Exploiting the Digital Twin in the Assessment and Optimization of Sustainability Performances

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***Abstract*—Digitalization has shown the potential to disrupt industrial value chains by supporting real-time, risk-free and inexpensive inputs to decision making towards enhanced companies' productivity and value networks flexibility. Developing a reliable and robust digital replica of the physical systems of the value chain is one of the most advanced (and challenging) approaches to digitalization, condensed in the concept of Digital Twin (DT). DT plays a fundamental role in creating a data-rich environment where simulation and optimization procedures can be run. With DT expected to become a commodity in the coming years, simulation and optimization become therefore a more accessible instrument for the improvement of manufacturing and business processes also in small enterprises with limited investment capacity. While scientific literature has analysed the adoption of DT in the optimization of products lifecycle, no contributions have yet focused on the exploitation of DT to improve the sustainability performances of whole value chains. In this paper we propose a reference framework where DTs built upon process and system data gathered from the field, allow to quickly assess the sustainability performances of both existing and planned production mixes and to compare achievable impacts with changing processes and technologies, thus enabling advisory features for sustainability-aware decision making in structured, multi-entity value networks. Internal validation will be deployed referring to real case studies.**

Keywords—Sustainability assessment; Digital twin; Sustainable value networks; Life Cycle Assessment

I. INTRODUCTION

In the challenge of transforming manufacturing towards a low-carbon, resource efficient and sustainable economy, the European manufacturing sector is undergoing a process of evolution impacting the way products are manufactured, supplied and sold [1]. Advancements in the context of the Industry 4.0 framework provide relevant opportunities for achieving sustainable manufacturing [2] by relying on what is called the Smart Factory: a fully-integrated, collaborative manufacturing system that responds in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs [3]. Beyond the vertical focus on the manufacturing system of each factory composing the value network, the achievement of sustainability-related goals has to be pursued by addressing resources, equipment, users and their consumptions, wastes, and emissions that come into play throughout the product lifecycle. Therefore, a sustainability-oriented organization has to focus on the efficient allocation of products, materials, energy, water and wastes, by taking into account the dynamic constraints of the system it relies on (logistics, smart grid, supply network and customers) [2].

In this context, the concept of Digital Twin (DT) comes into aid by providing a constantly updated digital representation of physical systems behaviours, that is able to address (i) real-time mirroring of physical systems and interaction with the virtual space [4], (ii) fast comparison between back or estimated data and real-time data [5], (iii) autonomous evolution of the represented system [6]. On the top of DT, different layers of analysis can be plugged, in order to enable the optimization of system performances through offline/predictive behaviour simulation.

On the methodological side, Life Cycle Assessment (LCA) provides a widely accepted methodology able to assesses the environmental impacts and used resources throughout a product life cycle, i.e., from raw material acquisition, through production and use, until re-using, dismantling and waste management [7]. According to Hellweg & Canals [8], LCA is considered a decision-support tool supporting companies in benchmarking and optimizing the environmental performances of their value network, and authorities in designing policies for sustainable consumption and production.

This paper describes a framework where the integration among DT and LCA methodology across value networks drives to a semi-automated, modular and scalable approach to industrial sustainability optimization and accounting.

II. RELATION TO EXISTING THEORIES AND WORK

A. The evolution of the digital twin concept

The concept of the Digital Twin (DT) has evolved since its first adoptions in the aerospace sector till today where it is largely adopted, pushed by the Industry 4.0 wave, especially in the manufacturing sector. Main uses reported in literature are related to (i) the support of analyses for improved maintenance and planning, (ii) the digital mirroring of the physical entity, and (iii) the support in the decision-making phase through engineering and statistical analyses [9].

Deloitte experts [10] define a DT as "an evolving digital profile of the historical and current behaviour of a physical

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object or process that helps optimize business performance", highlighting that:

- the DT consists of three parts: physical asset, virtual counterpart, and connected data that tie the two parts and that are subject to three phases: data acquisition, data warehousing and data analysis [10], [11];
- the DT should be characterized by real-time reflection, interaction and convergence in physical space, between historical data and real-time data, and between physical and virtual spaces, and self-evolution [10], [11];
- the DT can support companies to better understand and predict the performance of their machines during all the factory lifecycle [10].

The DT concept goes beyond the digital product one, being created by gathering data from various sources such as physical, manufacturing and operational data, and insights from analytics software [12]. In the last decade, this concept has been largely associated also with the simulation concept: it is the virtual and computerized counterpart of the physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field. Boschert and Rosen [13] pointed out the full integration of the DT in the simulation, proposing a DT with its own architecture that connects engineering data, operational data and behaviour descriptions through different simulation models. The information required across the life cycle of the considered asset can be exchanged by means of a data model connecting different systems and applications within the same enterprise [10]. Whether based on a semantic data model, simulations along the entire life-cycle of a product for different purposes can be performed by means of the DT [9]. On one side simulations can help to predict the future behaviour of the asset, on the other side the semantic data model helps to continuously update the virtual representation with real-time data.

Limitations in digital technology capabilities, including computation, storage and bandwidth, have been the major reasons behind lack of adoption of the DT concept in real manufacturing contexts until recently. Such obstacles have been limited in recent years [14]: it is now possible to access affordable information and communication infrastructures in an easier way. Some challenges still need to be faced [15]:

- real-time interaction between the real and the virtual twins can be reached only working on advancements in sensors, communication and data processing technologies;
- effective data models are becoming a fundamental issue to achieve a reliable virtual twin: production mixes and production technologies variability, unpredictability of the physical solution space require a robust reference data model to let the digital counterpart adapt to changing reality and manage inconsistences with the real entities;
- addressing complex real environments makes it hard to create discrete virtual spaces able to evolve with the physical one along the lifecycle, gathering data from heterogeneous entities, and building reliable virtual counterparts. In these contexts, how to integrate and converge the increasing data complexity is an actual challenge;
- data security is also a big issue, especially when collected data come from several detached entities along the supply chain.

To face these challenges, Gartner [16] has identified four best practices and recommendations enabling the future development of DT concepts:

- involving the entire product value chain assuring data exchange and data consistency;
- keeping the virtual models living by establishing well-documented procedures for models' creation and modification;
- assuring the inclusion of data from multiple sources, also unknown when the first model has been created. This means assuring scalability and modularity;
- ensuring long access life cycles in order to assure a life-long convergence of the physical and the virtual. Especially buildings or major infrastructures are the target of this challenge.

A reliable DT needs to evolve with changing reality characteristics that are often (at least partially) unknown when the first model has been created.

B. Sustainability assessment in the digital era

Sustainability statements and reports are becoming a standard request especially from customers of large enterprises, forcing an increasing number of companies in including sustainability-related objectives in their strategies [17]. The measurement of the sustainability performances of products and companies has been largely recognized as a focal pre-requisite for the actual translation of these strategies into operations, towards the implementation of the triple bottom line concept in everyday industrial practices [18]. For these reasons, proper metrics must be adopted enabling the standardized calculation of appropriate indicators measuring the economic, environmental and social performances at product and company levels. Monitored data empower: performance optimization, support to guarantee standardization and legal compliance, sustainability communication and marketing [19], [20], [21]. The exploitation of indexes is recognized to be an effective support to decision-making [22] [23], allowing designers and managers to check the current sustainability performances, fix benchmarks and thus promote product, processes, company and supply chain sustainability enhancement, and understand where to act in order to obtain more effective improvements. The monitoring of product and company through quantifiable measures is also fostering the compliance with mandatory regulations and voluntary standards, since a more complete and deep knowledge on internal and external processes is encouraged [24]. Eventually, being sustainable is becoming a picklock to satisfy or even reach sustainability-conscious customers, thus reports and labels based on reliable measures have grown to inform and differentiate market perception of products and brands [24].

Despite the academic and the industrial contexts are permeated by a huge amount of sustainability assessment methodologies and indicators, only a handful are able to provide an integrated approach that jointly takes into consideration environmental, economic and social aspects, in a quantitative way, and addressing the whole lifecycle of firms, goods or services [25]. Amongst them, the ones based on Life Cycle Thinking (LCT) such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) have been acknowledged as holistic, reliable assessment methodologies widely exploited both in research and industrial applications [24]. Currently, only LCA, born in 1970s, has been formalized starting in early 1990s with the work performed by the Society of Environmental Toxicology and Chemistry (SETAC) [26], and then supplemented by the International Organisation for Standardisation (ISO) that consolidated the LCA methodology in the ISO 14040 series [27].

Following the ISO 14040 principles, the LCSA can be structured in four phases [27]: i. Goal & Scope definition that details the reason of the study, to whom it is intended for, and relevant technical characteristics; ii. Life Cycle Inventory (LCI) that has the aim to collect input/output data, thus identifying and quantifying all the emissions released into the environment, the resources used along the whole life cycle of the system being studied, the related costs properly allocated and data concerning social issues classified into the different social categories; iii. Life Cycle Impact Assessment (LCIA) where the LCI results are translated into impacts on the eco-sphere and society, and costs are aggregated by categories. At the end of this phase, indicators are calculated; iv. Interpretation, that is meant to analyse the assessment results in order to identify the hot spots of the system, to check the data (from the quality, completeness and consistency points of view) and preparing conclusions and recommendations.

The application of LCA, LCC and S-LCA can present several barriers for businesses due to their high degree of complexity, demand for high-quality data and considerable requirements in terms of monetary and human resources [28]. The implementation of the "check, improve and communicate" approach supported by LCT methodologies, cannot be solved through the mere calculation of indexes. The assessment has to be supported by tools that are real-timely highlighting which are the possible improvement paths, allowing to analyse, store, search and retrieve data and knowledge [29]. For these reasons, tools and methodologies are needed in order to: collect, throughout the life cycle, the data needed for the sustainability assessment of products and processes; calculate the sustainability performances available to all members of the supply chain under common quality assessment procedures and calculation standard; advise decision-makers in determining the best materials, production processes, supply paths… to produce low impacting products and solutions.

LCI is universally recognized as the most time- and resource-consuming phase in the whole LCSA implementation path [30], and data gathering from the different entities along the supply chain is probably the most critical issue to be solved, also considering that completeness and quality of gathered data is fundamental for the reliability and repeatability of the calculated impacts [30]. In fact, the use of primary data enhances the quality of LCSA results, since they address specific products flowing through a given set of machines and systems. At the same time, the collection of foreground data (e.g.: impacts of national energy mixes) requires extraordinary effort especially when real-time assessment or traceability of a specific production lot is needed, or when the data in analysis has to be collected from suppliers and, especially, from (n-tier) suppliers of suppliers. In order to depict a framework aiming at supporting the development of a collection and exchange data infrastructure, an analysis of the Life Cycle Sustainability Inventory (LCSI) has been provided by Valdivia et al. [31] and by Bicalho et al. [21], for the specific case of environmental LCI, bringing to the definition of dimensions that can guide the framework implementation, such as: data format and type, focus of the assessment, data source, automatization.

As a first critical element, it must be noted that LCSI data are in specific and different data formats since they describe different sustainability areas. If a consensus seems to be reached for the environmental LCI exchange data format, assured by the ISO/TS 14048 and based on XML-technology [32], a common standard is not yet recognized for sustainability assessment but it is needed in order to share information between the different supply chain partners. Moreover, LCSI data address different types of information covering the economic, environmental and social dimensions of sustainability and thus addressing very different themes such as costs, resource consumptions, emissions, workers injuries, charitable contributions of a company.

A further dimension to be considered in LCSI data gathering and elaboration is the focus of the assessment and, thus, the level at which the information is gathered. As already highlighted by Sorlini at al. (2014) [33] and Fontana et al. (2015) [20], the sustainability assessment could address both products and companies, thus product-specific data and company/supply chain-specific data are collected, depending if the scope of the assessment is more focused on the single product or on the whole company and their suppliers. Theoretically, as suggested by the European Product Environmental Footprint (PEF) and Organizational Environmental Footprint (OEF) methodologies [34], the sum of all the PEFs within an organisation is equal to the OEF. Even when the focus of the assessment has been established, it is often important to collect data at production unit and at organization levels because not all the information about the three areas (environmental, economic and social) could be found at both levels. This means that data are gathered at company level and then allocated at product level, or vice versa. Enabling the possibility to uniquely identify and track everything, anywhere, and anytime, the emergence of Internet of Things (IoT) and DT concepts introduce a further level of detail of the assessment focus that is the lot-wise or batch-wise evaluation. This is meant to address a single product produced in a specific moment, following a specific manufacturing path [35]. Traditional LCT-based assessment methodologies provide average values not keeping into account each item performances; this means that a product or a batch processed in a given production line results in a set of pre-calculated (and average) impacts. Should users monitor sustainability performances of each single batch, they would also be able to dramatically increase the amount of information used to improve the overall performances of a company or to be communicated to their customers.

The third dimension considered to structure LCSI data collection is the source of data, a theme strictly connected to the data type and the assessment focus already discussed. In order to perform sustainability assessment at product, process, company or supply chain levels, different sources of data are expected: single production equipment, production lines, company bills regarding for instance water and energy consumptions, PLM, ERP, CAD and other software used by companies in their daily activities, external database such as LCI and LCIA repositories (e.g. ecoinvent [36] for the analysis of the environmental impacts) and many others. In addition to that, the IoT and DT concepts introduced a larger set of possible sources of information that can be exploited during sustainability assessment. As already stated, IoT is meant to enable the real time collection of precise and very specific information from the single production equipment. On the other hand, DT assures a mutual promotion process between virtual and physical spaces of product lifecycle [4]. Within the virtual space of the DT, it is thus possible to exploit simulation, forecasting activities and real word data, so that various activities of the entire product lifecycle are monitored and optimized.

The ability to integrate such different sources of data is eventually related to the automatization of data collection, the last dimension here discussed that is crucial to solve the high time and resource-spending nature of LCSI. The coordinated but automatic collection of sustainability-related data coming directly from single production machines and lines of the supply chain via IoT, or coming from the simulation performed within the DT environment or, again, from other company software is meant to drastically reduce the time needed to obtain a reliable and real-time evaluation of the single item and/or of the entire supply chain. At the same time, the automatic collection and management of these data could support the ex-ante assessment performed during the design, when most of the middle of life data are not available from direct measures and can be only deduced from simulations or historical data stored.

III. A FRAMEWORK FOR INTEGRATING DIGITAL TWINS IN VALUE NETWORKS SUSTAINABILITY ASSESSMENT

The realization of a robust LCA requires current and accurate data necessary to create the knowledge base supporting the calculation of the lifecycle impacts to be assessed. Despite advances in (open-source/free) databases and software platforms supporting the gathering and/or calculation of these data, procedure of doing a careful and transparent LCA is still remarkably time-taking. Moreover, the complexity associated to the data acquisition, organization and integration in an LCA engine becomes exponential with the extension of the value network boundaries.

The integration of DTs can have a relevant impact in streamlining this process by enabling the collection of real-time data (e.g. energy and carbon input/outputs) associated with objects via network of sensors, that can make LCA much more precise and automated compared with today's conventional methods [37]. If available technologies are already able to theoretically address this need, the actual implementation of such a solution across a complete value network is still a chimera. The reasons of this misalignment are manifold, just to cite few: (i) complexity of LCA methodology doesn't enable companies to directly apply LCA, but often need the support of consultancy companies in the set-up and maintenance of studies with related costs and timings; (ii) need of a strong rework of the acquired data due to the different possible levels of the focus to be applied in the LCA; (iii) limited or no visibility on supply network data mostly deriving by the complexity associated with data retrieving; (iv) an increasing number of stakeholders to be mapped in the aim of assessing a complete value network.

The first step shortening the distance among theory and practice is therefore the definition of a framework aimed to align current technological capabilities (i.e. streamlined acquisition of real-time data through DT), with the actual needs of industrial stakeholders.

In order to create a reference framework taking into consideration actual market needs and the issues currently faced by practitioners and Academia when applying LCA methodology throughout different value networks, the following requirements have been taken into account:

1) *Scalability of the assessment domain:* a comprehensive framework has to take into consideration all the points of view on which a company can decide to put the focus (product, process, company, supply chain level) integrating different sources of data in the flexible LCA boundaries [33], [20], [34], [35];

2) *Heterogeneity of the assessment scope*: as identified by [19], [20], [21], [24], the adoption of the LCA analysis is prone to different industrial needs, going from product and process monitoring and optimization to sustainability communication and marketing. Decision-making at different levels in the value network has therefore to be supported in an integrated way, by providing the means to exploit the different uses that LCA derived indicators can offer [22], [23].

3) *Ease of integration of value network data*: this aspect has been reported to be relevant under two domains. In first instance standardized data have to be acquired [32] in order to foster applicability of analysis across the whole value network; ease of integration of data gathering and aggregating technologies has to be supported in order to largely simplify data acquisition in each phase of product lifecycle [35], [4].

A. Introduction to framework boundaries

For the scope of this work, the total life-cycle of a product has been taken into account by applying two levels of granularity: stages of product lifecycle and boundaries of LCA. The first allows to focus on single lifecycle stages, while having a vision on the whole product history; the second one sets the scope for the integration of the DT in the framework and for the scalability of company vision across the value network.

Starting from what proposed by Jawahir et al. [38], product lifecycle has been therefore divided in six key stages in a closed loop system: pre-manufacturing, manufacturing, distribution, use, re-use and end of life (Fig. 1).

Pre-manufacturing consists in the first stage in the life-cycle of any product. It goes from the extraction of material from their natural reserves to the processing in semi-finished products. This stage also involves packaging, storage and transportation of the processed/semi-processed products.

Manufacturing is the phase where semi-processed materials coming from downstream suppliers are transformed into finished goods for sale. Assembly is considered as an integral part of the manufacturing phase of a product life-cycle where manual or automated processing is used to join or integrate the various parts. Depending by the focus of the model and the structure of the reference sector, the manufacturing phase can have a flexible positioning within the value network, taking the role of the single last step before distribution to final customer, or considering a set of steps carried out by different industrial partners.

Distribution is the phase that links the manufactured product to the final customer in terms of transportation and logistics.

Use phase of the product life-cycle takes in consideration the amount of time the consumer owns and operates the product, and all the resources and impacts associated to its use.

Re-use accounts for all those steps, typical of a Circular Economy (CE), that take back used products, or some of their parts, to a previous stage of product lifecycle. Three main sub-stages are therefore considered: (i) Reuse/Redistribution: products that are directly redistributed, being sold as services or because re-sold in lower value markets without any interventions, or with very limited maintenance in the middle; (ii) Refurbish/Remanufacture: products that are take back to manufacturing stage through the remanufacturing of one or several parts; (iii) Recycling: products or part of it that are taken back to the stage of raw material or of semi-finished part.

End of life: for products or part of them that can no longer fulfil their function and that can't be reintroduced in the CE loop, the end of life is reached. This phase consider landfill or burning depending by the type of product/material and regulatory policies.

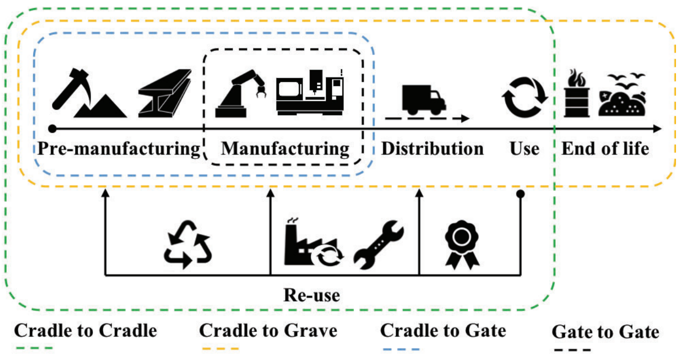

Fig. 1 Mapping of LCA boundaries product lifecycle stages

Beyond the stages of product lifecycle, the boundaries of LCA have been taken as drivers for the aggregation of data in the framework context. Four boundary dimensions have been considered and highlighted in Fig. 1: Gate to Gate, Cradle to Gate, Cradle to Grave and Cradle to Cradle.

Gate to Gate represents a partial LCA looking **at only one value-added process in the entire production chain. It includes the analysis from reception of the semi-finished products, ready to use, to the end of production, when the product, service or activity is ready to be used or received by the final user, while not considering distribution or further.**

Cradle to Gate: Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (i.e., before it is transported to the consumer). The use phase and disposal phase of the product are omitted in this case.

Cradle to Grave: it represents the full Life Cycle Assessment from resource extraction (cradle) to use phase and disposal phase (grave).

Cradle to Cradle: it includes everything considered by the previous steps, but also the recirculation of what could be considered as waste into the process itself. No more waste actually exists in this arrangement as products or components are remanufactured or recycled to be re-introduced within the lifecycle of a new product. While from Gate to Gate to Cradle to Grave, the three boundaries can be seen as sequential extensions of the focus of product lifecycle, when speaking of Cradle to Cradle the whole product value network is affected, by requiring a complete restructuring of the way of doing business.

B. *Sustainability framework to support optimizaiton of industrial value networks*

According with the analysis carried out above, a framework for the LCA based optimization of industrial value networks has been developed. The framework takes into consideration the integration within a single environment of all the elements necessary to generate the assessment (stakeholders, data sets, LCA boundaries, etc), and the related sustainability-oriented decision support means peculiar to the boundaries the company is interested to analyse.

In the following picture (Fig. 2) the *LCA based industrial optimization framework* is briefly presented by highlighting the four layers composing it. From the bottom to the top, data are acquired, filtered, elaborated and presented, as described in the following paragraphs.

Data acquisition: the acquisition layer describes the framework domain dedicated to the integration of IoT, DT or database data required to perform assessments. While IoTs provide raw data to be aggregated and elaborated in impact data during the second elaboration phase, databases provide directly impact data related to the considered process specification. DTs can eventually provide not only real time data describing the current behaviour of the process, but should be also interrogated to get (wherever possible) simulated data, supporting LCA forecasting. The exploitation of edge computing by means of local DT based simulations of LCA related performances is meant not only to provide the most accurate prediction of system performance, but also to reduce the computational effort to be deployed in cloud applications.

According to the specific lifecycle stages, different data granularities are expected to be gathered. From highly representative and detailed data sets deriving from shop floor Twins or from Product Avatars [39] respectively in the manufacturing process or use phase, to less structured information respectively describing supply chain, Re-use phase and End-of-Life.

Eventually, due to the high granularity of data types (from shop floor, supply chain, use phase), the acquisition should be managed considering Integration as a Service (IaaS) as the main methodology for the custom integration of external data.

Assessment domain scoping: the framework conceives an infrastructure able to manage several levels of assessment according to the four main LCA boundaries. In order to minimize the computational effort and extract only required data, the focus on the boundaries each company is interested in, is applied before performing the actual calculations. The extensibility of the framework conceives indeed the possibility, for the same company, to apply different levels of focus on LCA boundaries, for different evaluation needs. The computation only of the data that are strictly necessary becomes therefore stringent.

Data elaboration and assessment: the core of the framework conceives an engine that allows to calculate the environmental impacts (calculated in line with the LCA methodology) of the given product and to release, in real time, a set of standard evaluations describing impacts at each level of the value network. The main function of this framework component is to calculate the sustainability impacts of the modelled processes gathering all the information such as indicators, methodologies, characterization factors and other essential data from the previous layers.

Sustainability oriented decision making support: the last section of the framework addresses the need of consistent indications to drive decision making according to the calculated data. The different layers of data presentation (LCA, sustainability labels, product centric analysis, process centric analysis, etc) are meant to advise decision-makers in determining the better materials, production processes, supply path to produce low sustainability impacts products and processes. In doing so, the nature of the processes composing the supply network can be *de facto* reconsidered, providing insights that go far beyond the assessment of the environmental impact.

C. *Answering framework development requirements*

As introduced in the previous chapters, the LCA based industrial optimization framework has been developed in order to provide guidance to bridge the gap between theoretical capabilities in LCA analysis and actual possibilities of industrial companies. In doing so, three main requirements have been set:

1) Scalability of the assessment domain: the framework addresses scalability by working on the flexibility applied to

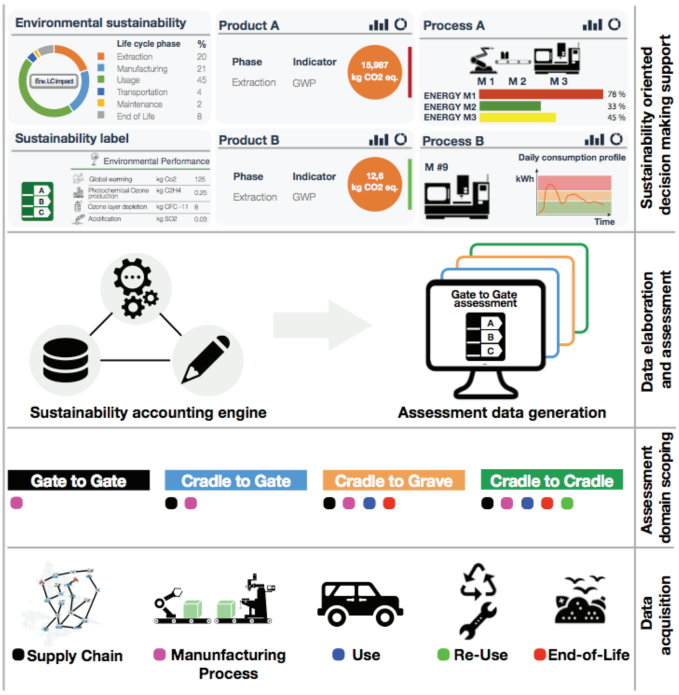

Fig. 2 LCA based industrial optimization framework

lifecycle phase coverage: the power of the framework consists in its ability to cover all the life cycle phases (from Pre-manufacturing to End-of-Life). To do so, a wide perspective has to be taken, not only on the assessment purpose set by the methodology, but also in the technological coverage supporting the integration of different data streams (E.g. automated data gathering form IoTs & DTs in manufacturing phase, manual upload of model data for End-of-Life characterization)

2) Heterogeneity of the assessment scope: by changing the point of view, data sets can disclose very different information. Following this motto, the framework has been developed as an aggregator of elaborated data to be showed For example, importing general databases, such as ecoinvent or GaBi, allows the tool to evaluate the sustainability using general-knowledge data. Instead, the compatibility with different files, machines, sensors and information systems enables the evaluation using corporate/process-wise data or even lot-wise data.

3) Ease of integration of value network data: The framework aims to cover the assessment of complete value networks, across the whole product lifecycle. Its inner nature of accounting platform, supporting the integration into a single infrastructure of data deriving from the whole value network becomes therefore undeniable. The large usage of technological means (IoT, DT) strongly reducing the burden behind data gathering and information extraction at all the levels of the value network is directly intended to transform LCA tools into ease to use, self-assessing instruments to be deployed in daily enterprise sustainability improvement measures.

IV. PRELIMINARY VALIDATION OF THE MODEL IN THE WOODWORKING SECTOR

A preliminary validation scenario in the woodworking sector has been adopted in order to partially test the applicability of the proposed concept in a real scenario. In this validation scenario the Gate to Gate perspective has been taken. The validation scenario is realized in order to showcase two levels of assessment of the developed framework, i.e. sustainability communication and production system optimization.

As described in [40], [41], [42] the proposed testing scenario consists in a compact manufacturing system able to create personalized furniture, based on the need of the customer. The machining system performs the main tasks required to manufacture panels-based furniture: loading, routing, boring, edge application, edge finishing, and unloading. The manufacturing system is equipped with a IoT infrastructure enabling the monitoring of the most relevant actuators present on the machine (i.e. energy sensors, flow meters for lubricants & glue, load sensors for wood positioning and edges installation). Each sensor communicates with the Sustainability Accounting Engine providing raw data to be therefore transformed in manufacturing process impact data.

Impact data are calculated and two levels of information are therefore generated: on the one side, the system provides impact data calculated in real time according to the custom furniture manufactured. For each custom product a sustainability label is therefore created with product specific impact data and delivered to the customer. On the other side, the impact data related to specific actuators of the machine are presented in an aggregated way, showing consumption/impact characteristics over the time, thus enabling to identify degradation trends or recurrent consumption behaviours.

The data acquisition and elaboration procedure has been validated by producing 62 cabinets, each of them with different configuration characteristics in terms of dimensions, configuration and colours. Upon customizing a cabinet, the product design was automatically transferred to the manufacturing system that could therefore start its production. The data acquired from the manufacturing system where elaborated in order to derive, for each different product configuration, the impact assessment indicators. The impact data were eventually used to generate a product label that was delivered to the product final user. An example of the delivered labels is presented in Fig. 3.

Fig. 3 Automatically generated sustainability label for a furniture asset, providing environmental impact acquired during product manufacturing lifecycle

V. CONCLUSION

With the coming of data-driven manufacturing era, IoT and DTs technologies, companies gain the possibility to gather data generated in various phases of the whole product lifecycle, and to analyse and exploit them for optimizing and improving their production sites. In this paper, an *LCA based industrial optimization framework* has been proposed, relying on the advantages of factory DT as a data-rich representation of company's products and processes. The framework entails the integration within a single environment of all the elements needed for the generation of the sustainability assessment of company's product or production, based on the LCA methodology. The framework has been created considering a semi-automated, modular and scalable approach to industrial sustainability optimization and accounting, complying with different requirements: ensuring the scalability of the assessment scope, its heterogeneity, and easing the integration of value network data.

The woodworking sector has been adopted as the preliminary validation scenario to verify the applicability of the framework, its modularity and scalability. In particular, data gathered from machining systems have been elaborated by means of an LCA-based sustainability assessment engine and used for (i) communicating sustainability performances, and (ii) optimize the production according to consumption behaviours.

This paper preliminarily investigated the application methods and frameworks of DT-driven sustainability assessment and optimization of performances. At present, the research is in the initial stage and still needs a lot of research work. Future work will concentrate on the following aspect: (1) automated collection of sustainability-related data coming directly from single production machines and lines of the supply chain via IoT, or coming from the simulation performed within the DT environment, (2) DT data construction and management, (3) smart sustainability-based service analysis method based on DT data.

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