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Sustainability of Industry 4.0/Smart Manufacturing

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Abstract

Although sustainability is still considered the cornerstone and backbone of manufacturing industries, the sustainability of Industry 4.0 (I4.0) has become a buzzword in manufacturing environments, particularly after adopting and implementing emerging manufacturing technologies (EMT). The EMT is characterized by advanced manufacturing technologies (AMT) and digital technologies (ADT). Sustainability for Industry 4.0 ($S_{I4.0}$) in manufacturing industries, in common, is separated into three primary layers. These layers are represented by the adoption of emerging technologies as the first layer, called the core layer, which depends on adopting advanced manufacturing and digital technologies. The second layer is the chosen layer, which is based on the selection of feasible emerging technologies for Industry 4.0. The third layer, which is known as the given layer, is the implementation and site readiness of Industry 4.0. All these layers constitute $S_{I4.0}$ manufacturing industries. The major goal of this paper is to discover the $S_{I4.0}$ for these layers. Although these layers coincide or overlap at one point, there's an architectural link between them. A novel assessment for measuring the sustainability index of each layer individually and aggregated later will be analyzed and presented.

Keywords

Sustainability, manufacturing systems, Industry 4.0, and emerging technologies.

1. Introduction

Industry 4.0 (I4.0) is considered an innovation in the last decade, focused on implementing or adopting emerging or contemporary new manufacturing technologies in industries. Industry 4.0/Smart Manufacturing represents a new industrial paradigm. Adopting and implementing Industry 4.0/Smart Manufacturing in manufacturing industries is playing a big role in industrialized countries. Developed countries have been eager to capture the Industry 4.0/Smart Manufacturing strategy. Emerging countries (e.g. BRICS) and developing economies (newly industrialized countries) have been actively embracing and adopting emerging advanced digital and manufacturing I4.0 technologies.

These emerging technologies are divided into two main parts: advanced manufacturing technologies and advanced digital technologies. Advanced manufacturing technologies include additive manufacturing (AM) (e.g. 3D printing), updating robotics systems, and sensors and actuators. Advanced digital technologies consist of big data Analytics

(BDA), artificial intelligence (AI), the Internet of Things (IoT), cloud computing/cloud manufacturing (CC/CM), and blockchain. These emerging technologies are the backbone and cornerstone of Industry 4.0/smart manufacturing, which contributes to the improvement of organizational performance, such as product and innovation performance, operational performance, sustainability, and profitability (Zhou and Zheng 2023).

The sustainability of the current manufacturing systems and enterprises can be improved by adopting these Industry 4.0 technologies, which can potentially provide tremendous innovation and competitiveness growth (Bai et al. 2020) and enhance society. It seems that the major aims of adopting and implementing Industry 4.0 technologies in manufacturing systems are not limited to conventional performance measurements (time, cost, quality, …etc.) but will contribute to a more comprehensive sustainable performance (economic social, and environmental). Further understanding of Industry 4.0 technologies (either advanced manufacturing or digital technologies), which are known as emerging technologies and sustainability, is important and urgent for practitioners and academicians.

A manufacturing psychology enterprise is a new concept created by Garbie and Garbie (2024). It is just like the human being, that layers of sustainability of Industry 4.0/ smart manufacturing are connected algorithms that each layer will provide one or more objects to another following layer. In this situation, the core layer is based on adopting emerging (manufacturing and digital) technologies for Industry 4.0/smart manufacturing or shop floor technologies. This core layer is used as the basic layer for the chosen layer. The chosen layer mainly identifies which technologies are selected for the appropriate or feasible manufacturing industry. Latterly, the given layer is the final target of this psychological perspective, which presents and introduces the site readiness for implementation of the plant/factory to conduct Industry 4.0/ smart manufacturing (Figure 1).

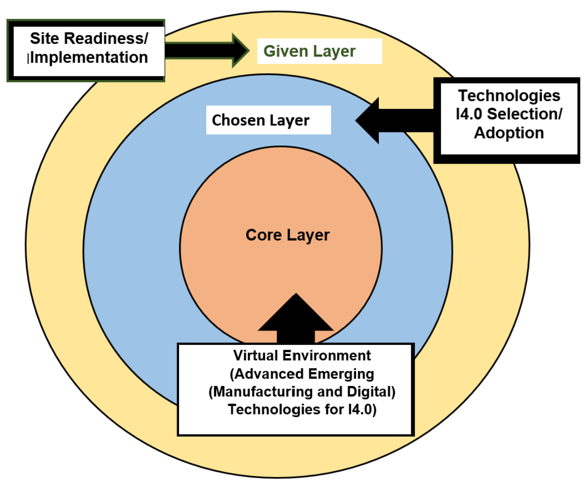

Figure 1. Architectural Layers in Industry 4.0/Smart Manufacturing

The remaining sections of this paper are organized as follows: Section two explains the problem statement, whereas Section three conducts a comprehensive literature survey related to sustainability in Industry 4.0. Section four portrays an explanatory system for distinguishing the way of connecting the Industry 4.0 layers from the point of view of sustainability. Section five will discuss an illustrated example with results. Finally, the last section gives a conclusion, the contribution of the existing research work, and a depiction of future research related to our recommended system.

2. Problem Description

Although most manufacturing companies are already engaged in Industry 4.0 activities in developed, emerging, and developed countries, the conditions for the adoption and implementation of Industry 4.0 are not yet mature. Most of the developed countries are not completely satisfied. Some developed countries have stronger infrastructure (e.g. Germany) or digital (e.g., United Kingdom). On the other side, most industrial organizations in emerging and developing countries are still in the "Industry 2.0~3.0" stage after conducting a survey, and this means that developing countries and some emerging economies have weaker physical and digital infrastructure. They are further from the I4.0 technologies frontier, and these manufacturing companies are not ready for I4.0 adoption and implementation. Therefore, these manufacturing companies hope to use these digital and manufacturing technologies revolutions to leapfrog the traditional stage of the industry from Industry 2.0 and Industry 3.0 into Industry 4.0. Small and medium-sized manufacturing enterprises, especially in emerging and developing countries, believe that their demand for I4.0 technologies will be inhibited because of many contributing factors. These contributing factors represent high implementation costs, employment disruptions, organizational and process changes, skilled employees, and a lack of knowledge management systems. Although adopting and implementing Industry 4.0 is still conceptual and not mature, there are several steps to be taken into consideration. These steps will be defined and identified in terms of unique specifications and characteristics to fully depict a picture of how to make Industry 4.0 sustainable through the new proposed technique of manufacturing psychology. To overcome these deficiencies of adopting and implementing Industry 4.0.

3. Related Research

Transitioning manufacturing enterprises/systems to Industry 4.0 and implementing it is very essential and recommended (Garbie and Garbie, 2024a and b). Industry 4.0/smart manufacturing technologies are divided into three main categories: basic technologies, intermediate technologies, and advanced technologies (Zaidi et al. 2022). Some of these advanced manufacturing technologies are classified and used as related to either the virtual environment and/or the physical environment (Garbie and Parsaei 2022). The digitalization of manufacturing supply chains positively impacts how the SC operates and improves productivity and growth (Garbie et al. 2023; Adeyemia et al. 2024).

The adoption and implementation of Industry 4.0 technologies seem to have overlapped definitions and meanings, but they are different (Zhou and Zheng 2023). Adopting Industry 4.0 technologies is highly recommended to enhance performance management in industrial organizations through measuring, evaluating, and augmenting employee performance (Pawar et al. 2023). Zaidi et al.(2022) presented the effect of adopting Industry 4.0 on manufacturing companies to gain competitive advantage and optimize performance. Adopting industry 4.0 technologies will enhance organizational performance by using lean Production (LP) (Ooi et al. 2023). Joint adoption of Industry 4.0 (I4.0) technologies and total productive maintenance (TPM) practices in manufacturing firms are presented (Tortorella et al. 2024) among sixteen countries around the world. The challenges of implementing Industry 4.0, including technical challenges, risks, critical success factors, opportunities, and enablers of implementation, were presented (Garbie and Parsaei 2022; Garbie and Garbie 2022).

4. Methodology

Sustainability in emerging technologies for Industry 4.0/smart manufacturing through the different types of technologies by identifying each one's sustainability enablers. A framework to analyze the emerging technologies for Industry 4.0 as a core stream will be illustrated and discussed to identify their enablers/indicators. A novel assessment for measuring the sustainability of emerging technologies will be analyzed and presented, considering a new architectural perspective. Emerging technologies (ET) are showing the advanced technologies of I4.0. The I4.0 technologies for the ET will include digitalization (e.g., information and communication technology, sensors, and robotic Systems) (f_1), industrial internet of things (f_2), big data Analytics (f_3), cloud computing/cloud manufacturing (f_4), cyber-security system (f_5), virtual reality/ augmented reality (f_6), additive manufacturing (f_7), cyber-production physical system (f_8),……f_n etc. The sustainability level of the emerging technologies for industry 4.0/smart manufacturing concerns at any time *t* for the core stream, $S_{ET}(t)$, can be numerically communicated as a work of all past technologies as appeared within the following Equation (1).

$$S_{ET}(t) = \sum_{i=1}^{n} f_i(t)/n \quad (1)$$

Where:

$f_i(t)$ in equation (1) can be calculated using the following equation (2)

$$f_i(t) = \frac{f_i(t)current - f_i(t)min}{f_i(t)max - f_i(t)min} \quad (2)$$

Where:
$f_i(t)$ is the normalized value of technology specified with the emerging technology (*ET*) at any time t,
$f_i(t)current$ is the existing value of technology specified with the emerging technology (*ET*) at any time t,
$f_i(t)max$ and $f_i(t)min$ are the maximum and minimum values of technology specified with the emerging technology (*ET*) at any time t, respectively.

n is the number of technologies in the emerging technology available (*ET*).

Identifying sustainability in technology selection for Industry 4.0 is highly appreciated to identify which emerging technologies can be adopted and selected for the appropriate applications. This can be done by mapping design principles (DP) of Industry 4.0 with different types of emerging technologies (either advanced manufacturing or digital), through identifying the sustainability enablers of either DP or emerging technologies, The DP includes six common principles that satisfy the requirements of implementing Industry 4.0, like interoperability, virtual reality, decentralization, real-time capability, service orientation, and modularity. A procedure to integrate emerging technologies with DP as a chosen stream will be illustrated and discussed. Also, is this chosen stream of Industry 4.0 connecting and linking to the next layer, "chosen given"? A novel assessment for measuring the sustainability of technology selection will be presented, taking into consideration a new architectural perspective. It is important to express this mapping by a numerical mathematical equation to clarify for readers how the mapping is done, as the following equation (3). The technologies I4.0 selection (TS) is based on the design principles (DP) and the core stream, which is mainly dependent on the types of emerging technologies.

Therefore, the sustainability of TS depends on design principles and their associated emerging technologies. These design principles are interoperability (g_1), virtualization (g_2), decentralization (g_3), real-time capability (g_4), service orientation (g_5), and odularity (g_6). At that point, the sustainability of the industry 4.0/smart manufacturing concerns technologies selection (TS) at any time *t*, $S_{TS}(t)$, it is numerically defined as the taking after equation as a function (3).

$$S_{TS}(t) = \sum_{i=1}^{6} W_i(t)\, g_i(t) \quad (3)$$

Where:
$g_i(t)$ is the value of pillar design principles based on the assigned emerging technologies at any time *t*.
$W_i(t)$ is the relative weight between pillars of design principles at any time *t*.

The sustainability index of implementing Industry 4.0 will be discussed by explaining the issues/challenges/barriers facing site readiness of the plant/factory. Site readiness is classified based on the five different categories, and the sustainability of site readiness depends on these five issues. These issues are technical implementation challenges, risks, critical success factors, opportunities, and implementation enablers. Each issue will be analyzed with several indicators and the sustainability index of each issue will be estimated individually later the whole sustainability index of the site readiness will be explicitly illustrated. The sustainability level of Industry 4.0 in terms of site readiness at any time *t*, $S_{SR}(t)$, can be mathematically expressed based on the type of issues of site readiness: technical challenges of implementation (h_1), risks (h_2), critical success factors (h_3), opportunities (h_4), and enablers of implementation (h_5) (Equation 4).

$$S_{SR}(t) = \sum_{i=1}^{5} h_i(t)/5 \quad (4)$$

The index of sustainability of Industry 4.0 will be based on the sustainability index in each stream: $S_{ET}(t)$, $S_{TS}(t)$, and $S_{SR}(t)$. At that point. the sustainability index of Industry 4.0 is mathematically expressed at any time t, $S_{SI4.0}(t)$, as the following Equation (5) (Garbie and Garbie, 2024a).

$$S_{I4.0}(t) = [S_{ET}(t)]^{\frac{1}{[w_{TS}(t)S_{TS}(t) + w_{SR}(t)S_{SR}(t)]}} \quad (5)$$

Where:
$W_{TS}(t)$ and $W_{SR}(t)$ are the relative weights between technology selection and side readiness, respectively.

5. Results

This numerical illustration is utilized to demonstrate the proposed methodology for assessing the sustainability index of Industry 4.0 concerning the architectural perspective based on the available emerging manufacturing technologies, technology selection and implementation, and site readiness. Due to the limitation of space of the paper, the results will be illustrated as shown in the following Tables (1-3). The sustainability index of Industry 4.0 equals 25 percent. This value seems low, and there is a lot of effort and time to reach medium and high percentages of sustainability in Industry 4.0, especially in emerging technologies and the selection/adoption of these technologies.

Table 1. Sustainability indexes in emerging technologies

Indicator (*f*)	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
Normalized Index	0.25	0.50	0.50	0.25	0.50	0.33	0.75	0.50
$S_{ET}(t)$	0.4475							

Table 2. Sustainability indexes in technology selection

Indicator (g)	g_1	g_2	g_3	g_4	g_5	g_6
Normalized Index	0.2145	0.1783	0.1605	0.2034	0.1183	0.1250
Relative weights	0.4519	0.500	0.4433	0.4575	0.4660	0.4575
$S_{TS}(t)$	0.3534					

Table 3. Sustainability indexes in site readiness

Indicator (h)	h_1	h_2	h_3	h_4	h_5
Index of enablers	0.8142	0.6000	0.8500	0.9200	0.8285
$S_{SR}(t)$	0.8025				

Then, $S_{SI4.0}(t)$, can be estimated as the above Equation (5) as follows

$$S_{I4.0}(t) = [0.4475]^{\frac{1}{[0.50\times0.3534+0.50\times08025]}} = 0.25$$

6. Conclusions

In this paper, a mental point of view as a psychological perspective of connecting Industry 4.0 layers was proposed and analyzed through the three primary layers of sustainability. The concepts of the core, chosen, and given layers were based on several unique characteristics of elements, such as novel and inventive approaches. In each layer, the essential elements were recognized and identified, and the sustainability index was assessed separately. Afterward, the global sustainability index of Industry 4.0 was also verified and assessed through the numerical illustration. It was observed that there's a mental interface between the layers of Industry 4.0. This psychological system plays a critical role, impacting not only the behavior and decision-making of individuals within manufacturing enterprises but also the interactions between the layers themselves. To further understand the influence of psychological factors, future research should investigate and assess their effects in real-life case studies.

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Biographies

Ibrahim Garbie

Dr. Ibrahim Garbie is currently a full Professor of Industrial and Systems Engineering in the Department of Mechanical Engineering at Helwan University in Egypt. Dr. Garbie received his Ph.D in Industrial Engineering from the University of Houston, Texas, USA. He also received his M.Sc. and B.Sc. in Manufacturing Engineering from Helwan University in Egypt. He has been a visiting professor at several universities and participated in several national/international educational development programs in many capacities, such as consultant and research investigator. His research interests encompass Industry 4.0 and Smart Manufacturing systems, Sustainability of Manufacturing Enterprises, Design and Reconfiguration of Manufacturing Systems, Lean Production, Agile Systems, and Engineering Education. He has authored over 100 articles in well-regarded international peer-reviewed archival journals, conferences, technical reports, and book chapters. Dr. Garbie published three authored books, one in Springer under the title “Sustainability in Manufacturing Enterprises, in March 2016”, and two books in CRC Press, Taylor and Francis, titled “Reconfigurable Manufacturing Enterprises for Industry 4.0, in July 2022” and the third one under title “Sustainability 4.0, in August 2025”. Dr. Garbie has been a frequent speaker at international conferences with more than 60 papers to his credit and a frequent reviewer in 30 International Journals and Conferences. In addition, he is a member of the Editorial Board of the Journal of Manufacturing Technology Management and the International Journal of Information and Operations Management Education. Dr. Garbie is a Fellowship member in the IEOM Society and a Senior Member of the Institute of Industrial and Systems Engineers (IISE) in addition to other Professional societies.

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Dr. Hamid R. Parsaei, is a Professor of Industrial and Systems Engineering and the Director of the Accreditation and Assessment for the College of Engineering at Texas A&M University. He served as Associate Dean of Academic

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