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INDUSTRY 4.0 BASED SUSTAINABLE MANUFACTURING MODEL FOR APPAREL INDUSTRY IN SRI LANKA

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ABSTRACT

Global industrialisation creates many challenges in achieving the balance of sustainability pillars called social, economic and environmental. Manufacturing is the largest subsector of industrialisation. Hence the sustainability of manufacturing greatly affects the sustainability of industrialization. Thus, the research community and industry professionals give attention to the Sustainable Manufacturing (SM) concept. Further, they have realized the significance of technology when focusing on SM. Accordingly, they have aligned the path of achieving SM with the recent manufacturing technology called "Industry 4.0" (I4.0) for more innovative and efficient outcomes. The developed countries and some of the developing countries drive towards the I4.0 concept to achieve SM. However, in terms of the Sri Lankan context, there is no clear evidence to demonstrate the integration of the I4.0 and SM. But there are few studies based on implementing I4.0 for apparel manufacturing in Sri Lanka. Thus, this study aimed to investigate the present status of the application of the I4.0 concept towards achieving SM in apparel manufacturing in Sri Lanka by selecting three large scale apparel manufacturing case studies. This was tested using a model which links the I4.0 pillars and the key opportunities for three dimensions of SM from nine technology pillars observed through previous studies. The findings from the case studies proved that there is a huge gap in the application of I4.0 for SM in the Sri Lankan context.

Keywords: *Industry 4.0 (I4.0); Industry 5.0 (I5.0); Manufacturing Sector; Nine Technology Pillars; Sustainability; Sustainable Manufacturing (SM).*

1. INTRODUCTION

The present industrialization is experiencing significant challenges in ensuring the balance of social, economic, and environmental sustainability dimensions while aiming to attain the product demands in the competitive market (Jamwal, et al., 2021; Menon, Shah and Coutroubis, 2018). Manufacturing holds the largest portion of industrialisation that can highly impact sustainability (Stock and Seliger, 2016). According to Sartal et al. (2020), from the perspective of manufacturing, sustainability is adjoining with transforming resources into economically valuable final products while being socially and environmentally responsible. However, it is a great challenge and, hence, the research community and industrial sector pay great attention to Sustainable Manufacturing (SM) to overcome sustainability challenges in present industrialisation (Sartal, et al., 2020). Under this context, it is vital to use technology when focusing on SM (Gholami, et al.,

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2021). Based on the recent technological trends, it is observed that Industry 4.0 (I4.0), the current phase of the industrial revolution, which is developed on many technologies, offers excellent opportunities for SM (Jamwal, et al., 2021; Mehnen, et al., 2021; Sartal, et al., 2020; Sharma and Jain, 2020). The I4.0 technologies are implemented by different sensors that can physically monitor and create a virtual demonstration of the physical world using Cyber Physical Systems (CPS) (Menon, et al., 2018). The CPS can be defined as the concept of embedding software in a machine that can understand itself (Sharma and Jain, 2020). In Sri Lanka, the implementation of the I4.0 in the apparel manufacturing industry has been discussed in several studies (Lakmali, Vidanagamachchi and Nanayakkara, 2020; Jayatilake and Withanaarachchi, 2016).

Presently, many countries drive their industrial value creation towards I4.0 to strengthen SM (Jamwal, et al., 2021; Stock and Seliger, 2016). Further, due to continuous improvements and innovations in automation, Industry 5.0 (I5.0) has become the latest development which is not an entirely new paradigm; it is an upgradation of I4.0 (Pramanik, et al., 2020). Further to the authors, the organizations will be eligible to have more focused and customised manufacturing with effective collaboration between humans and machines as the benefits of I5.0. As observed, the manufacturing-related global studies still focus on I4.0 to grab the actual benefits of nine technology pillars called the foundation of I4.0 to enhance SM (Machado, Winroth and da Silva, 2020; Pramanik, et al., 2020; Sartal, et al., 2020; Sharma and Jain, 2020). Specifically, Pramanik, et al. (2020) stated that I4.0 will be replaced by I5.0 in near future, but to achieve that the absolute implementation of I4.0 is required. Accordingly, this study was limited to I4.0.

It has been ten years since the I4.0 concept was introduced and still, there is no clear evidence to prove the proper identification and application of the I4.0 for SM in apparel industry in Sri Lanka. Further, there are no studies based on demonstrating the integration of I4.0 and SM under the Sri Lankan context. Hence, this research aims to investigate the existence of I4.0 towards the enhancement of sustainable manufacturing in apparel industry in Sri Lanka. The objectives of the paper are (1) to develop an I4.0 based SM model that demonstrates the impact of I4.0 for SM; (2) to apply the proposed model in the apparel industry to assess the level of existence of I4.0 based SM.

2. LITERATURE REVIEW

2.1 THE CONCEPT OF INDUSTRY 4.0

Germany had introduced I4.0 which represent the recent era of the industrial revolution in 2011 at the Hannover Fair event (Tay, et al., 2018). The I4.0 will make the manufacturing process fully integrated and automated through the communication among single automated cells (Javaid, et al., 2022; Rüßmann, et al., 2015). According to Ghobakhloo (2018), the heart of I4.0 is based on the integration and fusion of the physical and the virtual world through the CPS. Numerous authors stated that the I4.0 is a collection of innovative foundational technological advances (Machado, Winroth and da Silva, 2020; Rüßmann, et al., 2015). The Boston Consulting Group (BCG) defined nine foundational technological pillars in I4.0, including Industrial Internet of Things (IIoT), big data analytics, augmented reality, additive manufacturing, autonomous robots, simulation, horizontal and vertical system integration, cloud computing and cybersecurity as the foundation of I4.0 (Rüßmann, et al., 2015). Additionally, those technological pillars have been used and adapted in several studies to conduct their studies covering the concept of I4.0 (Erboz, 2017; Hughes, et al., 2022; Luque, et al., 2017; Machado, Winroth and da Silva, 2020; Noor Hasnan and Yusoff, 2018; Rehman and Ejaz, 2020; Saturno, et al., 2018; Sharma and Jain, 2020). Therefore, the nine technology pillars introduced by BCG (Rüßmann, et al., 2015) have been selected to enrich the definition of the I4.0 concept in this study.

1st first pillar (IIoT): IIoT facilitates the machines with sensor systems, electronics, and embedded software which allows to capture and exchange data using internet connectivity (Luque, et al., 2017; Pramanik, et al., 2020).

2nd Pillar (Big data): Big data facilitates real-time decision making through the comprehensive evaluation of data collected from different sources (Rüßmann, et al., 2015).

3rd Pillar (Augmented Reality): Augmented reality consists of a real-time virtual model of a physical world environment that has been enriched by the several computer-based information components called displays, input devices and tracking (Craig, 2013).

4th Pillar (Additive Manufacturing): Additive manufacturing is called sequential layering-based 3D printing, widely used for producing small batches of customized products (Pramanik, et al., 2020).

5th Pillar (Autonomous Robots): Autonomous robots represent the recent robots that collaborate more closely with humans (Menon, et al., 2018).

6th Pillar (Simulation): The simulation creates a virtual model of the physical manufacturing system including machines, products, and humans (Rehman and Ejaz, 2020; Rüßmann, et al., 2015; Tay, et al., 2018).

7th Pillar - Part I (Vertical Integration): Vertical integration refers to the connection between systems inside of the factory with each other for achieving better performance (Erboz, 2017).

7th Pillar - Part II (Horizontal Integration): Horizontal integration includes the connection of partners within the supply chains (Erboz, 2017).

8th Pillar (Cloud Computing): Cloud computing permits real-time data sharing through the creation of a digital cooperated and integrated environment (Kumar and Nayyar, 2020).

9th Pillar (Cybersecurity): Cybersecurity is an innovative technology, which protects critical industrial systems and manufacturing lines from cybersecurity threats (Mehnen, et al., 2021; Rüßmann et al., 2015).

2.2 THE CONCEPT OF SUSTAINABLE MANUFACTURING

Sustainable Manufacturing (SM) involves the transformation of resources into economically valuable goods by operating socially and environmentally responsible processes (Sartal, et al., 2020). Thus, SM requires to consider the implications of social, economic, and environmental dimensions associated with the manufacturing stages (Sajadieh, et al., 2022). The base of the social dimension of sustainability is ensuring safety and equity to the employees, stakeholders and community (Sangwan and Bhatia, 2020). The focus on economic performance, market presence, indirect economic impacts and procurement practices is the base of sustainability's economic dimension (Sangwan and Bhatia, 2020). The focus on preserving supply, waste handling and direct usefulness is the basis of the environmental dimension of sustainability (Sangwan and Bhatia, 2020). Thus, SM can be defined as a process of creating socially responsible, economically viable and environmentally friendly products.

2.3 THE RELATIONSHIP BETWEEN INDUSTRY 4.0 AND SUSTAINABLE MANUFACTURING

The I4.0 is one of the recent applications to achieve SM (Gholami, et al., 2021; Sartal, et al., 2020). Further, Sartal, et al. (2020) proved that the ICT based infrastructure, technological advances, human-machine and machine-to-machine interaction of I4.0 enables SM. According to previous studies (Erboz, 2017; Ghobakhloo, 2018; Javaid, et al., 2022; Mehnen, et al., 2021; Menon, et al., 2018; Psarommatis, et al., 2022; Rehman and Ejaz, 2020; Rüßmann, et al., 2015; Sajadieh, et al., 2022; Stock and Seliger, 2016; Tay, et al., 2018), the technology pillars of I4.0 facilitates manufacturing process with numerous opportunities covering all three dimensions of SM; social, economic and environmental. Those opportunities derived from the above-mentioned studies were captured under each dimension of SM (refer Table 1).

Table 1: Opportunities from I4.0 for SM

Dimension of SM	Derived Key Opportunities from I4.0 Technology Pillars
Social dimension of SM	Ensure occupational safety, reduce human errors, ensure better communication and reduce workload and demands-based product designing.
Economic dimension of SM	Reduce maintenance costs by early predictions, ensure energy cost saving, decrease product failure rate, decrease time to market and save resource handling costs.
Environmental dimension of SM	Prevent waste generation by controlling defective manufacturing, ensuring energy saving, facilitating eco-friendly product development, raise efficient resource handling and space utilization.

The relationships among the derived key opportunities (Table 1) and the I4.0 pillars were used to develop a conceptual model (see Figure 1) to visualize the I4.0 based SM.

Colour code: Green - IIoT; Yellow - Big Data; Red - Augmented reality; Blue - Additive manufacturing; Pink - Autonomous robotics; Purple - Simulation; Orange - System Integration; Ash - Cloud computing; and White - Cybersecurity.

Accordingly, it can be logically concluded that the I4.0 can support meeting targets in manufacturing under three dimensions of SM and the concept of I4.0 is having a positive impact and unavoidable influence on the SM.

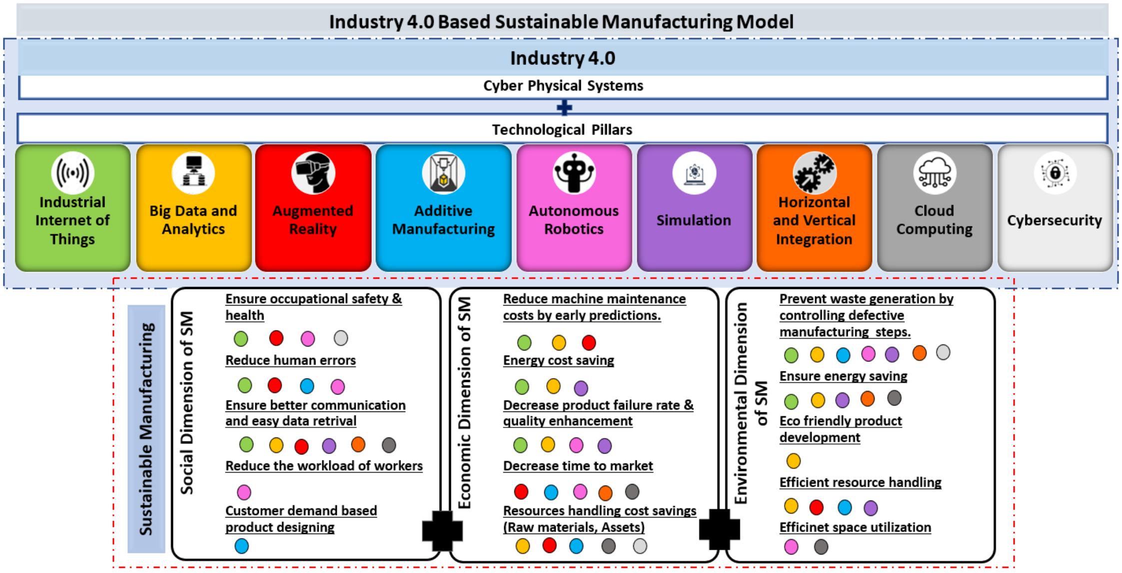

Figure 1: I4.0 based SM model

3. RESEARCH METHODOLOGY

The research was designed to investigate the application of I4.0 for SM in Sri Lanka. Since this study involves an in-depth investigation, the qualitative approach was preferred over the quantitative approach (Dawson, 2002). To investigate the application of I4.0 to enhance SM in the Sri Lankan apparel industry, the proposed conceptual model illustrated in Figure 1 was used in case studies after validation. The validation experts were selected based on their field and experience. The profiles of the experts are given in Table 2.

Table 2: Profile of the validators of the I4.0 based SM model

Name of the Validation Expert	Area of expertise
VE1	Director and consultant in business and industry development, production planning and industrial engineering with expert knowledge of the I4.0. The overall experience: 50 years
VE2	Senior technologist, productivity consultant for leading manufacturing organizations and Administrator in Industrial Engineering with knowledge of the I4.0 concept. The overall experience: 20 years

The unit of analysis was the application of I4.0 for SM. Perry (1998) stated, that when qualitative research comprises a wide study area, it is suitable to use only one or two cases and a maximum of four cases. Accordingly, the cases were limited to three leading wearing apparel manufacturing organizations (refer Table 3).

Semi-structured interviews were selected for collecting data. The validated "I4.0 based SM" model was introduced to the nine industry professionals (refer Table 4) and their views on the current level of applying I4.0 for the three dimensions of SM were obtained. The cross-case analysis was carried out to have better comparison and summarization.

Table 3: Details of the selected cases

Case	Description
Case 01	BOI approved apparel manufacturer and exporter, located in Pannala and employed over 1000 employees. The factory manufactures lingerie.
Case 02	BOI approved apparel manufacturer and exporter, located in Rathmalana and employed over 1000 employees. The factory manufactures lingerie, men's and women's underwear.
Case 03	BOI approved apparel manufacturer and exporter, located in Balapokuna and employed over 1000 employees. The factory manufactures kids wear, men's and women's underwear.

Table 4: Profile of the selected professionals

Case	Code	Profile	Experience
Case 01	C1R1	General Manager, Sustainable Business, Familiar with the I4.0 concept by participating in discussions and webinars.	15 Years
	C1R2	Manufacturing Plant Head, Familiar with the I4.0 concept by participating in discussions and webinars.	20 Years
	C1R3	Senior Executive, production, Familiar with the I4.0 concept by participating in discussions and webinars. Being a part of I4.0 based pilot projects in Case 01.	6 Years
Case 02	C2R1	Senior Executive, Engineering, Familiar with the I4.0 concept by participating in discussions and webinars.	6 Years
	C2R2	Deputy general manager, Engineering, Familiar with the I4.0 concept by participating in discussions and webinars.	12 Years
	C2R3	Senior executive, Compliance, Familiar with the I4.0 concept by participating in discussions and webinars.	8 Years
Case 03	C3R1	General Manager Engineering and sustainability, Familiar with the I4.0 concept by participating in discussions and webinars. Already experienced the availability of the I4.0 concept in foreign countries.	20 Years
	C3R2	Manager, Compliance, Familiar with the I4.0 concept by participating in discussions and webinars.	7 Years
	C3R3	Manager Operations, Familiar with the I4.0 concept by participating in discussions and webinars.	10 Years

4. FINDINGS

4.1 THE EXISTENCE OF INDUSTRY 4.0 MANUFACTURING IN SRI LANKAN APPAREL INDUSTRY

Findings revealed that all of the technology pillars are available to some extent with few initiatives, except simulation and additive manufacturing. It was further observed there were several technological applications are aligned with some of the technology pillars (refer Table 5).

Table 5: Current availability of I4.0 technology pillars in Sri Lankan apparel industry

Technology Pillar	**Availability**			**Description**
	C1	**C2**	**C3**	
IIoT	★	★	★	Case 01: Smart routing flexibility and looking for applying sensor-based product counting; Case 02: Sensor-based innovations are going on, use iAuditor called QR code-based human-machine communication, PLC-based innovations are going on; All three cases: use energy monitoring systems and solar energy systems
Big Data	★	★	✕	Case 01: ANDON boards (real-time alert generator), finished good management digital screens, data analysis on environmental footprint; Case 02: discussing on installing real-time data displaying screens, VOC level data calculations and analysis; Case 03: Higg product module.
Augmented Reality	★	★	★	The design teams of all three cases are applying augmented reality and computer vision for sample fitting. But still not applying this technology to communicate with machines.
Additive Manufacturing	●	●	✕	Case 01 and case 02: 3D printing is in the Research and Development (R&D) stage.
Autonomous robotics	★	★	★	Case 01: Automated Guided Vehicle (AGV); Case 02 and Case 03: Using Ring Robot
Simulation	✕	✕	✕	All three cases have not reached this level
Horizontal and vertical integration	★	★	★	All three cases: Apply SAP as the Enterprise Resource Planning (ERP) system to integrate all the internal systems; Case 01 and case 02: Discussing on spreading data connectivity along with the supply chain.
Cloud Computing	★	★	★	All three cases are covered with cloud computing
Cybersecurity	★	★	★	All three cases are covered with cyber security systems. But comparatively the strength of the cyber security system of the case 01 is higher than both case 02 and case 03.

(Guide: ★ Available to some extent, ● Discussion Level, ✕ Not Available)

4.2 THE LINK BETWEEN INDUSTRY 4.0 AND THE THREE DIMENSIONS OF SUSTAINABLE MANUFACTURING IN SRI LANKAN APPAREL INDUSTRY

4.2.1 Industrial Internet of Things

Social dimension of SM: Case 01 is focusing on applying RFID chips and sensor-based automated manufacturing steps that can reduce human-based errors. C1R2 revealed, *"The recently installed smart routing flexibility will enhance the communication among machines, materials and processes through sensors and internet connectivity"*. C2R3 stated, *"We are discussing machine-related smart sensor-based upgrading to enhance the easy data retrieval"*. However, none of the cases used internet connectivity-based safety sensors and real-time hazard warnings that can ensure occupational safety.

Economic dimension of SM: All three cases align with self-energy generation by installing solar applications. However, none of them has sensors and detectors to check the status of manufacturing machines to reduce operation and maintenance costs. C1R1 pointed out that *"We can familiar with the consumption patterns through our energy monitoring system and plan for cost savings".* All cases do not include sensor-based product quality checking and failure detections.

Environmental dimension of SM: C1R1 expressed that *"We are focusing on upgrading the existing system into a real-time smart energy monitoring system, then there will be a capability as well".* Similarly, case 02 disclosed their intention to use a smart energy motoring system. However, none of the cases used sensor-based applications for sensing the defects of machinery in real-time that can reduce defective product outputs.

4.2.2 Big Data

Social dimension of SM: C1R1 mentioned, *"ANDON system will display target levels and condition of machines in real-time".* Further their *"Finished good management digital screens"* ensure better data retrieval on finished products than traditional methods. Both case 02 and case 03 stay behind in applying big data initiatives for real-time data retrieval.

Economic dimension of SM: C1R1 revealed, *"The ANDON system notifies the condition of the machine as working or malfunctioning. If there is a malfunction then the maintenance team can attend before further loss".*

Environmental dimension of SM: The ANDON system applied in case 01, notifies the conditions of machines before occurring defective manufacturing from those machines. C1R1 mentioned, *"We evaluate the environmental footprint of the products in terms of carbon composition and we do material-based comparisons using a software application".* In case 02, both C2R1 and C2R2 raised their VOC level calculations for eco-friendly product development. In addition, C3R1 mentioned a method called *"Higg product module"* used to calculate the life cycle impact of a product before commencing the manufacturing *"We use Higg Product Module, for calculating the life cycle impact based on the raw material compositions".*

4.2.3 Augmented Reality

Social dimension of SM: All three cases are applying augmented reality for virtual sample fitting in some instances. C3R3 stated that *"Use of virtual samples can avoid the human-based errors occurred during sample making and redeveloping".* The current sample fitting application of all three cases increase the accuracy of the designs. C3R3 elaborated *"Augmented designs transfer more accurate data about the designs that can be easily customized with instructions".*

Economic dimension of SM: The virtual sample fitting control of design lead time. C3R2 mentioned, *"Virtual sampling will ensure resource handling cost savings, further, it will be more flexible in making changes without reusing resources".*

Environmental dimension of SM: C1R2 mentioned, *"Virtual sampling avoid consumption of fabrics and other related raw materials".*

4.2.4 Additive Manufacturing

Social dimension of SM: Case 01 and case 02 are at the discussion level of applying additive manufacturing for reducing human errors. In this regard, they are working on adapting 3D printing which facilitates avoiding human-based errors. C1R2 commented that *"we have identified that the 3D printing can easily be customized with the demand, it is flexible enough for smoothing the demand changes"*.

Economic dimension of SM: 3D printing will contribute to the economic aspect by speeding up manufacturing. C1R2 commented that *"we have identified that 3D printing can speed up our product manufacturing"*.

Environmental dimension of SM: 3D printing can be used for waste reduction of the manufacturing process by controlling defective manufacturing steps. For instance, as per C1R3 *"If we can successfully implement 3D printing, there will be a huge reduction in manufacturing defects"*. The precise amount of resource-based manufacturing is not currently focused.

4.2.5 Autonomous Robotics

Social dimension of SM: Case 01 replaces humans with robots that can mitigate musculoskeletal disorders of workers and hence has a social impact. C1R3 mentioned, *"Currently we are replacing travelers who involve in material handling with AGV robot, that can load up to 600 kg weight"*. Further Cases 02 and 03 experienced in reducing human errors by using ring robot. C3R2 affirmed, *"ring robot will attach elastic bands in more efficient, speed and accurate manner with less supervision and hence manual labour has been cut down"*. The "AGV" robot in case 01 already reduce the workload of material handlers positively. C1R1 expressed that *"An automated material handling process will motivate the workers by avoiding heavy load handling workload"*. Ring Robots in Case 02 and Case 03 could able to reduce the workload of workers by automating a whole process.

Economic dimension of SM: The application of Ring Robot has contributed to product quality enhancement and failure reduction. C1R3 stated that *"Our AGV robots will speed up manufacturing because there will be no waiting time as from travelers"*. It can be derived that the use of AGV robots creates a positive impact on decreasing time to market. C2R1 highlighted that *"Ring robot is more efficient in use when compare with human involvement because it can work at same speed for any number of hours"*.

Environmental dimension of SM: The application of the *Ring Robot* is a fully automated process, and hence it has less impact on the environment through accurate manufacturing that can avoid waste generate from defects.

4.2.6 Horizontal and Vertical Integration

Social dimension of SM: The SAP-based ERP systems of all three cases ensure better communication among the internal parties through efficient data sharing and data availability. But the majority of respondents highlighted that those integrations need to be smoother for ensuring better operations.

Economic dimension of SM: The SAP-based ERP of all three cases ensures efficient communication between all the nodes of the manufacturing process. C1R2 declared, *"We can have speed access for each manufacturing section-based data without delaying in decision making"*.

Environmental dimension of SM: C1R1 mentioned, *"Since the relevant process updates available in SAP, the possibility of occurring miss communication based defective manufacturing will be controlled".* C2R1 stated, *"Once we logged to the SAP all the relevant process data can be captured, no need to wait and consume more energy with systems".*

4.2.7 Cloud Computing

Social dimension of SM: C1R3 raised *"Cloud facilitates easy communication; we can access the system from any location".* In case 02, the C2R1 mentioned *"There is a web-based data collection platform called Control Room, we can check the condition of our plant centrally without visiting the plant".* Further, in case 03, C3R1 pointed out *"Our cloud is a good source of data and information".*

Economic dimension of SM: C1R1 stated that *"Since we can have access to the cloud system at any time from any destination, it ensures the real-time update on the process of the plant for making our decisions and comments without any delay".* In case 01 they have almost replaced servers and paper-based data storage via the cloud. C1R3 stated that *"Our cloud includes all the data related to our manufacturing process, so there will be no cost to manage servers and paper-based files".*

Environmental dimension of SM: The energy-saving that can be gained through avoiding physical servers available in all three cases. The use of online data storage, instead of space allocation for servers is appeared.

4.2.8 Cybersecurity

Social dimension of SM: All three cases have a cyber-attack free environment that can create a positive mental health-based working environment. C1R2 mentioned, *"Since we are having a strong cyber security system, we feel safe to update our systems with sensitive data".*

Economic dimension of SM: All three cases, are aligned with the safety of organizational systems but not specified with manufacturing machinery. Hence the cost savings through preventing the damages occurring for machines are not focused.

Environmental dimension of SM: Cybersecurity and control of defective products are developing in case 01, and both case 02 and case 03 are focusing on it. Case 01 is developing the machine program safety via cyber security, but sill the other two cases are just focusing on machines based cyber security systems.

5. DISCUSSION

The manufacturing process of the Sri Lankan apparel manufacturing industry required both human and technological assistance. Hence, at first, the availability of recent technological applications was assessed by overviewing the availability of I4.0 initiatives. The majority of technology pillars were available to some extent with few initiatives but all the I4.0 initiatives need to be improved. As a result of investigating the present status of the application of I4.0 for SM, it was observed that the majority of links among nine technology pillars and respective opportunities from them to enhance SM; which are displaying in the model (refer Figure 1) was not even focused on the Sri Lankan apparel manufacturing industry. Concerning the already appearing links on the social dimension of SM, the application of autonomous robotics for reducing workload and human errors, and the use of cloud computing for easy communication among people was highlighted. Regarding the already appearing links on the economic dimension of SM, the impact of autonomous robotics on decreased product failure rate and decreased time to market was highlighted. In the matter of already appearing links on the environmental dimension of SM, the impact of vertical integration on preventing waste generation by controlling defective manufacturing steps and energy-saving was highlighted. As a positive factor, there are a few developing level and focused level links also observed. As the outcome of this study, the "I4.0 based SM" model (Figure 1) will be a tool for encouraging the Sri Lankan manufacturing industry to identify the application of I4.0 to achieve more SM environment.

The current status of the application of I4.0 for SM is categorized into four categories with unique symbols (refer Table 6) to facilitate better-summarized visualization (refer Figure 2).

Table 6: Categories of the current status of the application of I4.0 for SM

Category	**Symbol**	**Definition**
Link already appears	✓	The link well appears within the current technological applications and initiatives of the I4.0 technology pillars.
Link is in the developing stage	↑	The link partially appears and still developing within the current technological applications and initiatives of I4.0 technology pillars.
Link is currently focusing on	▲	The link is currently focused on within the current technological applications and initiatives of the I4.0 technology pillars.
Link is not focused yet	✗	The link is currently not considered or focused yet within the current technological applications and initiatives of the I4.0 technology pillars.

The summarized visualization of the present status of the application of I4.0 for SM in apparel industry in Sri Lanka was presented (refer Figure 2) with the aid of these four categories (refer Table 6).

Accordingly, Figure 2 notifies that the apparel industry should concern with more advanced manufacturing applications to achieve SM technologically. Because the majority of links among the nine technology pillars and respective opportunities from them to enhance SM; which are displayed in the conceptual model (Figure 1) were not even focused on the Sri Lankan apparel manufacturing industry. Hence, as an extension of this study, it is better to overview the exact reasons and barriers behind this current backward position of the Sri Lankan manufacturing industry in achieving SM through I4.0 and give strategies to overcome those barriers.

Assessed key areas of SM	IIoT			Big data			Augmented Reality			Additive Manufacturing			Autonomous Robotics			Simulation			Horizontal and Vertical Integration			Cloud Computing			Cybersecurity		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
Social Dimension of SM																											
• Ensure occupational safety and health	✗	✗	✗				✗	✗	✗				✓	✗	✗										✓	↑	↑
• Reduce human errors	▲	✗	✗				↑	↑	↑	✗	✗	✗	▲	✓	✓												
• Ensure better communication and easy data retrieval	↑	▲	✗	✓	✗	✗	↑	↑	↑							✗	✗	✗	↑	↑	↑	✓	✓	✓			
• Reduce the workload of workers													✓	✓	✓												
• Customer demand-based product designing										▲	▲	✗															
Economic Dimension of SM																											
• Reduce maintenance costs by early predictions	✗	✗	✗	✓	✗	✗	✗	✗	✗																		
• Energy cost saving	▲	▲	▲	✗	✗	✗										✗	✗	✗									
• Decrease product failure rate and quality enhancement	✗	✗	✗	✗	✗	✗							✗	✓	✓	✗	✗	✗									
• Decrease time to market							↑	↑	↑	▲	▲	✗	✓	✓	✓				✓	✓	✓	✓	↑	↑			
• Resources handling cost savings (raw materials, assets)				✗	✗	✗	↑	↑	↑	✗	✗	✗										✓	↑	↑	✗	✗	✗
Environmental Dimension of SM																											
• Prevent waste generation by controlling defective manufacturing steps.	✗	✗	✗	✓	✗	✗				▲	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✓				↑	▲	▲
• Ensure energy saving	▲	▲	✗	✗	✗	✗										✗	✗	✗	✓	✓	✓	✓	↑	↑			
• Eco-friendly product development				↑	↑	↑																					
• Efficient resource handling				✗	✗	✗	↑	↑	↑	✗	✗	✗				✗	✗	✗									
• Efficient space utilization													✗	✗	✗							✓	↑	↑			

Figure 2: Summary of the present status of the application on I4.0 for SM

6. CONCLUSION

The concept of I4.0 is having a positive impact and unavoidable influence on the three dimensions of SM. Then the relationship between I4.0 and SM was graphically represented with the aid of a unique colour code and named it as the "I4.0 Based SM" model. Then the model was validated by industrial engineering experts and used as a tool for the data collection. As the initial step of identifying the present status of the application of I4.0 for SM, the availability of nine technology pillars was assessed. As observed, IIoT, Big data, Augmented reality, Autonomous robotics, Horizontal and vertical integration, Cloud computing and Cybersecurity are available to some extent with very few applications and initiatives. Additive manufacturing is at the discussion level while the simulation is not even focused yet. In terms of the present status of the application of I4.0 for SM, the availability of the relationships displayed in the "I4.0 based SM" model was assessed. Findings from the case studies proved that there is a huge gap in the Sri Lankan context. The majority of links are not focused yet. But there were a few focused level, developing level and appeared level links as well. Since there are several pre-studies available on I4.0 for the Sri Lankan apparel manufacturing sector, the current performance in gaining benefits from I4.0 technology pillars are very low. Accordingly, the "I4.0 based SM" model guides the Sri Lankan industry to conduct a self-assessment on the application of globally recognized links between I4.0 and SM to install I4.0 technology pillars to achieve SM environment.

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