculation code so the system validation was successful in both levels of verification. The results of the Dynamic LCA system are showed in Table 7, following the structure of the ERP cost centers.

Table 7 Single Score results obtained from the Dynamic LCA system

Stages	Human Health [Pt]	Ecosystem Quality [Pt]	Climate Change [Pt]	Resources [Pt]	Human health indoor [Pt]	Human health local [Pt]	Total Damage [Pt]
Raw materials	7.36E-04	1.09E-04	4.00E-04	4.01E-04	8.14E-14	5.08E-07	1.65E-03
Plant general	2,31E-05	3,83E-06	1,06E-05	1,08E-05	-	-	4,84E-05
Body milling + Spray drying preparation	9.00E-05	5.32E-06	1.14E-04	2.30E-04	2.22E-12	1.38E-05	4.53E-04
Glazes preparation	2.74E-06	2.51E-07	4.38E-06	5.17E-06	1.09E-13	6.83E-07	1.32E-05
Pressing + Drying + Glazing + Decoration	8.85E-05	6.56E-06	1.45E-04	1.73E-04	4.77E-12	2.97E-05	4.43E-04
Firing	1.41E-04	7.01E-06	8.04E-05	3.79E-04	1.20E-11	7.48E-05	6.83E-04
Cutting + Squaring + Lapping	5.34E-06	6.07E-07	8.73E-06	1.03E-05	-	-	2.50E-05
Quality check + Packing	5.65E-05	2.65E-05	3.53E-05	5.79E-05	1.07E-15	1.34E-08	1.76E-04
AGVs - Parking	7,86E-06	4,53E-07	4,40E-06	4,79E-06	-	-	1,75E-05
Factory	1.18E-05	1.84E-06	4.36E-06	3.33E-06	-	-	2.13E-05
Δ energy	-5.92E-06	-5.61E-07	-1.53E-05	-1.82E-05	-	-	-4.00E-05
Distribution	2.42E-04	9.60E-05	1.94E-04	2.11E-04	-	-	7.43E-04
Installation	3.06E-04	5.72E-05	3.09E-04	1.50E-04	-	-	8.23E-04
Use	2.02E-04	8.02E-05	1.04E-04	7.92E-05	-	-	4.65E-04
End of life	1.44E-05	5.22E-06	1.62E-06	5.17E-06	-	-	2.64E-05
TOTAL	**1.92E-03**	**3.98E-04**	**1.41E-03**	**1.72E-03**	**1.92E-11**	**1.20E-04**	**5.56E-03**

4.3 Operational validation

The level of reliability achieved by the Dynamic LCA system, in terms of adherence between the environmental impact values determined with it and those obtained with the commercial software, was verified by means of an appropriate validation process (Sargent et al. 2016). Nevertheless, the system validation was carried with a retrospective environmental assessment on the production of the 2017 reference year and so not with a dynamic approach. In order to effectively dynamize the assessment, the month was selected as reference time unit and the Dynamic LCA system was tested with a narrower time horizon. The choice to consider a month and not a real-time monitoring depended on the fact that considering a lower unit of time (e.g. a day) could lead to unrealistic and variable results while considering a higher unit of time would lose the dynamic character of the tool.

The main problematic issues for the dynamization were related to those data that were not collected monthly, like for example the waste, the quantity of which are measured when they are transported for the disposal, and the atmospheric emissions that are evaluated periodically, according to the Integrated Environmental Authorization (IEA). With regard to the issue related to the waste, an assessment of the historical data for the last 5 years of production was carried out, taking into account all the waste produced year by year subdivided according to the EWC codes. The choice of a large and recent time horizon on which to carry out the calculation ensures the accuracy and reliability of the result; in fact, the variability with which waste is sent for disposal and therefore measured is quite wide and only one year may not be representative, so considering a 5-year scenario seems a robust and appropriate choice. From the analysis it was possible to calculate the amount of waste per square meter for each type of waste; once calculated, the amount of waste per square meter was included in the LCA tool in such a way that the monthly value is obtained and updated automatically when the square meters produced in the reference month change (which are dynamically measured by the system). As far as the assessment of air emissions is concerned, it was considered an average value of the measurements carried out in the previous year compared to the period under analysis, in terms of flow rate and concentration; in fact, the IEA is updated annually so it was decided to consider the most recent annual data.

5.Conclusions and discussion

This paper aimed to explore the potential of IoT technologies and the Industry 4.0 paradigm to automate, by digitizing, the inventory analysis phase underlying Life Cycle Assessment. To this end, some research questions were proposed and then empirically verified both from a conceptual and operational point of view. This research has mainly achieved the following goals:

1. First, it was verified that IoT technologies in the Industry 4.0 paradigm, which capture, process and store a large amount of data from sensors distributed within the production plant, can be used effectively to automatically perform inventory analysis (LCI) for environmental assessment (LCA) purposes. This result has allowed us to respond positively to the first research question stated in the introduction of this paper (RQ1).
2. Secondly, the factory sensors, which primarily perform a continuous process monitoring and control function, connect the decision level with the production level via the ERP. This bi-directional connection, thanks to the direct exchange of data, offers the possibility to have real-time information to dynamize the LCI. This result responds positively to the second research question (RQ2).
3. Finally, business intelligence combined with an ERP system and LCA analysis tool makes it easy to process data from the factory and provide real-time environmental impact KPIs. In this way it was possible to respond positively to the third research question (RQ3).

5.1 Theoretical contributions

This research provides several theoretical contributions.

i. A way to reduce the complexity of inventory analysis by proposing IoT technologies and using the industry 4.0 organizational model to collect primary data, was identified. Through a detailed one-to-one mapping of the production process steps, it was possible to relate each cost center to one or more LCA elementary unit.

ii. A conceptual and operational framework is proposed to integrate the ERP system with the LCA, overcoming the limits highlighted by other scientists in previous research. Thanks to the customization of the ERP database and Business Intelligence applications, it was possible to capture the data useful for environmental assessment collected by the factory sensors. This result has also solved the criticality related to the quality and updating of primary data, the use of the customized ERP module allows to have real-time process data useful for environmental impact assessment.
iii. In addition, the real-time availability of data for inventory analysis, allows to perform environmental impact analysis no longer statically based on historical data, but dynamically at the same time when the environmental damage is being produced. The effective dynamic integration between ERP and LCA offers the possibility to use the system as a predictive tool for the eco-design of new products or alternative manufacturing scenarios.
iv. Finally, this research proves, in a manufacturing operating context, that the Industry 4.0 paradigm and IoT technologies are indeed enabling technologies for environmental sustainability.

5.2 Managerial implications

This study also provides some managerial implications for practitioners.

i. The Dynamic LCA system allows the benefits of environmental assessment to be extended to more organizations and companies that have always seen LCA as too complex to use. This implies that environmental information is more readily available to better support the implementation of Corporate Social Responsibility (CSR) strategies.
ii. Due to its intrinsic ease of use, Dynamic LCA system can be easily integrated into business processes without the need for the intervention of a specialist when carrying out the assessment, which is only foreseen during the customization phase of the LCA Tool and in case of changes in the production process that necessarily affect the LCA tool. In this way, the company's employees can easily include environmental KPIs in the set of KPIs usually used.
iii. The real-time monitoring of the environmental performance of the process makes it easier for factory operators to identify and apply appropriate corrective actions, exploiting to the full the potential offered by the digital technologies of Industry 4.0.
iv. The Dynamic LCA system can be used as a possible tool to determine the Product Environmental Footprint (PEF) in accordance with the European Commission Recommendation 2013/179/EU, which aims at the significant goal of introducing common methodologies to measure and communicate environmental performance in the life cycle of products and organizations.
v. The environmental assessment system conducted with Dynamic LCA can also be used in eco-design framework to evaluate alternative process and product scenarios integrating it with economic (D'Adamo et al., 2021) and social (Almanza et al., 2020) analysis tools.

5.3 Criticism and limitations of the study

This research has highlighted some critical issues that should be explored in future studies.

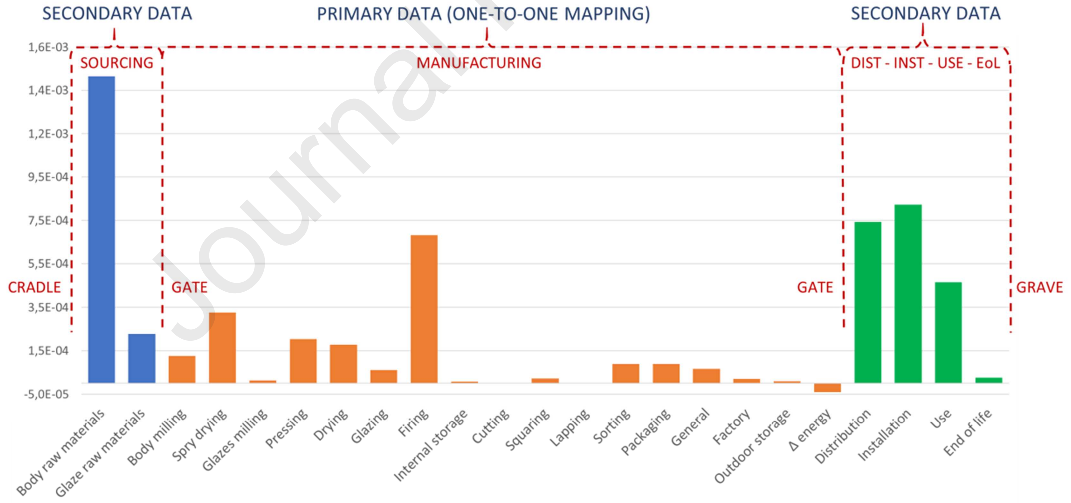
i. IoT technologies, and the Industry 4.0 organizational model, are able to provide with accuracy and precision a considerable amount of primary data that make the LCI phase particularly detailed in the gate-to-gate perimeter of the life cycle corresponding to the manufacturing phase (Figure 9). With regard to the sourcing (cradle-to-gate) and distribution & use (gate-to-grave) phases, the organization does not have primary data sources, so to adopt a cradle-to-grave approach it is necessary to use secondary data sources (databases), assumptions, conjectures and simplifications. Every company in the supply chain (raw materials and technologies) and distribution chain (B2B: business-to-business and B2C: business-to-consumer channels) considers the information related to their processes as sensitive data and is therefore reluctant to share it with the manufacturer who occupies a central position in the chain.

ii. In this case study, the lack of primary data for the sourcing phase was partially solved by the knowledge of the exact distances between mines and factory and between chemical industry and factory and the transport systems that are normally agreed in the commercial negotiations between suppliers and user. In this way it was possible to precisely determine the environmental impact at least of the transport system, while for the impacts of the manufacturing phases of the mining (raw materials), chemical (glazes and inks) and mechanical (machinery and equipment) processes it was necessary to use the supply data sheets and databases.

iii. Regarding the process of distribution, installation and use of the finished product that closes its life cycle, it should be pointed out that the lack of primary data is aggravated by the fragmentation that characterizes this phase. The ceramic product leaves the factory gate and is distributed worldwide through B2B and B2C channels with a variety of transport and installation methods (on the building site) which makes it difficult if not impossible to trace it. Similarly, for the use phase: the consumer uses and operates the maintenance of the ceramic floor and wall tiles following habits and customs related to the way the product is used as well as the culture, the geographical area and the social and climatic conditions to which it belongs.

iv. In this study, both primary data (especially for the manufacturing) and secondary data (especially for the sourcing, distribution, installation, use and end of life) have been used, as shown in Figure 6; in particular, for the distribution, installation, use and end of life, reliable scenarios were considered. For the authors it is important to stress the importance of considering the entire life cycle of a product in all its phases and not limiting the analysis to the gate. The difficulty in finding data for upstream and downstream processes could be overcome by defining scenarios that should be as representative as possible of real processes (i.e. for the distribution) and that represent the optimal solution (e.g. for the end of life treatments).

Figure 6 Schematic representation of data sources for LCA analysis for the overall product life cycle (cradle-to-grave) considering the functional unit of 1 m2 of ceramic tiles.



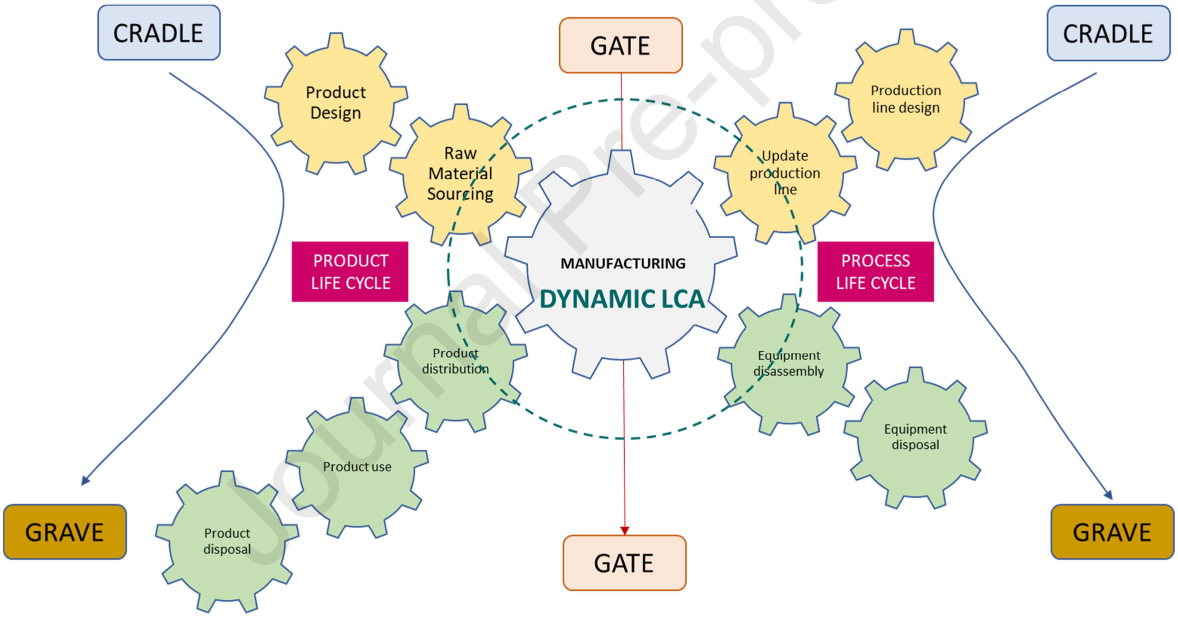
5.4 Overview and final remarks

The goal of this research was to design, implement and validate, both conceptually and operationally, a dynamic environmental impact assessment system which, exploiting the potential of IoT technologies and Industry 4.0, would be able to meet the environmental monitoring needs of a ceramic tile manufacturer. The complexity of the production process of ceramic tiles, described in detail in the paper, makes the results obtained and the critical issues that emerged, replicable and transferable to other manufacturing realities. The basis for future lines of research aimed at responding to the critical issues highlighted in this paper has also been identified.

In order to solve the problem related to the lack of qualitative consistency between primary (manufacturing) and secondary (sourcing, distribution, installation and use) data, one approach to be pursued could be the definition of scenarios, as indicated above. Another approach, currently quite difficult to adopt but certainly more rigorous and precise, would be that of industrial symbiosis (Neves et al. 2019). In fact, this approach not only indicates the exchange of resources between two or more different industries, but also the exchange of services, knowledge, information and skills. The synergic cooperation between suppliers and producers and between producers and distributors, can make mutually beneficial not only the exchange of goods, but also of sensitive information. Assuming that a relationship of mutual trust is created and maintained based on the "*do-ut-des*" paradigm (Gambetti and Giovanardi, 2013), which can also allow the joint eco-design of the product, the resources needed to manufacture it and the organizational models to bring the product to market. But not only that, within a relationship of industrial symbiosis it would be possible to exchange also the methodological modalities with which to conduct environmental assessment, in order to realize an effective and not only claimed, holistic perspective of the product life cycle.

Moreover, it would like to deepen the process life cycle approach which should complement the product life cycle approach as stated by Jacquemin et al. (2012) and shown in Figure 7. These authors stress that the process is mainly seen as part of the product life cycle (manufacturing of the product), and also highlight the advantages of seeing the process with its own life cycle. This path is interesting in order to offer manufacturing companies an additional opportunity to monitor the process steps even better while the product is being manufactured.

Figure 7 Product and process life cycle approaches (adapted from Jacquemin et al. 2012).



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Highlights

- Industry 4.0 and IoT technologies offer real-time manufacturing environmental data.
- Enterprise Resource Planning and Business Intelligence are used for real-time LCI.
- The real-time LCI based on ERP has been integrated with a customized LCA tool.
- Dynamic LCA provides real-time environmental assessment of tiles manufacturing.
- Dynamic LCA data has been successfully validated with a static commercial tool.

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: