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Sustainable Enterprise Design 4.0: Addressing Industry 4.0 Technologies from the Perspective of Sustainability

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Abstract

The introduction of Industry 4.0 and sustainability in production is currently on everyone's mind. However, companies face difficulties to address these trends in their long-term enterprise strategy and design. Industry 4.0 promises strategic advantages for companies in many respects, but there is a lack of instruments and concepts for integrating emerging technologies in an overall enterprise system design. Similarly, the multiple perspectives regarding economic, environmental and social sustainability provide a framework for thinking about a strategy for sustainable enterprise design. Based on the three principles presented in this paper for Sustainable Enterprise Design, this article aims to present an approach to better address sustainability as well as Industry 4.0 in terms of a long-term strategic, enterprise design that is sustainable. As a result, a list of needs, functional requirements as well as possible Industry 4.0 physical solutions is proposed to achieve a long-term sustainable enterprise design. The consequence of the perspective of an enterprise as a system that can be designed provides a rigorous approach that takes advantage of Industry 4.0 technologies and the multiple perspectives and candidate physical solutions that the research community offers.

Keywords: Industry 4.0, sustainability, triple bottom line, sustainable enterprise design, industrial revolution

1. Introduction

The approach of this paper postulates that to develop a sustainable business requires business leaders to develop their businesses as a sustainable enterprise system design. When leaders treat their businesses as an enterprise system design the tone and mindset, thinking, structure and work within an enterprise change.

Long-term enterprise sustainability requires a thought process that focuses on meeting the needs of all constituents who are involved with an enterprise. For example, Tesla's mission statement is, "to accelerate the world's transition to sustainable energy" [1]. The company was renamed from Tesla Motors in 2017 to simply Tesla to align company structure to achieve this stated purpose. Accelerate is the keyword in the statement. Accelerate for Tesla means that it affects the mindset of how to do design and engineering changes. Being able to enact change rapidly is the tone and mindset that changes the approach to all work. The impact of this mission statement means that the focus is to no longer concentrate on the reduction and optimization of the unit cost of individual tasks. Instead, the focus is on how to advance sustainable energy as rapidly as possible - instead of how to develop technology for the lowest cost. The tone and mindset of this mission changes everything. This mindset represents the mindset of the Fourth Industrial Revolution.

What is the result of this mission? Tesla has a market cap of $105B versus General Motors of $38B as of April 10, 2020 [2]. Yet, Tesla's Net Income has been negative for the past 4 quarters. The market must view Tesla's design intention as

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expressed by its Mission Statement and its ability to deliver on that design intention as having longer-term value than the Mission of General Motors, which has the number 1 market share in the United States.

This paper asserts that a sustainable business is the consequence and result of sustainable enterprise design. A sustainable enterprise design practices three principles:

1. Collective and shared agreement - about an enterprise's design intention.
2. Convert complexity - to predictability.
3. Improve solutions and "the work" to better achieve design intention.

In this work, the authors want to combine the above three principles with the new waves of Industry 4.0 and Sustainability. The introduction of Industry 4.0, as well as Sustainability, should be part of a comprehensive and sustainable enterprise design instead of implementing single Industry 4.0 or sustainability concepts that are not coordinated among each other and not integrated with general sustainable enterprise design. Therefore, the authors want to provide a framework for integrating Industry 4.0, sustainability and long-term sustainable enterprise design to support practitioners in the (re)design of their firms.

After a short introduction, a brief review of the theoretical background in Industry 4.0, sustainability and long-term sustainable enterprise design is shown in Section 2. Section 3 explains the research methodology used in this work and further evaluates the anatomy of previous industrial revolutions. In Section 4, an ontological framework for sustainable enterprise design that investigates the needs, requirements and physical solutions for economic, environmental and social sustainability is developed. In Section 5, the authors present a critical discussion and an outlook for further research in the future.

2. Theoretical Background

2.1. Industry 4.0 and Sustainability

Industry 4.0 (I4.0) was first defined as a term at the Hannover fair in 2011. Industry 4.0 is the name given to the Fourth Industrial Revolution with the objective of a smart and connected factory in which products are connected with machines, with employees and with the external environment [3]. The last almost ten years of Industry 4.0 have been technology-driven, while for the coming years a data- and intelligence-driven era is expected [4]. According to Rüßmann et al. [5], the nine core technologies of Industry 4.0 include: 1) advanced robotics, 2) additive manufacturing, 3) virtual and augmented reality, 4) simulation, 5) vertical/horizontal data integration, 6) industrial internet of things, 7) cloud, 8) cyber-security as well as 9) big data and data analytics.

Within the framework of a data and intelligence-driven development of Industry 4.0, methods of artificial intelligence such as machine learning or deep learning will gain great importance in the near future in order to process and use data that can be generated on the shop floor in a meaningful way [6].

In addition to the use of artificial intelligence, further discussion is currently taking place with regard to Industry 4.0, both on the scientific level and on the level of management literature. It is discussed how Industry 4.0 is related to the hotly debated topic of sustainability and to what extent Industry 4.0 can also contribute to increasing sustainability, e.g. [7, 8]. When addressing sustainability, the authors refer to the well-known bottom line of sustainability, which includes (i) economic, (ii) environmental and (iii) social sustainability [9]. Many researchers confirm that Industry 4.0 has a big potential to increase productivity and thus long-term economic sustainability and "survivability" [5]. According to Jeske et al. [10] productivity should increase by 32% until 2025. Further, other researchers investigate the impact of Industry 4.0 on environmental sustainability (see the review of Stock and Seliger [11]). As an example, de Sousa Jabbour [12] states that Industry 4.0 technologies may unlock green manufacturing and therefore act as a lever for environmental sustainability. Finally, many scientists believe that Industry 4.0 will enhance the role of the human in manufacturing and therefore also increase social sustainability. Romero et al. [13] introduce the term Operator 4.0, where operators can increase their capabilities through Industry 4.0 technologies with sensorial, physical and cognitive assistance.

2.2. Long-Term Sustainable Development of SMEs

The three principles of sustainable enterprise design were introduced in Section 1. This section describes how these principles were derived and what is meant by, "the practice" of these principles. Ever notice that doctors and lawyers say that they have a "practice?" That they practice law or that they practice medicine. Designing and running an enterprise system may also be considered a practice.

The first principle acknowledges that when the constituents of an enterprise share a common purpose, the work becomes how to achieve that purpose. Sustainability in this context means that the people in an enterprise have a shared and collective understanding of what they seek to accomplish every day. By having a knowledge of what success is, people can then be successful. However, in many enterprises, success is never good enough. For example, a company president tells the managers that we need 300 units per hour, they achieve that target, and then they are told, no, we need to produce 320 units per hour, even though capacity is limited to 300.

There was a shared agreement about the purpose to make 300 units per hour, only to hear it change, unilaterally, to 320. The team gets demoralized and goes back to 240 units per hour. Collective agreement is an on-going process and practice of shared understanding and shared decision patterns.

The second principle of sustainability requires converting complexity to predictability. Complex systems as defined by [14] do not result in predetermined outcomes because of human decision making that is inconsistent. The second principle describes the need to create a decision pattern that results in predictable results -- even when the inputs are variable.

Principle three extends the first principle of shared agreement regarding design intention to improve "the work" itself to achieve a purpose. To express design intention, the enterprise constituents must understand "Why", "What" and "How". The Why expresses the needs of the systems' constituents. What expresses the purpose of the system and defines what success means. The "**What**" is NOT a stretch objective or an aspiration. Instead, the **what** is the expression of a shared commitment by the system design team to achieve a defined purpose. The "*How*" is the next step of design. A how defines the proposed physical solution to achieve the collective-agreed purpose. The *how* is the practice that Toyota implements as Standard Work [15], and represents the best way that we know at the present time to achieve purpose -- and according to Ken Kreafle, former Quality Manager at Toyota, is, "a record of all problems solved" to date [16].

3. Research Question and Research Methodology

3.1. Research Question

As mentioned in the introduction, many practitioners in industry have difficulties with integrating multiple objectives in enterprise design like sustainability as well as the introduction of promising Industry 4.0 technologies. Based on previous research conducted in collaboration and in workshops with over 60 firms from the US, Europe and Asia [17] there is a lack of practical tools and frameworks to support practitioners in implementing Industry 4.0. At the same time, they see a need in developing a long-term strategic vision including also ambitious objectives like Industry 4.0 and sustainability.

To support firms in this process and to help close this gap in research, the authors propose the use of a framework for Sustainable Enterprise Design that addresses Industry 4.0 and the multiple dimensions of sustainability. Therefore, the research question (RQ) in this work is the following:

RQ: "Given the multiple perspectives and dimensions of sustainability and Industry 4.0, is it possible to develop a Sustainable Enterprise System Design that addresses constituents' needs without Trial and Error?"

3.2. Research Methodology

The challenge of any system design is that it must answer the question, "How do we know?" that a design meets constituents' needs with validity [18]. Cochran [19] described the difference in approaching design from engineering versus a technology viewpoint. "Technology-driven fields are characterized by finding a solution based on the result of trial and error. A physical prototype must be built in order to prove a design result true or false. Science-driven fields use axioms to prove or disprove a design. A physical prototype is not required."

In this research, the authors concentrate on a more detailed view of the third principle of Sustainable Enterprise Design by looking at the Why, What and How as illustrated also in Fig. 1. As a basic concept to describe the multiple perspectives of sustainability, the Triple Bottom Line concept [9] is used. After a review of the past industrial revolutions, Section 4 of this paper, investigate what are typical needs (the Why), functional requirements (the What) for economic, environmental and social sustainability in an enterprise. Based on Industry 4.0 concepts and technologies the authors discuss possible physical solutions (How) to achieve the functional requirements.

The structuring of the Why, What, and How communicates the thinking about design. Foley and Cochran [20] affirm the ISO 15288 Standard for Systems and Software Engineering that an ontology provides, "a means for evaluating the efficacy of manufacturing system design and implementation." A manufacturing system is considered to be a subsystem within the larger enterprise or production system. Fig. 1 illustrates the proposed ontological framework for Sustainable Enterprise Design 4.0.

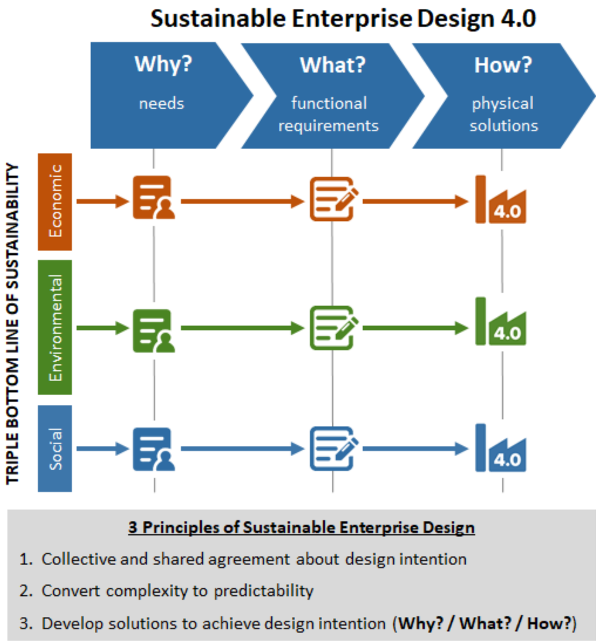

Fig. 1. Sustainable Enterprise Design 4.0 approach.

The outcome of Section 4 does not represent an exhaustive list of needs, requirements, and solutions, but instead serves as an initial starting point to further engineering science research to develop an ontology for Sustainable Enterprise Design 4.0 that is predictive of outcomes, without the need for exhaustive prototyping of solutions.

3.3. Anatomy of Industrial Revolutions

Industry 4.0 can be characterized as The Fourth Industrial Revolution [21]. Each industrial revolution builds on the previous industrial revolution. Thomas Kuhn [22] described the structure of scientific revolutions as having three phases: Crisis, Evolution and Normal Science.

The first industrial revolution in the U.S. was the result of the Armory System and Thomas Jefferson's proposal in 1785 that Congress mandate interchangeable parts for all musket contracts. In 1819, Roswell Lee introduced inspection gauges at Springfield Armory and in 1822 John Hall announced success at Harpers Ferry using a system of gauges to measure parts [19].

Table 1. The First Industrial Revolution: Needs, requirements and solutions for field serviceability of weapons.

N°	Needs	Functional Requirements	Physical Solutions
1	Soldiers could service and repair muskets in the field	Be able to replace parts from one musket with another musket	Measurement Standards and Gages to produce parts to a specification rather than by "file to fit."
2	Increase production volume and efficiency	Reduce human manual labor	Water-powered, belt-driven machine tools

The second industrial revolution brought mass production [23]. Mass production was made possible by the invention of the moving assembly line by Charles Sorensen and Henry Ford [24]. Black paint was used because it dried faster so that Ford could meet the high demand for vehicles, 90% of which were pre-sold [25]. Ford introduced the revolutionary five-dollar day so that the workers building the cars could afford the cars that they made. Most importantly, the Model T's success was due to its low cost and ease of maintenance…. which required much less time than maintaining animals for transportation.

Table 2. The Second Industrial Revolution: Needs, requirements and solutions for low cost and practical replacement.

N°	Needs	Functional Requirements	Physical Solutions
1	1878 State of Wisconsin Race, "A cheap and practical substitute for the use of horses and other animals on the highway and farm" [46].	Reduce maintenance time and cost	"Horseless Carriage" The Model T
2	Create a market for the product produced	Workers could afford to buy the product that they produced	The $5 day implemented by Henry Ford at Highland Park
3	A vehicle for every family	Meet customer demand (in high volume)	Moving assembly line (which relied on interchangeable parts)

Toyota changed the world by respecting the needs of the internal customers, by proclaiming "respect for the worker" and seeking to optimize the use and value of people instead of equipment [26]. Toyota's innovation was to break through the barrier that high quality meant high cost. Also, out of necessity the Toyota Production System out had to produce a higher variety of products in lower volumes at the same or lower unit cost than its mass production competitors [19, 23]. The pull system and the Single Minute Exchange of Dies [27] in stamping were the enabling technologies / physical solutions that achieved this requirement. The role of human beings in manufacturing changed again. People became an integral part of the control of production quantity, variety and quality as a result of the Toyota Production System (TPS) Design. Taiichi Ohno, likened the design of TPS as putting a "tight suit on a fat man," to underscore how TPS was designed to identify abnormal conditions and waste in the way that work was being done to meet takt time [28].

Table 3. The Third Industrial Revolution: Needs, requirements and physical solutions for high quality, low cost, product flexibility and on time delivery.

N°	Needs	Functional Requirements	Physical Solutions
1	Greater variety in the products offered at same or less cost than with Second Industrial Revolution	Produce the quantity and variety of products demanded by customers	Pull System and SMED: Single Minute Exchange of Dies (to enable small lot size production)
2	Higher Quality, more reliable products	Do Not Advance defects	Integrated quality control. Jidoka precepts and Poka-yoke Devices to prevent or not advance defects to customer line, cell or operation
3	Continually identify and reduce waste	Immediately identify an abnormal condition and resolve in a pre-defined way	Integrated production control by Team Members -- using Standard Work and Andon to resolve abnormal conditions and ensure production to takt time

4. Ontological Framework for Sustainable Enterprise Design 4.0

In this Section, an ontological framework for Sustainable Enterprise Design 4.0 is proposed as described in the research methodology section. According to the analysis of past industrial revolutions, the top-level needs, functional requirements as well as candidate physical solutions in the ongoing Fourth Industrial Revolution giving special focus on multiple aspects of sustainability are described. Afterward, the authors are looking from the perspective of the Triple Bottom Line concept to investigate the Why, What and How for economic, environmental and social sustainability based on physical solutions derived from Industry 4.0.

4.1. Needs, Functional Requirements and Physical Solutions in the Fourth Industrial Revolution

From an economic perspective, the main aim of Industry 4.0 is digitization to connect products with machines, workers and the enterprise environment outside the smart factory. Industry 4.0 aims to enhance automated manufacturing processes to be able to produce small lot sizes in a highly efficient way, which is also called mass-customized production [29]. Also, the aim of Industry 4.0 is environmental sustainability to do no harm to the environment. Here technologies such as additive manufacturing contribute to the replacement of the physical transport of materials, the atoms, to the transport of information, the bits, to the nearest location of production-on-demand centers equipped with additive manufacturing machines or other flexible manufacturing systems [30]. The Fourth Industrial Revolution also raises the awareness of environmental sustainability by making the degree of sustainability measurable through enabling technologies like IoT, smart sensors and real-time connectivity. Another aspect of sustainability lies in the integration of human beings in the digitized, smart-factory enterprise. The requirement is to provide the appropriate qualification and use of new technologies that provide new opportunities for Associates to collaborate and interact with machines, robots and computers, and with each other.

Table 4. Sustainable Enterprise Design 4.0 Framework: Needs, requirements and physical solutions for sustainability.

N°	Needs	Functional Requirements	Physical Solutions
1	Economic Sustainability	Associates are able to co-create products and services	Jidoka ++. Integrating human work with machines, communications, and IT. Further progress in integrating what people do well with technology
		Digitize and produce mass-customized products and services	Digitalization (e.g., cloud, big data analytics, IoT) and emerging mfg. technologies (e.g. digital tools, intelligent robots, computer vision, AI
2	Environmental Sustainability	Do no harm to the environment	Environmental sustainability and technology integration
			Local production on demand (e.g., additive manufacturing) and make sustainability visible and measurable (e.g. IoT, connectivity)
3	Social Sustainability	Expand Abnormal Condition ID and resolution to Enterprise	Enterprise wide feedback in all areas (e.g. design, manufacturing), using IoT
		Integrate people in an ethical and socially sustainable way	Human-technology (e.g. robots) collaboration with Jidoka mindset for enterprise

4.2. Addressing Economic Sustainability in Sustainable Enterprise Design 4.0

Table 5 gives an overview of identified needs, functional requirements and possible physical I4.0 solutions. On a strategic level, great emphasis is given to the shift from tangible products to innovative services or product-service systems as customers of the future expect intelligent and digital features. Further disruptive business models are a risk for traditional enterprises, but at the same moment show also a great potential for innovative enterprises. Enterprise system designers also need an individual Industry 4.0 strategy as well as a roadmap of how to implement concepts and technologies that promise to be the highest benefit for their company. Products are no longer developed only by an internal R&D department but in collaboration with customers (open innovation) [31] as well as with a large network of technology partners specialized in their field (e.g., enterprise collaboration network models) [32]. Increasing efficiency remains an important goal in the Industry 4.0 era. As with the Lean era the requirement is to right-size all work to meet the needs of the customer with the least possible waste. Industry 4.0 offers a new frontier with the application of new and innovative production and computational technologies aiming to connect products, machines, workers and processes of an enterprise. The collaborative use of manufacturing technologies (e.g. autonomous robots) will enable further reduction of lead time and will result in the production of custom products on demand.

Quality remains an important topic, too. As new technological concepts in computer vision and machine learning emerge, improved levels of quality detection and assurance are possible in manufacturing.

Digitization also brings a new concern onto the stage, namely the danger of cyber-attacks. In the future, suitable assessments and mitigation measures will be required to minimize security risks.

Table 5. Needs, requirements and physical solutions for economic sustainability.

N°	Needs	Functional Requirements	Physical I4.0 Solutions
1	Satisfaction of "non-material" customer needs	Increase the "non-tangible" value and benefit	Smart servitization [33]; digital product-service systems
2	Future business viability	Apply disruptive business models [34]	Sharing economy and digital business models (freemium, digital upgrade, etc.) [35]
3	Long term viability	Define a vision for the long-term future	Industry 4.0 strategy and roadmap
4	Business resilience	Be a pioneer in customer-oriented innovation	Open collaboration network models
5	Efficient business processes	Increase the efficiency of business processes	Cloud, digitalization; horizontal data integration (ERP/SCM); artificial intelligence and big data analytics to automate business processes and for better decision-making
6	Efficient operational processes	Increase the efficiency of operational processes	IoT; real-time connectivity; data integration and interoperability; AI; advanced and additive manufacturing; cyber-physical systems; simulation
7	Raise quality standards	Reduce failures in production as well as rework	In-process quality control through intelligent systems (using image processing, computer vision, machine learning, 3D scanning)
8	Protection against criminal activities	Reduce the risk of cyber attacks	Cyber-security assessment and measures/technologies

4.3. Addressing Environmental Sustainability in Sustainable Enterprise Design 4.0

Table 6 illustrates needs, functional requirements as well as physical Industry 4.0 solutions for achieving environmental sustainability. Technologies like IoT, real-time connectivity, smart sensors, and simulation allow in the future to monitor and predict energy consumption and therefore to enhance better decisions and measures for energy-efficient manufacturing. Computer vision and sensing technologies increase the precision in dosing and allocating the right amount of material to re. According to Nascimento et al. [36] Industry 4.0 technologies act also as an enabler for a circular economy and to reduce waste and facilitates the reuse of material. Industry 4.0 technologies support the usage of virtual mock-ups for prototyping and testing and thus to reduce material for physical mock-ups and physical tests. Traffic and logistics processes are one of the most discussed problems in environmental sustainability, where Industry 4.0 helps to bring production back to the place of consumption (reshoring) [37] and to produce-on-demand (additive manufacturing) [38].

New simulation tools, for example, AnyLogic or Simio, allows the design of economical, and also ecologically efficient logistics network models [39]. For example, Industry 4.0 technologies and digitalization can be used in service industry for substituting flights and traveling of technicians for repairing machines at the customer site by using Augmented Reality headsets. Furthermore, big data analytics, IoT as well as a digitized collection of sustainability key performance indicators enable measuring environmental sustainability and therefore to conduct sustainability benchmarking [40]. A final but important need is the minimization of paper in enterprises as today most of the paper can be easily substituted by digital devices and visualization technologies.

Table 6. Needs, requirements and physical solutions for environmental sustainability.

N°	Needs	Functional Requirements	Physical I4.0 Solutions
1	Awareness of current energy consumption	Monitor energy consumption	IoT; real-time connectivity; smart sensors
2	Awareness of future energy consumption	Predict energy consumption	Simulation, digital shadow/twin
3	More precise usage of resources and materials	Increase the quality of dosing (use and allocation of materials)	Computer vision; smart sensors; material flow simulation
4	Prevention of waste	Reuse material	Industry 4.0 as an enabler of circular economy (e.g. IoT, horizontal data integration)
5	Sustainable product development	Predict design results (i.e. reduce the need for physical mock-ups)	Usage of simulation tools for virtual prototyping and manufacturing; Computer-Aided Engineering; Virtual Reality
6	Sustainable delivery processes	Reduce waste in logistics and transportation processes	Additive manufacturing (transport of bits instead of atoms); increase reshoring through efficient Industry 4.0 manufacturing processes; simulation tools for sustainable logistics network modelling
7	Sustainable after-sale services	Reduce service and maintenance travel	Augmented Reality; IoT; digital instructions for maintenance and repair; identification and tracking/tracing technologies
8	Create competition in sustainability	Make environmental sustainability measurable and quantifiable	IoT, big data analytics and digitalization as enablers for measurement tools/methods of environmental sustainability (Co2 footprint calculator, green value stream mapping)
9	Paperless company	Reduce the usage of paper	Digitalization of business processes, IoT, visualization on digital devices instead of using paper

4.4. Addressing Social Sustainability in Sustainable Enterprise Design 4.0

Table 7 provides an overview of needs, functional requirements and physical Industry 4.0 solutions for social sustainability. From a basic perspective, several Industry 4.0 technologies help to increase worker safety and to reduce physical workload (e.g. through automation and use of sensing technology) and mental stress or workload (due to more effective information provisioning - right time, right content).

Even though the automation of routine tasks will lead to a reduction of mundane jobs, it will in parallel also lead to an increase in new jobs like data managers, data scientists, robot programmers or developers of AR applications [41]. This change will have a positive impact on the attractiveness of jobs as Sustainable Enterprise Design 4.0 oriented jobs will enable workers to align work with their individual and creative abilities.

However, this change in the role of people in future jobs also creates a need for qualification in new and digital skills that will necessitate the development of appropriate training programs for the Sustainable Enterprise Design 4.0. The digital transformation will lead also to a change in communication, holding meetings remotely and better combining work and private life or family as in many cases the physical presence of the worker is not needed for all the working time. In addition, digital technologies also help to verify and guarantee fair work conditions (e.g. no child labor) in the supplier network.

Table 7. Needs, requirements and physical solutions for social sustainability.

N°	Needs	Functional Requirements	Physical I4.0 Solutions
1	Safety at work	Increase safety at work	Automation of dangerous works; computer vision technologies for safe human-robot interaction; smart sensors for safe access to automated cells
2	Physical ergonomics	Reduce physical workload	Automation; autonomous and collaborative robots; passive/active exoskeletons;
3	Cognitive ergonomics	Reduce mental stress	Augmented and Virtual Reality; projection and laser-based assistance systems; voice control; artificial intelligence)
4	Job creation	Develop new roles and job profiles	Creation of new job profiles through Industry 4.0 (chief digital officer, production data scientist, robot coordinator, AR developer)
5	Attractive jobs	Increase the attractiveness of work	Reduction of heavy loads and manual work (e.g. automation) while increasing creativity at work
6	Qualification and Training	Qualify employees according to new needs for skills	Training and qualification programs in Industry 4.0 technologies; Augmented Reality
7	New ways of interaction and communication	Make communication independent of location and interactive	Usage of digital communication and meeting tools (e.g. MS Teams or Zoom); Augmented and Virtual Reality
8	Managing work and family	Create opportunities for smart working	Home office through digital devices; IoT; Cloud; real-time connectivity
9	Guarantee fair work conditions in the supply chain	Monitor and control fair work conditions in the supplier network	Digitalization; digital communication and verification tools; automated business processes for audits

5. Discussion and Outlook for Further Research

The presented framework aims to pave the way for further research in Sustainable Enterprise Design by addressing

Industry 4.0 as well as sustainability. The presented needs, functional requirements and physical Industry 4.0 solutions should be seen as examples and should not be considered to be exhaustive and do not yet adhere to the concept of CEME (collectively exhaustive and mutually exclusive) [42]. The authors will further develop the proposed framework in future work and want to motivate other researchers to join a scientific discussion.

Future research will address the need to study and to solve existing relationships and dependencies between the presented functional requirements and physical solutions in the three perspectives of economic, environmental and social sustainability. Not in all, but in some cases, physical solutions have a dependency and therefore an impact on the satisfaction of more than one functional requirement in the three perspectives of sustainability. An understanding of the design relationships between physical solutions and functional requirements may create enterprise design relationships that yield unpredictable or unintended system results.

Solutions should be developed to minimize complexity. This work will require agreement about how to define when an Enterprise Design is considered complex or not. To begin to address this research question, future research will posit the use of the application of well-known Axioms from design theory (in particular Axiomatic Design) to address the question of complexity and enterprise design. Axiom 1 in Axiomatic Design, the "Independence Axiom", stipulates that it is necessary for any system design to, "Maintain the Independence of the Functional Requirements" [43]. Independence is maintained through the selection of the Physical Solutions of the enterprise design. Ideally, each defined physical solution is only related to one functional requirement and does not have an influence on the other functional requirement, called an uncoupled design [44].

In addition, future research will also investigate the application of Axiom 2 in Axiomatic Design, which is called the "Information Axiom". The Information Axiom [43] helps the designer to choose among multiple possible solutions. The selected physical solution should be characterized by the smallest information content to ensure a higher probability to satisfy a defined functional requirement. Such an approach will help the system designer to select the most appropriate and promising physical solution in the presence of alternative candidate solutions. The ultimate goal is to convert a complex system to a system that is designed to be predictable.

A third step in further developing the presented framework for Sustainable Enterprise Design 4.0 will be to develop an exhaustive and detailed overview of physical solutions satisfying all identified functional requirements. Here the authors plan to use a top-down decomposition and mapping process extended from Axiomatic Design theory called Collective System Design [45]. This means that functional requirements and physical solutions will be identified at different operational levels starting from an abstract top-level and going towards lower levels needed to describe tangible solutions that can then be further used by the systems designer for long-term sustainable design of the enterprise. The result of applying the 12 Steps of the Collective System Design Methodology is that the authors will derive a Collective System Design map and a list of design guidelines and measures for Sustainable Enterprise Design 4.0 based on collaborative research with Industry.

6. Conclusions

In summary, the authors have examined the third aspect of Sustainable Enterprise Design 4.0: The Why, What and How. The main academic contribution of this work is to present a framework for integrating Industry 4.0, sustainability and long-term sustainable enterprise design for starting a scientific discussion about Sustainable Enterprise Design 4.0. Future work will address collective and shared agreement - about an enterprise's design intention through the use of the Collective System Design methodology. The research will be conducted with respect to the second aspect of Sustainable Enterprise Design 4.0: Convert complexity - to predictability by first developing collective agreement about the relationships between enterprise design and complexity.

It is important to note that each Industrial Revolution builds on the previous Industrial Revolution. The authors present an Ontological Framework for communicating the underlying system design of the prior three Industrial Revolutions and use this framework to discuss the future of Industry 4.0 as Enterprise Design 4.0 from the three perspectives of sustainability as described by the Triple Bottom Line.

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