

Towards Sustainable Manufacturing with Industry 4.0: A Framework for the Textile Industry

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Abstract

Due to increasing sustainability demands, textiles manufacturing, an industry that uses substantial amounts of natural resources, energy and labour, are facing tough challenges in the years ahead. One of the more overlooked concepts with great potential for sustainable manufacturing is Industry 4.0. This paper addresses how the textile industry is engaging with Industry 4.0 technologies and applications in the context of sustainable manufacturing. A proposal for an implementation framework is introduced based on a literature review within this field.

Keywords: industry 4.0, sustainability, characteristics and properties, textiles manufacturing

1. Introduction

Industry 4.0, or the fourth industrial revolution, is a term used to describe a modern era of manufacturing. It represents a set of concepts and technologies which can be connected into networks and enable uninterrupted operations - both within a single factory and throughout their supply chains. More importantly, a global concern for sustainability have led researchers to showcase Industry 4.0 technologies and applications as having a positive impact towards the triple bottom line of sustainability in manufacturing operations, (Machado, et al., 2019). Various industrial applications with Industry 4.0 technologies towards sustainable manufacturing are presented by (Stock & Seliger, 2016). Similar research by (Kamble, et al., 2018) and (Muller, et al., 2018) show that implementing Industry 4.0 will have positive effects on sustainability throughout some of the main manufacturing sectors such as automotive, electrical, and chemical industries. Finally, case studies are emerging that present Industry 4.0 applications and technologies for improving economic sustainability in manufacturing companies, (Stock & Seliger, 2016). (Braccini & Margherita, 2018) also highlighted environmental and social sustainability benefits when implementing Industry 4.0 concepts. As manufacturers are becoming more aware of the importance of Industry 4.0 and sustainability, they are still faced with numerous challenges such as lack of general Industry 4.0 knowledge, strategic planning and financing (Majumdar, et al., 2019), (Calabrese, et al., 2021) and (Frank, et al., 2019).

One of the industries that have a particularly high interest in the triple bottom line is the textile industry. Some studies show that the textile sector ranks lowest in terms of Industry 4.0 awareness and adoption, when compared to other manufacturing sectors, (Bai, et al., 2020) and (Sari, et al., 2020). Thus, the aim of this paper is to explore how Industry 4.0 is used within textile manufacturing, and furthermore, if Industry 4.0 is used achieve sustainable manufacturing.

2. Sustainability and Industry 4.0 within textile manufacturing

The textile industry, being one of the larger industries in the world, has a substantial impact on the economies, environments and people. Specifically, the textile manufacturing sector has been receiving

attention on how it employs its labour and how textile factories affect the environment. As these factors are being more acknowledged by retailers and textiles consumers, it becomes necessary to fulfil them in order to stay competitive and survive as a manufacturing business. As stated before, one of the potential answers to collectively address sustainability challenges is Industry 4.0, which puts forth many opportunities for sustainable manufacturing.

Institutions are seen to play a major role for textile companies when it comes to Industry 4.0. The European Technology Platforms' (ETP) Fibres, Textiles and Clothing division are one of the first to put Industry 4.0 in context for textiles manufacturing, (ETP, 2016). Researchers have also contributed with concepts and summarized Industry 4.0 for the textiles sector in three categories: smart products (textiles with integrated microelectronics, smart applications, nanotextiles, materials that adapt to different environments), smart networks (globally traceable products, smart retail services, new business models) and smart factories (connected processes and cyber-physical systems, micro-factories), (Bertola, 2018).

Many textiles manufacturers are positioned within global textile supply chains that include many stakeholders, which makes it difficult to implement changes. Process diversity is another barrier that challenges Industry 4.0 adoption. There are many subprocesses to manufacture a fabric, which are usually carried out by different factories, and connecting these processes into a unified network is a very challenging task, (Kemper & Gloy, 2017). One study suggests that the textile industry can benefit from certain Industry 4.0 technologies in the context of sustainability, but studies were inconclusive, (Bai, et al., 2020). Thus, it is unclear which Industry 4.0 applications are utilized by textiles manufacturers and how, especially in the context of sustainability.

In an ideal scenario, a typical textile manufacturer might need to consider the following:

- Industry 4.0 factors - technologies, standards, roadmaps and frameworks, such as the more popularly used Reference Architecture Model for Industry 4.0; equipment and application suppliers; ISO standards for Industry 4.0 such as Internet of Things (IoT) standards (ISO, 2018).
- Sustainability factors - regulations and policy; labour upskilling; financing opportunities; market demands for triple bottom line.
- Strategic factors - defining financial value; stakeholders; internal knowledge and skills; knowledge support and financing opportunities; implementation strategy.

Considering all these elements in detail, it often becomes a difficult and time-consuming task when a textile company needs to decide on changes or improvements towards a more sustainable business.

Thus, the aim and motivation of this study is to identify textiles manufacturers' adoption of Industry 4.0 towards sustainable manufacturing.

3. Literature review

The research will divide literature findings into separate Industry 4.0 components as proposed by (Hermann, et al., 2016). The findings will be used to create a more detailed approach needed to select certain Industry 4.0 technologies and applications for doing sustainable manufacturing.

A systematic literature review was conducted with three sets of keywords that are placed in the following categories:

- **Industry 4.0** (keywords: *Cyber-Physical Systems, Internet of Things/Internet of Services, Smart Factory, Cloud, Industry 4.0*)
- **Textile Manufacturing** (keywords: *textile industry, textile finishing/dyeing, knitting, weaving, non-wovens, sewing, textile manufacturing*)
- **Sustainability** (keywords: *economic/environmental/social sustainability, sustainable*).

The authors' university library database (SUPrimo REFERENCE) was used to conduct the search. This library includes all major scientific literature databases and was thus suitable to conduct this search. The keywords were combined in the search engine and the papers that included at least one keyword from each category were selected. A total of 18 papers were found using this method. Each paper was then evaluated and summarized based on two main criteria: Triple bottom line attributes and Industry 4.0 components that were found to be considered in each paper. Additionally, the contributions have been divided into conceptual contributions, surveys and case studies, as seen below in Table 1 and Table 2.

3.1. Conceptual contributions

This section addresses the articles that propose theoretical frameworks, concepts, and insights into the present and future state of the textile industry in the context of Industry 4.0 and sustainability. Table 1 summarizes these contributions.

Some papers worth addressing include (Bertola, 2018), in which Industry 4.0 components are incorporated within all primary textile business operations. The author provides a clear framework of how textile supply chain segments such as production, logistics, Supply Chain Management (SCM) and products are attributed to three main Industry 4.0 themes - smart products, smart factories and smart networks. Furthermore, the author discusses opportunities for environmental, social and economic improvements. (Kemper & Gloy, 2017) present an outlook of how Industry 4.0 technologies will shape the textile industry. A concept is presented that integrates vertical (hierarchical manufacturing operations) and horizontal (different value chain processes that extend beyond the company) operations into a streamlined Industry 4.0 platform throughout the supply chain.

Table 1. Conceptual contributions

Reference	Triple-bottom line attributes	Industry 4.0 components	Contribution
<i>Conceptual contributions:</i>			
(Bertola, 2018)	Environmental, Economic and Social	Smart Factory	An outlook on Industry 4.0 potential in textile and apparel industry.
(Kemper & Gloy, 2017)	Economic	Smart Factory, Smart Manufacturing Platforms	An outlook and conceptualization of future connected smart textiles companies.
(Cloppenburg, et al., 2017)	Environmental, Economic	Cyber-Physical System	CPS software for the non-woven industry machinery for reducing energy and equipment related costs.
(Park, et al., 2019)	Environmental, Economic	Cyber-Physical System and Smart Factory	Industrial IoT platform for improving efficiency and reducing costs for the dyeing and finishing industry.
(Park, et al., 2020)	Environmental	Cyber-Physical System	Cyber-Physical System for improving energy efficiency.
(Gokalp & Gokalp, 2019)	Economic	Smart Factory	List of potential Industry 4.0 applications for textile production and management.
(Tsai, 2018)	Environmental, Economic	Internet of Services	Profit maximization decision model which is defined for an Industry 4.0 application.
(Damodaram & Ravindranath, 2010)	Economic, Social	Internet of Services	Cloud Computing adoption framework, list of benefits of Cloud Computing for apparel manufacturing supply chains.
(Duarte, et al., 2018)	Environmental, Economic and Social	Smart Factory	Assessment of technological advancements in textile manufacturing equipment.

Authors also reflect on the future state of textile industry in high-wage countries as well as the challenges for implementing Industry 4.0 technologies for such countries. Standardization, technology availability, skilled workforce and process organization are listed as potential barriers, as well as the industry's

knowledge base on Industry 4.0 subjects. (Gokalp & Gokalp, 2019) present a list of potential Industry 4.0 use cases for textile manufacturing. Furthermore, the authors address both benefits and challenges of such use cases. It is also addressed that further work needs to identify applicability of such use cases in real life scenarios in textile companies.

3.2. Surveys and case study contributions

This section covers case studies and surveys. The articles are summarized in Table 2. There are a number of surveys that address the topic of Industry 4.0 within the textile industry, some of which also elaborate on the importance of sustainability within the sector. (Ahmad, et al., 2020) present a qualitative study gathered from 12 large textiles manufacturers, in which the results present detailed sustainability issues from each company and how these are addressed by implementing off-the-shelf business intelligence systems combined with different Industry 4.0 technologies. Some authors also urge to further analyse how Industry 4.0 may influence different manufacturing industries within particular sustainability dimensions.

Looking into more concrete examples, (Ku, et al., 2020) develop a smart factory setting for the textile dyeing industry, more specifically a decision support system for retrofitting a textile dyeing machine. (Manglani, et al., 2019) provide a review of IoT applications and engagement of IoT in the textile industry, as well as an overview of IoT application and service providers within particular textile manufacturing segments, namely weaving, knitting, dyeing and finishing, testing, non-woven and sewing sectors.

Table 2. Survey and case study contributions

Reference	Triple-bottom line attributes	Industry 4.0 components	Contribution
<i>Surveys and case studies:</i>			
(Ahmad, et al., 2020)	Economic, Social	Internet of Services	Qualitative analysis of textile companies that want to implement Internet of Services.
(Haseeb, et al., 2019)	Environmental, Economic and Social	Smart Factory	A survey presenting Industry 4.0 technology significance for local textile industry.
(Chen, 2019)	Economic, Social	Internet of Services	4 case studies for potential Industry 4.0-scenarios in textile manufacturing SMEs.
(Bai, et al., 2020)	Environmental, Economic, Social	Smart Factory	Evaluation of Industry 4.0 technology impact in various manufacturing industries.
(Ku, et al., 2020)	Economic	Cyber-Physical System	Industry 4.0 retrofitting case for textile machinery.
(Manglani, et al., 2019)	Economic	Internet of Things, Internet of Services	Applications of Internet of Things in textile manufacturing industry.
(Park, et al., 2020)	Environmental, Economic	Internet of Things, Cyber-Physical System	Creation of CPS through IoT devices in a textile manufacturing company.
(Tsai, 2018)	Environmental, Economic and Social	Cyber-Physical System	Smart decision model designed for Industry 4.0 environments.
(Lee, et al., 2018)	Environmental, Economic	Cyber-Physical System	Development of a CPS system in a textile manufacturing company.

The authors address certain challenges such as interoperability, i.e. the diversity of communication protocols of textile machinery. Even though solutions are developed to overcome the diversity of these protocols, the particular know-how within the companies can be limited, thus slowing down potential engagement with IoT. Additionally, a more in-depth analysis and presentation of the IoT developments, services and applications in the spinning industry are provided. What is worth mentioning is that the results from interviewees show a bigger interest in IoT wherein data is more difficult to obtain, such as product quality. Whereas already available data mentioned as energy and production environment did not rate of high importance for IoT applications.

Success factors are presented in some cases. For example, (Chen, 2019) describe how IoT can increase production efficiency and ease production monitoring, and CPS can improve communication in global supply chains. In more concrete case study, (Ku, et al., 2020) managed to reduce textile machinery setup times by an average of 63% by developing a decision support system based on smart manufacturing concept. Finally, in an energy saving case study, (Park, et al., 2019) developed a CPS for textile dyeing machines that saved up to 10% in energy consumption.

3.3. Summary of findings

The textile industry shows to have a preferred direction within the triple bottom line. First of all, researchers with conceptual contributions mainly address Industry 4.0 as an enabler for environmental sustainability, whereas only some researchers include a complete triple bottom line perspective. However, when looking at the surveys and case studies, the priorities shift to economic sustainability. It is reasonable to state that first and foremost, the textile manufacturing companies will consider their financial bottom line before committing to Industry 4.0 within the full triple bottom line.

Furthermore, practical implementations mainly focus on a specific process within a textile manufacturing segment and rarely within multiple processes. Enterprise-wide implementations are observed only on a conceptual level. Investigations that are driven by industry survey results are mainly from developing countries where mass manufacturing techniques dominate textile production. It is also noted by some researchers that the textile manufacturing industry has fell to the lower ranks when compared to other manufacturing sectors, (Bai, et al., 2020) and (Sari, et al., 2020). The overall potential of Industry 4.0 for textile manufacturers is mainly explored on a conceptual level.

Research is yet to show a framework which would help with decision making to achieve sustainable manufacturing through adopting Industry 4.0 technologies.

4. Designing an implementation framework

Based on the findings from Section 3, an Industry 4.0 implementation framework to achieve sustainable manufacturing is proposed for the textile manufacturing industry. It is designed so that textile manufacturers could better identify an implementation direction. In short, this direction can be achieved in three stages: defining implementation requirements, mapping out potential Industry 4.0 technologies, and selection of technologies and/or services. Each stage is presented in a separate subsection.

4.1. Requirements for Industry 4.0 implementation

First, manufacturing characteristics are defined as they can determine the relevance for different Industry 4.0 technologies. The most important characteristics that may influence the relevance of Industry 4.0 technologies and applications are: level of repetitiveness, product complexity and product volume. Research done by (Newman & V, 1995) and (Olhager & Rudberg, 2010) highlight the importance of these characteristics towards strategic decision making. Furthermore, strategic priorities also must be defined. In this research, these strategic priorities are Sustainability Objectives (SO's), but it can be noted that companies may as well have other strategic priorities that may work well with Industry 4.0 adoption, such as showed by (Agostini & Nosella, 2019). Also, an example of Industry 4.0 relevance based on manufacturing characteristics is shown by (Strandhagen, et al., 2017).

The SO's defined in this stage will indicate which manufacturing metrics and key performance indicators are desired to be improved. Some of the main SO's towards having a sustainable textile manufacturing business are as follows:

- Value chain transparency. This includes employing labour ethically, sustainable sourcing of raw materials and sustainable operations within global value chains.
- Energy and waste management. Some textiles manufacturing sub-sectors, particularly growers and processors of some raw materials, textiles dyers and finishers, require large amounts of energy and clean water for processing and creating textiles. It is expected that natural resources and energy will be used most efficiently, and waste managed without damaging the environment.
- Circular economy. This concept covers textile lifecycle concerns. Textiles is one of the least recycled products, and the circular economy concept has the potential to create significant value for textile companies, consumers and environment. Many companies are trying to engineer supply chains that enable reverse logistics for recycling, repair and remanufacturing of textiles.
- Manufacturing process efficiency. A more overlooked attribute towards sustainable operations is the ability to efficiently manage manufacturing processes, especially in cases of high resource consumption and expenses. Modernising (or retrofitting) equipment for data collection and applying production management techniques is a more economically viable alternative for many textiles companies but is yet to be used more widely by companies.

Finally, an Industry 4.0 value mapping is created, which is expanded into stage two and presented separately in the following subsection.

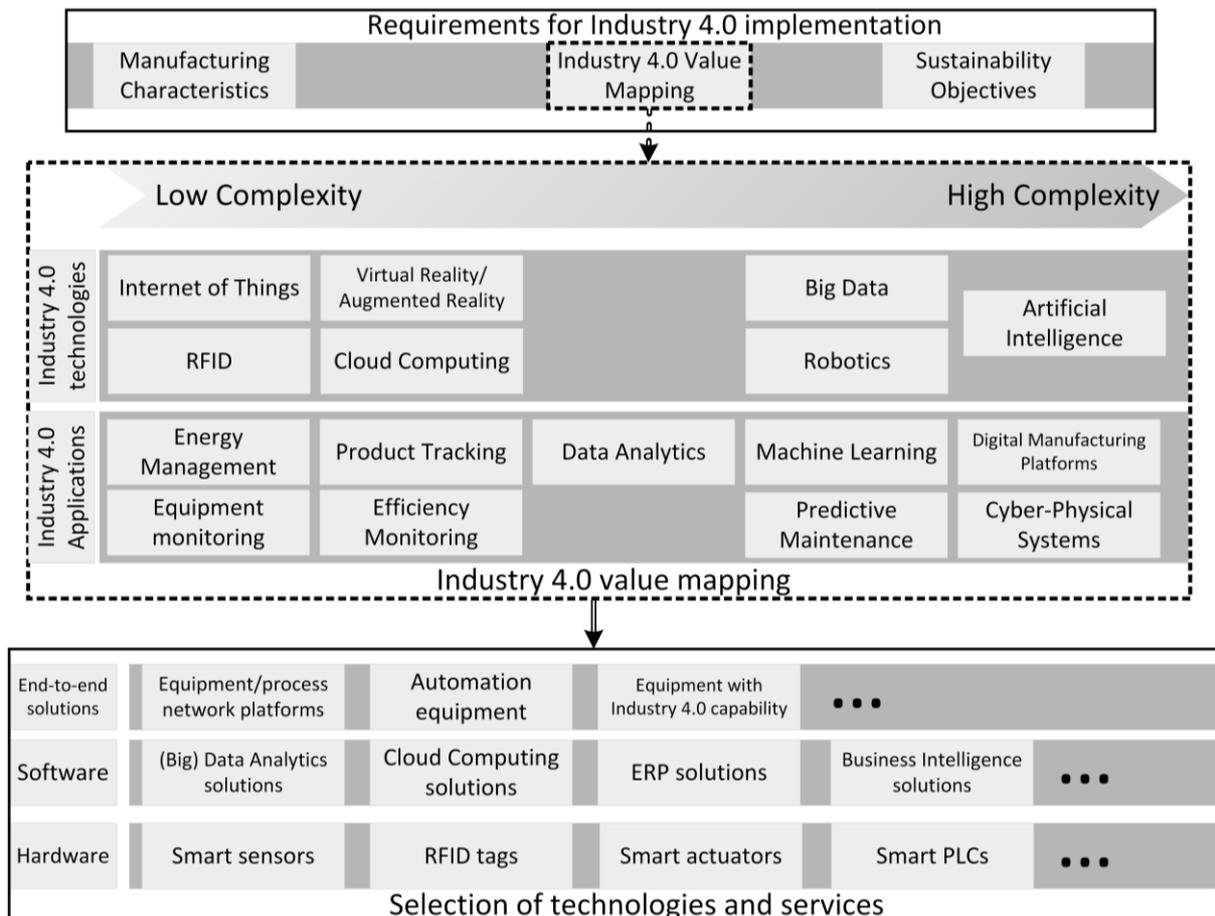


Figure 1. Implementation framework for sustainable manufacturing using Industry 4.0 technologies

4.2. Industry 4.0 value mapping

This stage presents selection of possible Industry 4.0 applications, and technologies that enable those applications. The applications and technologies for this stage have been depicted from literature findings

presented in Section 3. They have also been categorized based on technology and implementation complexity. This type of value mapping was inspired by similar work done by (Masood & Sonntag, 2020) and (Qin, et al., 2016).

To address some of these technologies used by the textile industry, IoT may well be the most commonly used technology found in the literature. In these cases, IoT is used mainly for collecting textile machinery data, but is also used as a sub-component for more complex Industry 4.0 systems. Cloud computing has been used to easier manage textile supply chains, (Kemper & Gloy, 2017) and establish better collaboration between companies, (Damodaram & Ravindranath, 2010).

Some of the Industry 4.0 technologies that are listed in the framework are not found to be used for sustainable manufacturing by the textile industry and thus not present in literature review in Section 2. However, they are observed to be used by textile manufacturers as well as service and equipment providers for the textile industry. Thus, they are recognized within this framework as potential technologies for sustainable manufacturing. As an example, Virtual Reality/Augmented Reality (VR/AR) is observed to be used in the retail sector for enhanced customer experience, and also used for labour upskilling, which is a major problem in the textile industry. This can contribute greatly to social and economic sustainability.

The second part of value mapping is identifying relevant applications that are enabled by the aforementioned Industry 4.0 technologies. For example, energy management and equipment monitoring are enabled by IoT as shown by (Tsai, 2018) and (Ku, et al., 2020). In a more complex case, CPS is viewed as an application that consists of multiple Industry 4.0 technologies. For example (Lee, et al., 2018) develop a CPS with IoT sensors, RFID readers and a custom software that connects different textile manufacturing processes and provides new data insights and better control of textile manufacturing processes.

4.3. Selection of commercial technologies and services

Finally, the framework proposes a selection of physical technologies, virtual services as well as end-to-end solutions. From a hardware perspective, technology such as smart sensors, RFID tags or smart PLCs are used to gather data. Typically, these hardware solutions will come with a third party software that, depending on the provider, can offer a range of applications. These applications, if properly selected, can enable an Industry 4.0 ecosystem in which the triple bottom line objectives can be collectively addressed. Specific to the textile industry, (Kemper & Gloy, 2017) have presented a case for an Industry 4.0 ecosystem.

5. Future work

Further work of this research will look at applying this framework within the industry. The results from the industry will lead to a much clearer presentation of how Industry 4.0 technologies and applications may be beneficial to certain textiles manufacturers with varying characteristics. This research then aims to find correlations between certain characteristics and relevance of Industry 4.0 technologies.

As observed from the literature, textile companies that focus on high quality and customized products are yet to be investigated in the context of Industry 4.0 adoption towards sustainable manufacturing. Engaging companies with such characteristics would have a significant impact for bringing the textile industry closer to Industry 4.0.

6. Conclusion

This paper focuses on bridging two fairly new concepts in textile manufacturing - sustainability and Industry 4.0. The textile manufacturing industry has been identified as a sector that has a significant potential when it comes to implementing Industry 4.0 towards sustainable manufacturing.

The paper's contributions can be divided into the following: first, a systematic literature review has been conducted and showed that Industry 4.0 concepts have been well-interpreted and to some extent re-designed to specifically fit the textile industry. However, further analysis has shown that the industry itself is only starting to explore Industry 4.0 concepts. Lack of knowledge and guidance towards certain Industry 4.0 technologies and their usefulness are mentioned consistently throughout literature.

Secondly, a framework for Industry 4.0 implementation has been designed based off literature findings. The framework helps with the design for implementation for Industry 4.0 towards sustainable manufacturing.

Limitations of the study include methodology and selected keywords for conducting literature review. It is likely that a different set of keywords selected for Industry 4.0, sustainability, and textile manufacturing might produce slightly different search results.

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