12th Conference on Learning Factories, CLF2022

A Sustainability Framework for Smart Learning Factories Based on Using Structured Information as Semantic Models

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Abstract

In this paper we present a holistic sustainability framework and an accompanying architecture for a Smart Learning Factory that will seamlessly connect, collect, and analyze data from all associated systems, subsystems, and components across its manufacturing ecosystem using structured information as semantic models. This sustainability framework is aimed at supporting the need for data interoperability between different stakeholders, protocols, and standards that could exist in a Smart Learning Factory's ecosystem. This sustainability framework is operationalized using an architecture that is composed of multiple layers. An Industrial IoT and control layer is deployed to collect data from the manufacturing assets and operations. In this layer an edge connector tags specific data to be collected and processes streaming data in real-time and simultaneously update a digital twin. This system federates the heterogeneous data with varied data formats coming from different data sources, contextualizes, relates, and stores the data as graph data in a data lake. Semantic models of devices, machines, and processes on the factory will be used to encapsulate the contexts of the data and make relations. The data lake will integrate and mediate all data described in various formats, and will understand and answer GraphQL in terms of context awareness to provide proper data sets through endpoints. The final layer integrates relevant apps for displaying and reporting the sustainability KPIs, analysis, and prediction, and digital twin for real-time monitoring and control through web-based services such as the Microsoft Sustainability Cloud. This sustainability framework was used to demonstrate its application in a learning factory to address sustainability at product, process and system levels in a undergraduate manufacturing educational program.

Peer Review statement: Peer-review under responsibility of the scientific committee of the 12th Conference on Learning Factories 2022.

Keywords: Sustainability, Semantic Models, IoT, Digital Twin, Manufacturing Ecosystem

1. Introduction

Sustainability has become one of the keywords in manufacturing today, particularly after the earlier industrial revolutions which have resulted in exponential increase in exploitation of natural resources, air pollutant emissions, toxic waste disposal and water contamination. This was premised on a linear economy that follows the step-by-step "take-make-dispose" strategy where raw materials are collected and transformed into products that are used until they are finally discarded as waste. Value is created by producing and selling as many products as possible which in the long term is unsustainable due to the degradation of natural resources and the accumulation of waste. The 4th Industrial Revolution is enabling the circular economy for mitigating these negative impacts by shifting focus toward developing systems that will equally benefit businesses, people, and the environment. The United States Environmental Protection Agency (EPA) refers to the circular economy as an economy that uses a systems-focused approach and involves industrial processes and economic activities that are restorative or regenerative by design. This approach reduces material use, redesigns materials to be less resource intensive, and recaptures "waste" as a resource to manufacture new materials and products [1] [2].

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The environmental and climate impacts are also rapidly becoming a major issue. The manufacturing industry must accept its heavy responsibility for emissions of greenhouse gases. In the US, manufacturing accounts for almost a quarter (23%) of direct carbon emissions, according to the Environmental Protection Agency. In Europe the situation is equally dire: the industry emits an annual total of 880 million tonnes of carbon dioxide equivalents making it one of the largest emitters of greenhouse gases on the continent. In 2020, the industrial sector accounted for 36% of total U.S. end-use energy consumption and 33% of total U.S. energy consumption. Within the industrial sector, manufacturing accounts for the largest share (77%) of annual industrial energy consumption for the physical, mechanical, or chemical transformation of materials or substances into new products.

All these data suggest a strong motivation to develop sustainable factories that are focused on reducing waste, impact on the environment, and resource consumption (energy, water and materials). Equally important is tackling these significant challenges in academic programs using a learning factory to incorporate knowledge needed to promote sustainable manufacturing education at product, process and system levels. Achieving this requires a framework for learning factories with an integrated approach to tackle the sustainability of the factory and its manufacturing ecosystem as a whole. In this paper we propose a holistic framework using structured information as semantic models aimed at achieving the integration and interoperability between the various methodologies and tools supporting the design and management of a sustainable factory. This will be addressed by developing a common environment for the learning factory using a cloud platform where all information associated with various aspects of the factory operations are modelled in a manner understood by all systems connected to it in the manufacturing ecosystem.

This paper is organized as follows. In section 2, we present an overview of the literature contribution related to the sustainable factory in the manufacturing domain and describe the related work and limitations of the proposed solutions. Section 3 provides background for developing the sustainability framework proposed in this work. Section 4 presents the sustainability framework, its main components, and a deployment of the framework based on a cloud implementation. In section 5 we discuss deployment of the sustainability framework in a learning factory to support manufacturing sustainability in an undergraduate program. Finally, section 5 summarizes the paper and discusses future work.

2. Related Work

Research into reducing the negative environmental impacts of the manufacturing industry has increased as a result of the growing global pressures, stakeholders placing stronger emphasis on carbon neutrality, and governmental regulations, is creating pressure on industries to address sustainability. For manufacturers this means integrating sustainability measures into their operations, and considering the impact at each stage of the product life-cycle. While this appears to be a complex and multifaceted challenge for manufacturers to be both sustainable and profitable, intelligent and digitally connected smart factories can address this challenge by taking advantage of the technological innovations of Industry 4.0. Technologies such as artificial intelligence (AI), cloud computing, and Internet of Things (IoT) that enable smart factories with connectivity, real-time control, and data driven insights could be used to support the sustainability in manufacturing.

The scientific research community, along with public and private enterprises are now paying increased attention to this topic. Global and national research programs have been launched, such as “Horizon 2020” in Europe [3] and “Sustainable Manufacturing Program” by the National Institute of Standards and Technology [4] in the United States. In 2021, Microsoft launched the Sustainability Cloud to help manufacturers drive sustainability while saving costs and improving safety in their operations, using cloud-based automation, machine learning, and artificial intelligence (AI). All these efforts leverage the technologies of Industry 4.0, also seen as an enablers for achieving the sustainable manufacturing goal. Although the convergence of digital transformation and sustainability still remains under-developed [5][6], research have identified multiple links between Industry 4.0 technologies and sustainable operations. De Man and Strandhagen [7] in their work discuss the influnce Industry 4.0’s has on creating sustainable business models. Kamble, Gunasekaran, and Dhone [8] in their work focused on the effects of Industry 4.0 technologies on Lean Manufacturing Practices in sustainable organizations, and Ghobakhloo [9] presented Industry 4.0 implementation in the sustainability context.

Among of the challenges of the convergence between Industry 4.0 digital transformation and sustainability is the lack of integration, particularly between the software, hardware, legacy equipment, and tools used for the evaluation of sustainability [10] of operation in a manufacturing ecosystem. Use of non-standard protocols as well as data formats represents one of the leading causes for a lack of interoperability between the disparate systems, and they hinder the possibility developing a cohesive solution that can interrogate the data from these systems. Despite their usefulness, they fail to provide an integrated sustainability solution of the factory ecosystem as a whole. The objective of the sustainability framework proposed in this work is to answer the need of an integrated approach to tackle the sustainability of the factory as a whole. This will be addressed by developing a common environment where all information associated with various aspects of the factory operation can be modelled in a manner understood by all systems connected to the platform.

3. Smart Factories and Semantic Interoperability

Monitoring the sustainability of manufacturing systems requires well-defined measurement methodologies and corresponding manufacturing information models crucial to consistently compute and evaluate sustainability performance indicators of manufacturing processes. Presently there are no formal methods for acquiring and exchanging sustainability-related information across a manufacturing ecosystem. Information integration across all manufacturing subsystems from different lifecycle phases, stakeholders and standards are important to establish a cohesive information base to enable a shared meaning of the data exchanged, as well as the ability to similarly interpret the data. This is important considering each type of data may have its unique data format and language, and semantic interoperability is a priority requirement.

Semantic models provide a common vocabulary that allows for this data to be interpreted the same way across the ecosystem. In this work we will use a sustainability semantic data model and a learning factory manufacturing data model designed as a knowledge representation of the manufacturing ecosystem. These semantic models will enable the management, analysis, and exchange of data with common understanding by explicit and distributed meaning.

4. Sustainability Framework and the Smart Learning Factory

Smart factories as a concept describes an intelligent, digitally connected plant that the applies and integrates advanced technologies to achieve the goals of Industry 4.0. Automation, industrial IoT, cloud computing and data analytics all play a critical role in creating a fully connected smart factory that runs on digitally supported insights and decision making. Each of these elements also is pivotal to achieve sustainability goals in manufacturing. As part of this process, collecting and understanding data allows manufacturers to be acutely aware of their current factory landscape, giving them insights needed to make the necessary changes to systems and processes in within their manufacturing ecosystem. IoT and data analytics go hand-in-hand to help manufacturers become aware of the inner workings of their factories, which can be achieved by understanding their assets, operations, recognizing how they work, determining what parameters contribute to efficiency, and ultimately to sustainability. Manufacturers cannot achieve this without IoT. However, many assets are old and lack the ability to communicate their current status and "vitals." Smart IoT sensors can bring these assets to life and open a window into their operating behaviors as they provide the ability to measure many data points in real-time, such as heat, energy consumption, pressure and output, among other key sustainability indicators. Once these vitals are tracked and communicated, a smart factory can then store these data points in a data lake. By applying data analytics, manufacturers can begin to gain a much deeper understanding of what is happening on the production and operational levels within the factory. With this insight, transformation in the direction of sustainability is possible.

Industry 4.0 has enabled efficient monitoring, analyzing, and forecasting energy consumption through the cloud. This involves collecting sensor data which is filtered and aggregated into meaningful information through cloud computing. This information can then be converted into knowledge by applying decision support or other analytics routines using Artificial Intelligence (AI) and Machine Learning (ML), and the resulting knowledge can be fed back into product, processes, and/or service lifecycle. A digital twin can be utilized to provide real-time visualization of the manufacturing operations, plus the data associated with these digital twins can be used to provide insights for improving the operations.

Despite this, industries have been unable to exploit the advantages of these new technologies to achieve sustainable manufacturing. This is because sustainability in a factory's ecosystem has been for the most part assessed in a nonintegrated manner by evaluating the sustainability of the disparate subsystems involved in the design and management of the manufacturing ecosystem. Even though advanced technologies such as big data and analytics, horizontal and vertical system integration, and the cloud have been improved rapidly, the lack of guidelines to address problems with the aggregation of those subsystems has remained a challenge.

4.1. Sustainability framework

We present in this section a sustainability framework considering the aggregation of all subsystems that constitute the manufacturing ecosystem. This framework would support industries toward achieving their sustainability goal and become a better and responsible partner for society and the environment. For this reason, a sustainability framework for smart learning factories is proposed as a reference and guideline for the design of ecosystems in manufacturing. The proposed sustainability framework is comprised of Ingestion, process layer and twin/model storage, analytical, and presentation as follows:

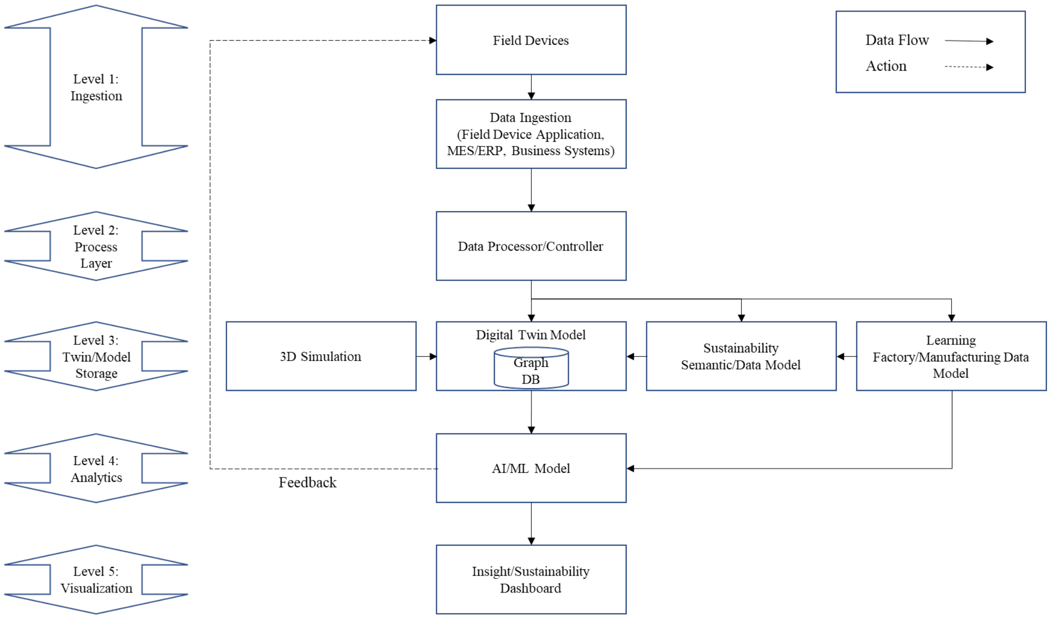

Fig. 1. Sustainability framework

- Ingestion Level: In this layer the manufacturing operational data from different data sources are captured and pipelined to a data lake or to a cloud object storage to be further analyzed. This includes event based, streaming, and batch based data ingestion into the system. This will use IoT sensors for gathering data from field devices, MES, and business services such as ERP, CRM, Warranty, and Supply chain [11]. The seamless interconnection of the networked IoT devices facilitates the sharing, gathering, and creating of information without human intervention [12].
- Process Level: The process level is a transformation engine that processes the ingested data into semantic data models. This is where translation such as quality, transformation and other data cleaning occurs. This layer also federates the heterogeneous data with varied data formats coming from different data sources. To enable data federation, in this layer the collected data is validated and transformed into a specfied format and language to achieve semantic interoperability. This is accomplished by linking each data element to an semantic model which provides the capability of machine interpretation with logic by shared vocabulary.
- Twin/Model Storage Level: In this level the digital twin is used to provide a 3-D visualization of the operation/s in the manufacturing ecosystem. The digital twin includes the Graph DB and is created using the domain ontologies which are the semantic models of the manufacturing assets, processes, and services. The Graph DB helps link the different entities in the manufacturing ecosystem to each other and to the sensor data. The sustainability semantic data model is a domain ontology and includes such KPIs as percentage of materials used that are recycled, direct energy consumption, energy saved as a result of conservation and efficiency improvements, percentage of water recycled and reused, total direct and indirect greenhouse gas emissions by weight, total weight of waste by type and disposal method, etc. The learning factory semantic data model is also a domain ontology and includes information about the facilities and processes associated with manufacturing the product. Together the sustainability and learning factory semantic data models will enable interoperability with the digital twin. Graph DB when used together with semantic models also offer extensibility, reusability, and scalability across other sustainability application within the same domain.
- Analytical Level: This level concentrates on using data from the digital twin to generate analytical insights into the sustainability of the manufacturing ecosystem. Input datasets derived from the sustainability and learning factory semantic data models will be used to train the AI/ML model for forecasting sustainability and provide feedback action to control associated manufacturing operation/s.
- Visualization Level: This level provides information to make data driven decision by providing insights through mobile, web or dashboard type applications. This could be in the form of push notifications or pull based. Providing insights with context is allows to increase productivity for the workers and increases efficiency.

4.2. Implementation details

Corresponding to the five levels of the sustainability framework proposed in this paper, Figure 2 details the cloud implementation of this framework using the Microsoft Azure Cloud platform. The IoT Edge in this design will ingest data from the variety of subsystems within the manufacturing ecosystem. This data will be bundled using a common data format and language to be pipelined to the cloud via the IoT Hub. The IoT is also a gateway for sending data securely into the cloud. The data processor/controller performs data transformation/translation for use by the Digital Twin to display sustainability KPIs across all manufacturing operations of the learning factory in real-time. In this implementation we provide option for structuring machine learning or deep learning models using Microsoft Azure cloud tools. Visualization is provided by Power BI and Power Apps for generating and customizing visualizations for different uses and scenarios.

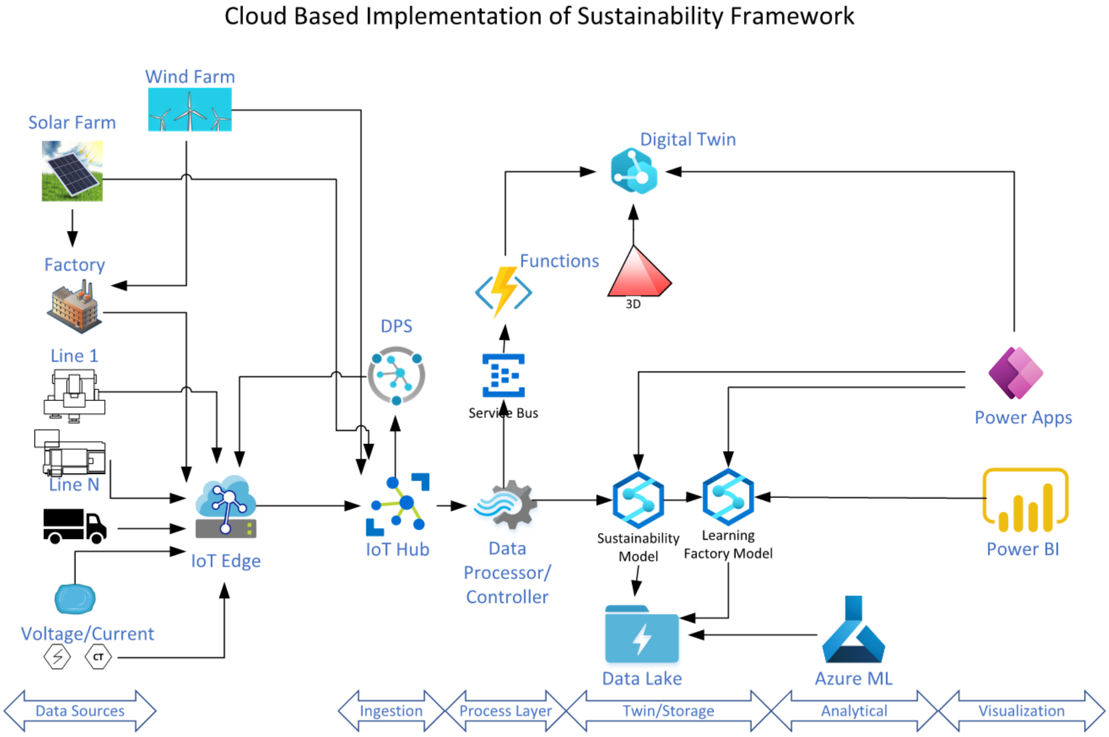

Fig. 2. Sustainability implementation

5. Manufacturing Sustainability & Undergraduate Education

One of the major concerns with undergraduate education is the increased compartmentalization of disciplines, which in the end produces graduates who are unable to view problems from any perspective other than taught in their own disciplines. All sustainability problems, including those in sustainable manufacturing involve complex issues, particularly at the systems level, that cannot be addressed by looking through the lens of one single discipline. Future engineers, scientists and managers must be taught skills and capabilities to view complex sustainability problems from all perspectives to enable robust solutions that are resilient to different externalities that may be encountered. Traditional model for undergraduate education in engineering and manufacturing has been highly discipline-specific, not providing the broad and well-rounded education needed to address sustainable manufacturing problems.

A recent unique effort in this area is an innovative cross-disciplinary undergraduate program in Smart Manufacturing & Industrial Informatics developed at Purdue University. In this program students are trained to address sustainability issues from a systems thinking perspective by using problem-based learning in a smart learning factory. This facility designed as a scale model of a smart cyber physical production system (CPPS), will provide students the opportunity to design, prototype, test, and implement Industry 4.0 technologies for application in manufacturing systems, products, and processes. The sustainability framework was used in developing the digital infrastructure for the learning factory so students can gain an understanding of the context and interconnection between the interdependent structures in a sustainable manufacturing ecosystem. This was achieved by making the learning factory a part of an ecosystem of horizontally/vertically integrated manufacturing value chain network sourcing designs, sub-assembly parts, and components necessary for production operation in the learning factory and feature integration between humans, machines, products, and processes using connectivity, intelligence, and real-time data.

6. Future Work & Conclusion

This paper discusses the advances and application of Industry 4.0 to smart learning factories and the use of the new technologies to have positive impacts on all the sustainability dimensions in an integrated way across a manufacturing ecosystem. Starting from the analysis of the state of the art in smart factories, this paper showed a holistic sustainability framework using structured information as semantic models aimed at achieving the integration and interoperability between the methodologies and tools, the aggregation of all subsystems that constitute the manufacturing ecosystem, and to support the design and management of a sustainable factory. The preliminary implementation regarding the structure of the framework have been presented and the upcoming developments of this research project will be validated over industrial use cases and implemented in the learning factory to support the undergraduate program at Purdue University.

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