Impact of Industry 4.0 Technologies on Sustainable Manufacturing

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ABSTRACT

Industry 4.0 (I4.0) and its associated technologies are increasingly becoming a key aspect of the manufacturing industry in an age where sustainable manufacturing has become a fundamental consideration. Despite Industry 4.0 technologies such as robotics, autonomous systems and Internet of Things (IoT) considered dominant enablers of sustainable manufacturing, the precise impact of these technologies on sustainability remains relatively unexplored as the research in this context remains limited. Therefore, the need for meticulous study and the development of a framework for the assessment of I4.0 technologies' impact towards enhancement of sustainable manufacturing is evident. The report contains an extensive literature review on several I4.0 technologies, the Triple Bottom Line (TBL) aspects of sustainability and how the respective I4.0 technologies impact the factors contributing to the TBL aspects of sustainability. Through a combination of theoretically available information and practical case studies in the Sri Lankan manufacturing industry, a conclusive framework is developed on how the implementation of the identified Industry 4.0 technologies contribute to achieving holistic sustainability across the Triple Bottom Line aspects. Additionally, through further study and multiple-criteria decision analysis methods, the most sustainably impactful technologies are determined with regards to the manufacturing industry.

KEYWORDS: *Industry 4.0, Sustainable Manufacturing, Impact of Industry 4.0, Sustainability, Triple Bottom Line*

1 INTRODUCTION

Industry 4.0 can be understood as the variety of initiatives, technologies, procedures introduced and followed in the industry that have brought upon a fourth industrial revolution. The conceptualization of Industry 4.0 was initiated as a strategic implementation by the German government initiative in 2011 across all manufacturing industries. (Kagermann et al., 2013). Further, Industry 4.0, is the industrial revolution brought upon by the combination of the upcoming next generation technologies employed in various sectors of the industry which include Internet of Things, 5G technology, big data analytics, artificial intelligence, and cloud manufacturing.

Upon having an insight of the contents of Industry 4.0, it is necessary to comprehend the practicalities of adopting Industry 4.0 and its impacts on sustainable manufacturing which requires an understanding of sustainability as a concept. As a result of several reports and conferences including the UN Conference on Environment and Development (UNCED) and the Bruntland report of the World Commission on Environment and Development in 1987, the manufacturing industries across the globe have been expected to achieve an equilibrium of economic, social, and environmental objectives which is often considered as the Triple Bottom Line (TBL). The earliest known adaptation by industry leading entities dates back to 1997 by Shell, Nike, Hewlett Packard, IBM, etc. A brief overview of the three aspects of the triple bottom line is as follows,

The economic aspect of the TBL is for an industrial model to generate and maximize profit in a sustainable manner that secures the long-term economic success and survival of the entity. This can be achieved through ensuring that the entity has positive and profitable returns with maximized productivity and liquidity is made available along with other economic factors. As seen in past research studies, adaptation of the environmental aspect must consider all living and non-living factors. Moreover, despite sustainability having multiple aspects, as seen in the 17 different global goals (SDGs), sustainability in the industrial sector is primarily considered to be of the environmental aspect. Gradually it has become evident that disregard for sustainability and singular commitment to profit maximization is no longer a viable and tolerated design for manufacturing. (Kiel et al., 2017) In turn however, manufacturing organizations in the present day treat sustainability and the adhering to corporate social responsibility as a means of achieving high quality, high yield production with minimal input resources and minimal negative impact to all related stakeholders. The key aim of this research is to address the following primary objectives:

- Study the relationship between the Industry 4.0 technologies and their respective impacts on sustainable manufacturing.
- Create an assessment framework that contributes to the assessment of the impact of implementing Industry 4.0 technologies on sustainability in the manufacturing industry.
- Provide an extensive insight for all stakeholders in the manufacturing industry into the pros and cons of individual Industry 4.0 technologies and the entire concept with regards to sustainability.
- Developing a guideline for the stakeholders related to manufacturing to analyze and assess the risks and limitations of implementing the Industry 4.0 to potentially improve sustainability through utilizing Industry 4.0 technologies.
- Demonstrate the continuous need for methodical research and implementation of Industry 4.0 and the need to take advantage of the positive impacts to strive towards attaining the sustainable development goals.

2 LITERATURE REVIEW

Sustainability in all manufacturing processes has become the primary concern in the ever-developing manufacturing industry of present day in the context of research and development of the said industrial processes. In order to achieve such sustainability, the most common modern-day approach is to introduce advanced technologies including cyber physical systems, big data analytics and several others involving the involvement of IT and automation of the mechanical systems. The implementation of such “next generation” technologies in the manufacturing industry is what has given rise to the concept of Industry 4.0.

2.1 Developments of Industry 4.0 and its Technologies

Despite the absence of a clearly specified standard definition in the present day, Industry 4.0’s origins stem from the German conceptualization in the early 2010s. The fourth industrial revolution, the industrial Internet of Things, smart manufacturing and cloud manufacturing are some of the various terms allotted to be Industry 4.0. The concept is seen as a modern revolutionary era of development in the entirety of the manufacturing industry which involves the advanced automation of manufacturing processes utilizing the plethora of technologies that enhance the pre-existing manufacturing procedures, subsequently yielding numerous benefits. Benefits including increasingly successful commerce, elevated levels of production efficiency, product quality and even improving beneficial working conditions to the labour force indulged in the industries. (Hofmann and Rüsch, 2017) However, the key benefit that is of most interest to multiple stakeholders, is how this revolution affects and impacts the sustainability factors for a sustainable future.

Despite to the diverse range of benefits, limitations and drawbacks are present in the concept of Industry 4.0 as well. The main barrier to Industry 4.0 technologies, can be identified as the visible lack of facilities for adoption in several parts of the world where the economy is relatively less developed than most highly developed industrial nations from which the Industry 4.0 concept originated from and is implemented in. As discussed previously, Industry 4.0 technologies are primarily implementations of the modern ICT systems and concepts with an integration of advanced manufacturing process methodologies. Therefore, the key barriers regarding the implementation of the technologies are economic and infrastructural development in addition to the evident lack of knowledge and regulations that increasingly complicate the convenience of adoption into a country’s manufacturing industry as the technologies are relatively novel opposed to the pre-existing procedures followed and therefore require an adoption phase where all infrastructure and knowledge must be made available for successful implementation. (Saberi et al., 2018)

2.1.1. The foundational constituents of Industry 4.0 technologies

Industry 4.0, despite its various ambiguous definitions, consists of the same key technologies that enable it. For instance, Culot et al. (2020) conducted meticulous research which suggests that Industry 4.0 comprises of 13 central technologies which are seen to be accomplishing one of the two objectives which is either to bridge the physical peripherals and the digital world or to enhance connectivity. Similarly, Gilchrist (2016) in his book "Industry 4.0: The Industrial Internet of Things" further elaborates that the building blocks of Industry 4.0 are primarily constituent of nine individual technologies that influence the manufacturing industry. Another relevant research conducted by Jamwal et al (2021) on the topic of Industry 4.0 technologies for manufacturing sustainability, classifies the key constituents that Industry 4.0 comprises of, similarly to Gilchrist (2016). Hence the key constituent technologies that have been repeatedly seen to be the primary contributors to the concept of Industry 4.0 are identified as follows,

- Internet of Things
- Big data analytics
- Robotics and Autonomous systems
- Cloud manufacturing
- Additive manufacturing
- AI & Machine learning
- Block-chain technology
- Cyber-physical systems

2.2 The need for sustainable manufacturing

Manufacturing industry has always been seen as a function which creates produce through engineering solutions whilst optimizing for the economic value. This perspective has drastically changed in the past few decades due to the essential need to factor and consider the social and environmental aspects of sustainability making the manufacturing function not as straightforward as it once was viewed by the engineers. Developing countries are ever improving to elevate the quality of life for their increasing populace and hence manufacturing capacities need to increase. Similarly, developed countries do not downscale and instead always intend to expand and develop as well, resulting in the manufacturing industry to be an ever-expanding global industry. Therefore, an unsustainable scenario arises which needs to be addressed, hence sustainable manufacturing.

The three pillars of sustainable manufacturing; society, environment and the economy are widely addressed in the present-day industry which is. The three pillars are addressed by several terms including the triple bottom line (3BL), the pillars of sustainability and the 3Ps. The three Ps are essentially a simpler method of identifying the three pillars through simpler terms, society being people, environment being the planet and economy being profit or prosperity. It is crucial to further understand how the three pillars of sustainability are being addressed in order to achieve sustainable manufacturing, hence this is further reviewed in the following sections.

2.2.1. The persistent issues to achieve sustainable manufacturing

As per Alayón et al. (2022) there are estimated twice the number of barriers than enablers in sustainable manufacturing and these barriers can be classified into seven key aspects. Some of which include, contradictory managerial attitudes to sustainable manufacturing concepts, lack of awareness, absence of government policies, lack of financial capacity and the availability of technologically advanced infrastructure.

Furthermore, the need to accommodate the increasing cost of manufacturing is identified to be the main barrier in sustainable manufacturing practices. This is followed by the lack of awareness and lack of a guideline for implementation as key reasons for the lack of implementation of sustainable manufacturing practices.

2.2.2. The Triple Bottom Line aspects of sustainable manufacturing

The key areas that economic sustainability concerns itself in the manufacturing industry have been identified as manufacturing costs, profit, and investments. The profit aspect deals with the aim to increase revenue and minimize the costs of manufacturing. The investment aspect prioritizes the evaluation of the economic performance improvements as a result of the investments made with the goal to achieve better performances. Finally manufacturing cost aspect includes most aspects of the manufacturing procedures including operating costs, equipment performance (lifespan and resultant depreciations), etc. In the context of industry 4.0 and the manufacturing industry, it can be seen that the impact of Industry 4.0 has more immediate effects and if implemented correctly can contribute positively to reach social and economic sustainability.

The key areas of concern for environmental sustainability in the context of manufacturing can be classified into four categories. First is the emissions from manufacturing procedures which often include several by-products, wasted energy, etc. The second is the pollution which involves the release of detrimental substances into the surrounding environment. The third is the consumption of resources in a possibly unsustainable manner which could include scarce raw materials, energy, and other such consumables. Finally, it is the impact on biodiversity caused by the manufacturing industry due to the disruption of nature to obtain raw materials, operate the industrial facilities, etc.

Social sustainability is a crucial dimension of sustainability which intertwines with the other aspects in many ways. Social sustainability is the social aspect which often enables the welfare of people and society as a whole through the provision of equal opportunities, equal wealth distribution, human wellbeing and a healthy environment. From research it is seen that the key issues that impact social sustainability in manufacturing include issues pertaining to work management and human rights from within the manufacturing enterprise and externally on the societal responsibilities, and business practices of the entities and any issues concerning the customers.

2.3 Existing models of evaluating the impact of Industry 4.0 on Sustainable Manufacturing

The study of the impacts of Industry 4.0 in the context of sustainable manufacturing is a relatively under researched area, though there have been studies that have come up with models that aim to evaluate the impact of Industry 4.0 technologies.

One such study is done by Ghobakhloo (2020), which studies the opportunities for sustainability through the implementation of Industry 4.0. The study initially undertakes the comprehensive literature review of the fundamentals of Industry 4.0 followed by the creation of a model relationship between Industry 4.0 and sustainability by applying the interpretative structural modelling technique (ISM). The results of the ISM revealed the existence of complicated interdependent relationships between the Industry 4.0 and sustainability factors. In order to assist the ISM, a MICMAC analysis is done which allows for a comparative analysis between the attributes and provides an insight to the driving and dependence powers of the sustainability factors.

Another related research was conducted by Bai et al. (2020) under the topic, “Industry 4.0 technologies assessment: A sustainability perspective”. The aim of the research study is to emphasize the importance for organizations to evaluate Industry 4.0’s impact on sustainability and assist these organizations as pre-existing frameworks for guidance are scarce. Subsequent to the literature review, a framework is developed with regards to sustainability aspects based on the 17 UN Sustainable Development Goals. The result showed big data analysis, cloud and mobile technology to be the most impactful of the 17 identified I4.0 technologies. The general consensus and conclusion reached from the study is for manufacturing organizations to implement and adapt Industry 4.0 technologies since they have a positive impact, but also to evaluate individual technology cautiously since some technology adoptions might not be worth the risk, investment and/or the promised improvement.

3 METHODOLOGY AND EXPERIMENTAL PROCEDURE

The below step-by-step procedure demonstrates the initial steps to be followed in order to initiate the development of the assessment framework to conduct the research.

- Step I – Identification of the problem statement which is to develop a detailed framework and analyzing the sustainability impact of Industry 4.0 technologies’ implementation in the industry.
- Step II – Conduct exhaustive literature review of related studies to the research problem.
- Step III – Identification and establishment of relationships between the identified Industry 4.0 technologies and the contributing factors to manufacturing sustainability.
- Step V – Case studies at manufacturing organizations and obtain expert input
- Step VI – Identify, assess and evaluate the impact of the identified Industry 4.0 technologies

- Step VII – Develop a generic conclusive model of the impacts of Industry 4.0 on sustainable manufacturing and develop a guidance framework for Industry 4.0 implementation

3.1 Initial Deductions from Literature Review

From initial literature review, the key Industry 4.0 technologies are identified to be as additive manufacturing, cyber-physical systems, cloud computing and manufacturing, Internet of Things, big data analytics, autonomous systems, blockchain technology and machine learning concepts.

Subsequently, the need for sustainability, issues hindering the achievement of sustainability, aspects of sustainable manufacturing, and the key concerns regarding sustainability in the sense of the triple bottom line aspects are identified as well as the impacting factors on the TBL aspects of sustainability with their associated weightage contribution to the sustainability aspect.

Table I – Economic sustainability concerns and their associated weightages

Economic Sustainability Concern	Associated Weightage (%)
Manufacturing – Operating Costs	25
Manufacturing – Raw Material Costs	25
Manufacturing Equipment Performance	15
Profitability	20
Return on Investment	15

Table II - Environmental sustainability concerns and their associated weightages

Environmental Sustainability Concern	Associated Weightage (%)
Energy Utilization	30
Raw Material Utilization	20
Emissions	30
Impact on bio-diversity/eco friendliness	20

Table III - Social sustainability concerns and their associated weightages

Social Sustainability Concern	Associated Weightage (%)
Impact on Employment Rate – Work Management	20
Ergonomics	30
Provision of Equal Opportunity and Social Security	15
Employee Skill and Continuous Professional Development	20
Business Practices and Societal Rights	15

The third and final section of the literature review improves the understanding of the barriers leading to the adoption of Industry 4.0 to enhance sustainability, sustainable value creation and identification of previous studies that address the sustainability impact of Industry 4.0 implementations.

3.2 Industry expert input and case study

In order to gain a practical insight to the research problem, it is necessary to study the real-life scenarios in addition to the literature pertaining to the research problem. This need for real life research is addressed through input from industry experts involved in the manufacturing industry through questionnaires and interviews regarding the existent Industry 4.0 technology implementation and the various impacts they could or could not have resulted in.

Case Study I - The first organization where a practical case study is to be conducted is a leading hosiery apparel manufacturer that engages primarily in the production of socks and has an extensive manufacturing facility that utilizes Industry 4.0 technology in specific sections. In order to gain an extensive understanding and insight to the manufacturing organizations’ implementations and understanding of Industry 4.0, several key personnel of the operation who are industry experts are to be contacted and input is to be collected with regards to the extent of Industry 4.0 implementation and its impacts on the various concerns pertaining to the triple bottom line of sustainability, enablers and barriers, and specific historic and performance data of the changes that have been realized through implementing Industry 4.0 technologies for the purpose of comparison and analysis.

Case Study II - The second organization chosen for a case study is an organization primarily manufacturing industrial tires used in the agriculture, construction, sports and defense industries. Data collected will include an initial assessment of the implemented Industry 4.0 technologies, the enablers and barriers, followed by the impact on the factors affecting the three TBL aspects of sustainability by the Industry 4.0 technologies that are actively utilized. Input is also taken on how the I4.0 technologies that have not been implemented will benefit or not benefit the sustainability of the manufacturing plant, etc.

3.3 Assessment models for Case Studies

Initially, an implementation and readiness assessment of the manufacturing organizations' presently available facilities needs to be performed in order to collect useful and relevant data as per the research problem. In order to do so, the 4 levels of implementation shown in Table IV are used as benchmarks for the identification for each of the identified 8 Industry 4.0 technologies. Utilizing the defined levels of implementation, the organizations' manufacturing facilities can be assessed as to how well or not Industry 4.0 has been integrated as a concept by individually assessing the 8 key technologies. The results are noted through a simple assessment matrix.

Following the implementation assessment, the sustainability impact is to be studied. For the purpose of data collection and initial assessment, a pair-wise comparison matrix will be utilized. The data is collected from the interviews and questionnaires posed to the relevant industry experts at the sites of the case study along with further refinement of the assessment model. Additionally, literature review data from various sources is used to determine the impact in order to make a conclusive model for the sustainability impact assessment.

Table IV – Level of implementation descriptions for implementation assessment

Level of Implementation	**Description**
Level 0	The manufacturing operation does not have the capability to introduce I4.0 due to barriers or lack of applicability in the area of expertise.
Level 1	The organization has fundamental operations and basic infrastructure that can be upgraded in the near future to realize Industry 4.0.
Level 2	The Industry 4.0 technology has recently been fundamentally implemented with the potential for increased utilization and integration.
Level 3	Advanced Industry 4.0 technology implementation and utilization in the organization with high levels of integration with the other key I4.0 technologies.

Table V – Description of scoring for sustainability impact assessment

Scoring/Weightage	**Description**
1	Detrimental sustainability impact post-implementation of the Industry 4.0 technology due to various possible reasons.
3	Minor or negligible sustainability impovements post-implementation of the Industry 4.0 technology. I4.0 provides a minimal change in terms of sustainability, despite possible improvement in other areas of the organizations' capabilities.
5	Moderate improvement seen in at least one of the triple bottom line aspects of sustainable manufacturing due to the implementation of the I4.0 technology.

7	Noticeable and significant improvements in multiple aspects in the triple bottom line of manufacturing sustainability as a result of the Industry 4.0 technology
9	Improved sustainability in all triple bottom line aspects and reaped major benefits after implementation compared to previous technologies available at the organization

In order to assess the sustainability impact of an Industry 4.0 technology's implementation at an organization, a scoring method will be utilized to describe the relationship between the I4.0 technology and the sustainability concern/aspect. A description of the reason for the scoring will be attached to provide justification. The above table provides the scoring system to be utilized which ranges between 1 and 9. The scoring and analysis assessment of the sustainability impact will be performed separately for each of the three triple bottom line aspects of sustainability. The final output, however, will be a weighted average between all three triple bottom line aspects.

3.4 Identifying the most sustainably impactful Industry 4.0 technologies

As aforementioned, eight Industry 4.0 technologies are being considered and for the development of a guideline for fundamental implementation and sustainability improvements in manufacturing, they are to be treated as alternatives. Therefore, in order to determine the most impactful Industry 4.0 technology which positively benefits all of the triple bottom line aspects of sustainable manufacturing, multi criteria decision making is to be utilized since it allows for accurate decisions to be made from the data collected in the form of a pair-wise comparison matrix in the previous stages of the study.

Višekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) is a broadly utilized MCDM method that provides a ranked solution to multiple criteria problems which require discrete optimization and resolution of possibly conflicting criteria. In order to carry out the VIKOR method, the below given steps are followed to determine the most impactful Industry 4.0 technology and also to identify which I4.0 technologies address which concern factor most effectively.

3.4.1. Steps to conduct VIKOR analysis

Initially, the criteria must be determined whether it is beneficial or non-beneficial (e.g. higher value beneficial), however as seen in previous sections, the scoring of the criteria is done in such a way that it is always beneficial. Once this is determined, the best and worst values (alternative) must be identified for each criterion for the decision matrix of values to be normalized.

The best value in a beneficial scenario being identified as $f_i^+$and for the worst value in the beneficial scenario as f_i^-. S_j is the utility measure and R_j is known as individual regret and are to be computed as follows,

$$S_j = \sum_{j=1}^{n} \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \times W_j \quad (1)$$

$$R_j = Max\left(\frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \times W_j\right) \quad (2)$$

Where W_j is the criteria weight and n is the number of criterion. Following the utility measure and individual regret calculation, Q_j, the overall rank, can be determined as follows,

$$Q_j = \frac{S_j - S^+}{S^- - S^+} \times \upsilon + \frac{R_j - R^+}{R^- - R^+} \times (1 - \upsilon) \quad (2)$$

Where υ is taken to be 0.5 & R^+ = Min(R_j) ; R^-=Max(R_j) & S^+=Min(S_j) ; S^-=Max(S_j)

Once the ranking is completed, two conditions need to be checked for effective decision making.

Condition 1 – Acceptable Advantage in Decision Making

$$Q(A^2) - Q(A^1) \geq DQ \quad (3)$$

Where DQ=1/(j-1) and j is the number of alternatives

Condition 2 – Acceptable Stability in Decision Making

This condition is such that A^1 which is the first ranked alternative must also be the best ranked alternative by the S and/or R value scales as well.

If one of the conditions is not satisfied, a compromise set of solutions is proposed. If only condition 2 is not satisfied, then alternative 1 and 2 are considered as a compromise set. If condition 1 is not satisfied, the same condition is applied for the subsequently ranked alternatives, until the condition is satisfied. All the alternatives that do not satisfy the condition after the rank 2 alternative will also be included in a compromise set. The above steps to perform a VIKOR have been developed into a MATLAB code, seen below, that can be utilized by entering the decision matrices and weightages.

```
%Decision matrix values entered as a variable array 'dm_array'
%Criteria weightages entered as a variable array 'weightage'
%Variable array 'criteria_bnb' of 0s and 1s entered, indicating whether the
criteria is beneficial or not
v=0.5
dm_alt=length(dm_array(:,1)); %Number of alternatives

%Checking if criteria are non-beneficial for each criterion entered
for c_no = 1:length(weightage) %Number of criteria
    if criteria_bnb(1,c_no)== 1
        fi_pos(1,c_no)= max(dm_array(:,c_no));
        fi_neg(1,c_no)= min(dm_array(:,c_no));
    else
         fi_pos(1,c_no)= min(dm_array(:,c_no));
        fi_neg(1,c_no)= max(dm_array(:,c_no));
    end
end
for altn = 1:dm_alt
  for c_no = 1:length(weightage) %Number of criteria
%Normalizing the decision matrix dm_array and storing it in 'normalized'
   normalized(altn,c_no)=(fi_pos(1,c_no)- dm_array(altn,c_no))./(fi_pos(1,c_no)-
fi_neg(1,c_no));
%Calculating utility measure values
   S_ij(altn,c_no)=(normalized(altn,c_no).*weightage(c_no));
%Calculating Sj, Rj and Qj values for ranking scores
   Sj(altn,1)= sum(S_ij(altn,:));
   Rj(altn,1)= max(S_ij(altn,:));
   Qj(altn,1)=(v*((Sj(altn,1)-min(Sj))/(max(Sj)-min(Sj))))+((1-v)*((Rj(altn,1)-
min(Rj))/(max(Rj)-min(Rj))));
  end
end
Sj
Rj
Qj
```

4 RESULTS AND DISCUSSION

4.1 Determining the most sustainably impactful Industry 4.0 technologies

The VIKOR MCDA method has been utilized to determine the most sustainably effective I4.0 technologies for each triple bottom line aspect for both case studies. The initial step is to normalize the decision matrix in order to calculate S_j and R_j. The data is obtained through the initial implementation assessment and the sustainability impact assessments that are conducted. Normalizing the decision matrix needs to be done for each criterion, by identifying the maximum and minimum values in the criteria and finding the ratio of variation of the element to the maximum difference multiplied by the weight of the criteria. Following the normalization of the decision matrix, the S_j, R_j and Q_j values can be calculated to determine the ranking for sustainability impact. In VIKOR analyses, the lowest output value from the calculations indicates the most preferred alternative and hence, ranked in an ascending manner. The following table is an example of a completed VIKOR analyses conducted for economic sustainability impact of the Industry 4.0 technologies implemented in the hosiery apparel manufacturing organization. The analyses are conducted for each TBL aspect of sustainability and the complete impact ranking results for each case study can be seen in Table VII and VIII.

Table VI – Summary of the VIKOR analyses results for Case Study I

	Economic Sustainability Concern Criteria					S_j	R_j	Q_j	***RANK***
	0.25	**0.25**	**0.15**	**0.2**	**0.15**				
	EC1	*EC2*	*EC3*	*EC4*	*EC5*				
Cyber-Physical Systems	7	7	7	5	7	0.3583	0.2000	0.5792	**4**
Cloud Manufacturing	3	3	5	5	5	1	0.2500	1	**5**
Internet of Things	9	7	7	9	9	0	0	0	**1**
Big Data Analytics	9	5	7	9	9	0.1250	0.1250	0.3125	**3**
Robotics & Autonomous Systems	9	7	7	9	9	0	0	0	**1**
Best Scenario (f_i^+, S^+, R^+)	*9*	*7*	*7*	*9*	*9*	*0*	*0*		
Worst Scenario (f_i^+, S^-, R^-)	*3*	*3*	*5*	*5*	*5*	*1*	*0.2500*		

4.2 Findings from Case Study I

The hosiery apparel manufacturer is an organization that is planning to implement an Industry 4.0 ecosystem with increased sustainability and therefore in a state of transition from second and third generation industrial practices towards an Industry 4.0 ecosystem. The facility did not possess a holistic Industry 4.0 ecosystem, but nonetheless implemented some Industry 4.0 technologies/aspects in its manufacturing processes. Of the eight Industry 4.0 technologies considered in the research study, additive manufacturing as a technology/concept is not applicable due to the nature of apparel manufacturing and thus was not considered for further analysis. Robotics and autonomous systems, along with cyber-physical systems and cloud manufacturing were some key technologies that have been implemented. The most advanced implementation Industry 4.0 technology is divulged to be Internet of Things which also allows for big data analytics. IoT and big data analysis have been the most revolutionary implementations for the organization allowing for multiple improvements which address several concern factors impacting the triple bottom line aspects of sustainability.

In the following table, the rankings of the five Industry 4.0 technologies that were evaluated are summarized and the overall ranking for sustainability have been derived through averaging the results. From the results it can be seen that for case study I, Internet of Things is the implementation that has holistically impacted sustainability the most, followed by the autonomous system and cyber-physical systems implementations being ranked second and third most impactful in terms of the TBL aspects of sustainability. Analyzing the results, the VIKOR analyses yielded similar results to the qualitative data obtained from the interviews with the key personnel at the organization. During the site visit and the associated interviews, IoT was identified to be the most fundamental and beneficial implementation at the organization due to having relatively minimal barriers to implementation. The implementation of the cyber-physical autonomous machinery however was deemed to be the highest beneficial and revolutionary change in the organization but the barriers to implementation persist due to the financial requirements. This is further supported by the fact that the transition to advanced machinery is still at 47% and the transition phase for the machinery in particular will take at least two more years. Another consideration is that big data analytics despite being quantitatively ranked 4, is more of a value addition and complementary to I4.0 technology.

Table VII – Summary of the VIKOR analyses results for Case Study I

Industry 4.0 Technology	**Rank in Economic Sustainability**	**Rank in Environmental Sustainability**	**Rank in Social Sustainability**	***Overall Rank***
Cyber-Physical Systems	4	4	1	**3**
Cloud Manufacturing	5	4	2	**5**
Internet of Things	1	1	2	**1**
Big Data Analytics	3	2	5	**4**
Robotics & Autonomous Systems	1	3	2	**2**

4.3 Findings from Case Study II

Similar to the first case study, the tire manufacturing organization is also in its transition stages of achieving an Industry 4.0 ecosystem with the main focus on achieving holistic sustainability. The first Industry 4.0 technology investigated, additive manufacturing, is not extensively used as of yet, however its implementation has allowed for improvements in production in use, cases including engraving. The use of robotics and semi-automated systems are utilized in the tire material development and tire development sections. Cloud computing and manufacturing is also utilized in a fundamental manner to assist in the production process and the production floor which integrates into the IoT implementations. Similar to the first case study, IoT is the most extensively implemented Industry 4.0 application through use of sensors, cloud computing, databases and many more to enhance manufacturing processes in various manners. The use of IoT also enables the collection of big data that is used for big data analytics through refinement and study. Three of the eight Industry 4.0 applications focused on this research, cyber-physical systems, AI and blockchain management are not present at this facility, and thus further analyses cannot be conducted and therefore, will not be discussed. At the present state of the manufacturing ecosystem cyber-physical systems are considered to be sub optimal since complete automation and no human interaction is not preferred.

The sustainability impact results obtained from the analyses seen below indicate that Internet of Things is the most beneficial implementation, followed by a compromise group between robotics and big data analytics. Further studying the results, the ranking obtained through the VIKOR analyses is identical to the input received from the key personnel at the organization. The most sustainably impactful is the combination of IoT implementations and the complementary big data analytics. The robotics systems were discussed to be the most socially impactful Industry 4.0 solution implemented due to the great levels of ergonomic benefits it provides the employees, which is one of the organization's key focuses. The combination of IoT and big data analytics were also identified to have created the most opportunities for economic advancements and eco-friendliness in the manufacturing procedures.

Table VIII – Summary of the VIKOR analyses results for Case Study II

Industry 4.0 Technology	**Rank in Economic Sustainability**	**Rank in Environmental Sustainability**	**Rank in Social Sustainability**	***Overall Rank***
Cyber-Physical Systems	4	3	2	**4**
Cloud Manufacturing	4	5	4	**5**
Internet of Things	2	1	1	**1**
Big Data Analytics	1	4	2	**2**
Robotics & Autonomous Systems	2	1	4	**2**

4.4 Further findings, discussion and guideline

As discussed, input was gathered qualitatively from the industry professionals at the respective organizations where the case studies were conducted, and this information with their assistance was utilized to complete the sustainability assessments for the 6 available Industry 4.0 technology implementations. Due to the limitations present in the Sri Lankan industry, two of the eight identified Industry 4.0 technologies, AI/machine learning and block chain technology, were not assessed.

From both case studies it is seen that the Internet of Things (IoT) implementation has been the most sustainably impactful Industry 4.0 implementation in the manufacturing environment. Robotics and autonomous systems are identified to be the second most impactful in both case studies since their implementation often revolutionizes the manufacturing process and provides a multitude of sustainable enhancements. Looking at the enablers and barriers of implementing these technologies, IoT is relatively the easier I4.0 technology to initiate implementation at an organization due to the fact that the financial pressure is significantly lower than overhauling manufacturing processes with advanced robotics systems.

It is crucial to recognize that big data analytics is often considered as a complementary implementation to IoT in many circumstances as IoT enables the acquisition of big data. As a result, it can be deduced from the results that big data analytics is the third most impactful Industry 4.0 technology that can be implemented in a manufacturing organization to enhance sustainable manufacturing. Similarly, cyber-physical systems and cloud manufacturing can be considered to be complementary to robotics and autonomous systems, since the initial transition does not involve direct transition towards implementing cloud manufacturing. This is reflected in the VIKOR analysis and is the reason for the relatively lower rankings in sustainability impact for cloud manufacturing and cyber-physical systems. Additionally, additive manufacturing is a useful yet situational implementation that could positively impact sustainable manufacturing. This is however not reflected in the results obtained from the case studies, since it is not applicable at the hosiery apparel manufacturing company and the implementation is very rudimentary in the tire manufacturing organization.

The fundamental requirements for implementing AI and block chain technology in the manufacturing industry is the need for an already existing Industry 4.0 standard ecosystem. If available, these technologies are supplementary to improve several manufacturing procedures that will promote sustainability. The ability to meet these requirements is not seen in the organizations chosen for the case study and even across the Sri Lankan manufacturing industry, due to several factors including primitive infrastructure availabilities.

Further looking into barriers and enablers of Industry 4.0 implementation for sustainable manufacturing, a key barrier that was identified as a part of the case studies is the lack of willingness amongst the employees to adapt and shift towards an Industry 4.0 ecosystem. This occurs due to several concerns including the anxiety of the possibility of employees being made redundant. This issue needs to be addressed through improving awareness amongst the population and displaying the mutual benefits that can be achieved through implementing sustainable Industry 4.0 solutions and an organization's commitment towards its employees' well-being. The recent COVID-19 pandemic and the subsequent severe economic crisis have also been major barriers in the manufacturing organizations' ambitions of transitioning to Industry 4.0 ecosystems. The need for comprehensive infrastructure to implement Industry 4.0 is also identified and emphasized by the feedback received whilst conducting the case studies. Sri Lanka is a developing nation and does not have universal (and affordable) access to broadband and other utility infrastructures which significantly restricts the improvements that can be made. Thus, it is important to manage these issues by implementing feasible I4.0 technologies that do not require high levels of investment.

5 CONCLUSION

A novel assessment methodology has been developed to assess the Industry 4.0 technologies available at a manufacturing organization and how the respective technologies impact the concerning factors of each TBL aspect of sustainability. Initially, the eight key Industry 4.0 technologies and the sustainability impact factors of each TBL aspect of sustainability were determined through the literature review. Subsequently, a comprehensive assessment framework was developed for analyzing the manufacturing sustainability impact of each Industry 4.0 technology that is being considered.

The developed framework analysis has been put into practice through means of two case study scenarios, a hosiery apparel manufacturer and a tire manufacturer. Through five interviews with the associated industry professionals and site visits for each case study, data was acquired to perform the sustainability impact assessment for the Industry 4.0 technologies that were implemented. Following the assessments, VIKOR analyses assisted in determining the most sustainably impactful Industry 4.0 technologies for positive impact using the data acquired from the assessments conducted. The results obtained were identical to the input acquired from the industry professionals who were consulted in the respective organizations, displaying the reliability of the assessment and the analysis model.

As a result, Internet of Things was concluded to be the most impactful Industry 4.0 technology that could be implemented in a manufacturing plant due to the several opportunities it presents for sustainable enhancements across the board. A key concern in the completion of this research is the need for case studies of organizations that have diverse and comprehensive implementations of Industry 4.0 technologies in an Industry 4.0 ecosystem which intends to be addressed in future work.

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