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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. Operationalized as an architecture composed of multiple layers it 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 semantic models of devices, machines, and processes in the factory will be used to encapsulate the contexts of the data. 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 for application in a learning factory. 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.

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

1. Introduction

Among 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 [1] of operation in a manufacturing ecosystem. The use of non-standard protocols, as well as data formats, represents one of the leading causes of a lack of interoperability between the disparate systems, and they hinder the possibility of developing a cohesive solution that can interrogate the data from these systems. Despite their usefulness, they fail to provide an integrated sustainability solution for the factory ecosystem as a whole. The objective of the sustainability framework proposed in this work is to answer the need for 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 modeled in a manner understood by all systems connected to the platform.

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2. Related Work

In 2021, Microsoft launched the Sustainability Cloud to help manufacturers drive sustainability leveraging 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 [2][3], research have identified multiple links between Industry 4.0 technologies and sustainable operations. Among of the challenges is the lack of integration, particularly between the software, hardware, legacy equipment, and tools used for the evaluation of sustainability [4] 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. Sustainability semantic data model can automatically identify change opportunities and propose alternatives based on the existing production scenario [5]. It can illustrate the innovative approach and idea of the sustainable factory as a whole set of aspects whose integrated analysis is a key factor [6].

3. Sustainability Framework and the Smart Learning Factory

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.

3.1. Sustainability Framework & Implementation

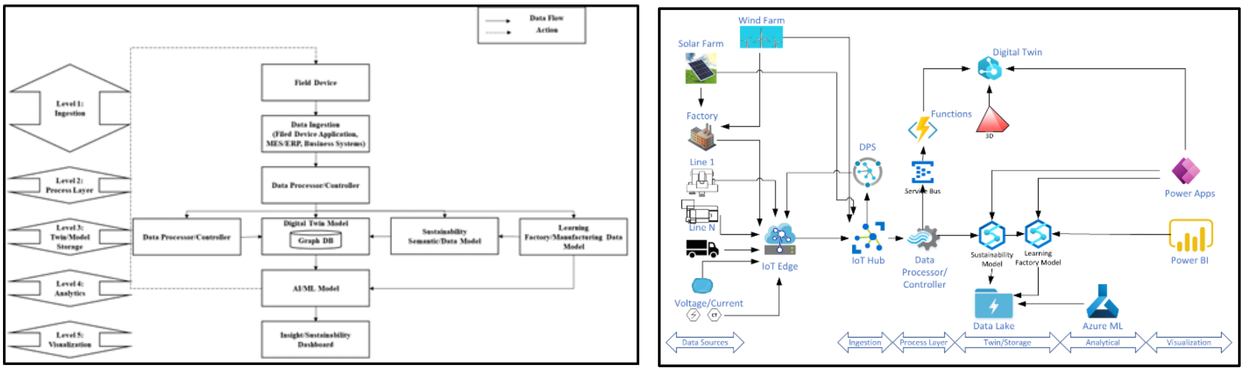

Fig. 1. (a) Sustainability framework (b) and implementation

We present in this section a sustainability framework with aggregation of all subsystems that constitute the manufacturing ecosystem. This framework will support industry toward achieving their sustainability goal. 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 as follows:

- Ingestion Level: In this layer, the manufacturing operational event-based, streaming, and batch-based data from different data sources are captured and pipelined to a data lake using a IoT Edge/Hub. This will use IoT sensors for gathering data from field devices, MES, and business services such as ERP, CRM, Warranty, and Supply chain [7].
- Process Level: The process level is a transformation engine that processes ingested data into semantic data models using JSON/Parquet open source format, which is a method of structuring data in order to represent it in a specific logical way. 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 specified format and language to achieve semantic interoperability.
- Twin/Model Storage Level: A digital twin is used to provide a 3-D visualization of the operation/s and is created using the domain ontologies using Knowledge Graph connect to the GraphDB via GraphQL. The

sustainability semantic data model is a domain ontology and includes such KPIs as percentage recycled materials used, direct energy consumption, energy saved, efficiency improvements, etc. All ontology information consisting of all learning factory assets, their relationship, configuration, and sustainability KPI are stored in domain ontology in a knowledge graph.

- 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 Artificial Intelligence and Machine Learning (AI/ML) model for forecasting sustainability and sustainability insights to the manufacturing operations.
- Visualization Level: This level provides information to make data-driven decisions by providing insights through mobile, web, or dashboard-type applications.
- Implementation : Figure 1(b) details the cloud implementation of this framework using the Microsoft Azure Cloud platform. The IoT Edge ingests data from the manufactruing subsystems using a common data format and this data is pipelined securely to the cloud. The data processor/controller performs data transformation for use by the Digital Twin to display sustainability KPIs across all learning factory operations in real-time. Machine/deep learning models were structured using Microsoft Azure cloud tools, and visualization is provided using Power BI and Power Apps for customizing visualizations.

4. 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 that 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.

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 from a systems thinking perspective using problem-based learning in a smart learning factory. 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.

5. 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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