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A Framework to Overcome Blockchain Enabled Sustainable Manufacturing Issues through Circular Economy and Industry 4.0 Measures

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Abstract
Adoption of Industry 4.0 (I4.0) and sustainable manufacturing practices plays an important role for manufacturing industries to sustain their globe market reputation. However, the adoption of I4.0 technologies in manufacturing practices is more concern for manufacturing industries. Volatile customer demands, changing manufacturing trends and market scenario has forced manufacturing organization to revisit their production system and incorporate sustainability practices. Blockchain enabled practices helps to maintain transparency and traceability in supply chain as well as manufacturing activities. But lack of framework related to blockchain enabled sustainable manufacturing has become a serious concern for policymakers and practitioners. Similarly, due to changing market scenario it is important to identify the solutions to overcome the blockchain enabled sustainable manufacturing issues through circular economy and I4.0 solution measures. The present study identifies the 28 critical challenges and 22 I4.0 and circular economy based solution measures to overcome the issues of blockchain enabled sustainable manufacturing. Further, a case study in electronics manufacturing industries is used to test the developed framework using hybrid multi-criteria decision making approach. The case study findings that organizational and managerial challenges are critical to blockchain enabled sustainable manufacturing adoption. In the end of study, we have proposed an integrated framework for blockchain enabled sustainable manufacturing practices for energy, waste, resource, quality and life cycle management. It is expected that present study will be helpful for the researchers, practitioners and policymakers to understand the complications in the adoption of blockchain enabled sustainable manufacturing practices.

Keywords- Industry 4.0, Blockchain, Sustainable manufacturing, Decision making, MCDM, Sustainability, Circular economy.

1. Introduction

The United Nations sustainability 2030 agenda can be categorized into the 17 major sustainable development goals (SDG). These 17 goals can be further categorized into three main dimensions of sustainability i.e., economic, social and environmental (Elliott, 2012). SDG 12 Responsible Production and Consumption focus on the producing more with less utilization of source and can be defined as:
"The use of services and related products, which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations" (Sachs, 2012).

Manufacturing industries plays an important role to complete the demand from societies related to basic needs and comfort lifestyle (Alcácer & Cruz-Machado, 2020). These manufacturing activities includes supply chain activities, basic manufacturing operations and logistic operations (Abdul-Rashid et al., 2017). In the past few years volatile customer demands and comfort lifestyle needs have put a pressure on the manufacturing industries as well as natural resources (Jayal et al., 2010; Garetti & Taisch, 2012; Haapala et al., 2013). Manufacturing activities have negative impact on the environment as well as on natural resources which affects all aspects of sustainability (de Sousa Jabbour et al., 2018). Increasing carbon emissions and greenhouse gases, customer awareness for environmentally friendly processes and strict government regulations have put a great pressure on manufacturing organizations to adopt sustainable manufacturing practices (Bhanot et al., 2017; Bhatt et al., 2020). Manufacturing sustainability in industries can be considered as an attractive strategy which can help to reduce the uncertainty in systems, complete customer demands with minimum environment degradation, reduce energy consumptions and increase resource efficiency (Sharma et al., 2020).

The development in industrial processes have led to a new manufacturing revolution which can be termed as Industry 4.0 or fourth industrial revolution (Awan et al., 2021; Romero et al., 2021). Few studies reported about the benefits of I4.0 practices in terms of sustainable production (Varela et al., 2019; Jamwal et al., 2021c). I4.0 can be broadly defined as the current trends of data exchange and automation within the different manufacturing activities in the industry (Kim, 2017). The main key enabling technologies are blockchain technology, cyber physical systems and Internet of Things. At present manufacturing sustainability can be addressed by “SDG 9: Industry, innovation and infrastructure” and SDG 12: Responsible production and consumption. The initial studies related to manufacturing sustainability discussed about the economic sustainability only. Later on, in 1999 article published by Fujita (1999) discussed the role of all three dimensions of sustainability in the manufacturing activities. However, Stock & Seliger (2016) discussed about the opportunities of sustainable manufacturing in the I4.0 era. Some other studies such as: Bag & Pretorius (2020) investigated the relationship between the circular economy, sustainable manufacturing and I4.0 technologies. de Sousa Jabbour et al. (2018) discussed how sustainable manufacturing or environmentally conscious manufacturing practices can revolutionize the wave of I4.0 revolution. The major critical success factors related to environment friendly practices in I4.0 were highlighted in the study. Sustainable manufacturing practices help to address the sustainability challenges at the global level which includes the green societies, need of optimized manufacturing systems, reduced energy consumptions and use of renewable materials (Malek & Desai, 2020). Sustainability practices in manufacturing activities allows the manufacturers to share the information related product life cycle and communicate within the inherent trust-less manufacturing network (Leng et al., 2020). The current manufacturing trend is based on the internet and social media in which there is need to manage, utilize and secure the relevant information related to the manufacturing organization. Cyber-security issues can be considered as the main global issue for the cloud-based manufacturing or manufacturing in I4.0 era.

With the development of I4.0 practices across the globe now the developing nations are also more focused on the adoption and implementation of I4.0 to compete with the industries of developed nations (Yadav et al., 2020a). In line with these efforts, several major issues related to manufacturing have arisen which includes product manifestation with information complexity, management of information coordination, lack of reference architecture and standards and limitation of information technology systems (Raj et al., 2020). These issues affect the I4.0 practices and sustainability issues in the manufacturing industries.

Both the blockchain technology and sustainable manufacturing practices has a great impact on the organizational performance in different industry sectors such as: manufacturing, healthcare and service sector (Jamwal et al., 2021b). It is important to investigate the impact of the blockchain and sustainability practices in current manufacturing scenario and assess the challenging issues related to both these two technologies. However, some studies related to I4.0 practices discussed about the framework related to the blockchain technologies and sustainability (Elmamy et al., 2020; Esmaeilian et al., 2020). These frameworks are more focused on the theoretical concepts and don't link the challenges related to blockchain and manufacturing sustainability with solution measures. The adoption of I4.0 technologies and circular economy related practices are important to compete the global market competition (Bag & Pretorius, 2020). Therefore, it is important to discuss the solution measures based on the circular economy as well as I4.0 technologies. Indian industries can be considered the largest manufacturing hub for the automotive and electronics components. Now more MNCs are investing in the India due to cheap labour and government policies related to industrial innovations (Jamwal et al., 2021e). In past studies, few authors have claimed that the Indian manufacturing industries have a major contributions in the Indian economy (Luthra & Mangla, 2018; Kamble et al., 2019; Bhanot et al., 2020). Hence, adoption of framework related to the blockchain enabled sustainable manufacturing will be helpful to improve organizational performance as well as sustainable future of organization. Based on the above discussion, two research objectives have framed in this study which are as follows:

(i) To identify challenges related to blockchain enabled sustainable manufacturing and compute their weights with hybrid MCDM approaches.
(ii) To identify and rank the solutions for blockchain enabled sustainable manufacturing based on circular economy and I4.0 measures.

To achieve above discussed objectives, an electronics manufacturing industry from India is selected as the case organization. Best worst method (BWM) is used to compute the weights of challenges related to the blockchain enabled sustainable manufacturing. ELECTRE method is used to rank the solution measures related to circular economy and I4.0 practices.

The next sections of paper discuss about the literature review in which relationship between sustainable manufacturing and I4.0, impact of blockchain technology on manufacturing sustainability, challenges related to blockchain enabled sustainable manufacturing and solution measures with I4.0 and circular economy is discussed. In the section 3 research gaps in published literature is discussed in which systematic literature review approach is followed to assess the research gaps. In the section 4 research methodology adopted in the study is discussed. In the section 5 case study results have discussed. In the section 6 implications for researchers, policymakers and practitioners have discussed. In the end of study conclusion and future research directions have discussed.

2. Literature Review

The quantity and quality assessment of available data is important in the literature. The literature review can be considered as the major element in the any research work. In this study, a systematic literature review approach and quality assessment approach is used to analyze the research work done in the blockchain technology and manufacturing sustainability. To ensure the quality of study all three major databases which publish articles related to the blockchain technology and manufacturing sustainability i.e., IEEE, Scopus and Web of Science (WoS) were considered. To make study more reliable few industry reports have been also considered in this study in Indian context. The literature review strategy started with the article collection using relevant keywords related to the study i.e., "Blockchain" OR "block-chain technology" AND "Sustainable manufacturing" OR "manufacturing sustainability" OR "triple bottom line" OR "sustainability". In this study inter-rater reliability methodology adopted by Jamwal et al. (2021c) have considered for final article data set validation purpose. The articles were finalized by few inclusion and exclusion criteria discussed as follows:

(i) The article must be related to the blockchain technology and sustainability.
(ii) The article should be discussed about the blockchain and sustainability as the major theme rather than the future scopes.
(iii) A full text of the article should be available and it should be in English only.

These above discussed inclusion criteria were used as the main selection criteria for the selection purpose. After the finalizing the final dataset by three independent experts (academia experts) qualitative assessment of study is done.

2.1 Relationship Between Sustainable Manufacturing and Industry 4.0 Practices

I4.0 technologies are expected to influence the sustainability practices in manufacturing organization (Azizi & Hakl, 2020). Sustainability at present can be considered as the core business strategy for the future of industries which in the report of United Nations Sustainability 2030 agenda which includes low impact industrialization, smart manufacturing, smart cities, responsible production and energy efficient buildings (Bag et al., 2018; Habib & Chimsom, 2019; Beier et al., 2020). I4.0 combines the production and physical entities in the manufacturing organization with the digital technologies, IoT and artificial intelligence tools (Machado et al., 2020). For the sustainable future of industries, business practices need to work on the environmental action at present stage. However, some studies reported about the benefits of I4.0 technologies and practices to reduce carbon emission and maintain environmental sustainability (Stock & Seliger, 2016; de Sousa Jabbour et al., 2018; Varela et al., 2019). I4.0 includes the different set of key enabling technologies which have a primary aim of connecting production processes with digital technologies. Bag & Pretorius (2020) discussed the relationship between the I4.0 technologies and sustainable manufacturing practices through a conceptual framework. Jamwal et al. (2021b) highlighted the role of I4.0 tools and technologies to achieve manufacturing sustainability with the help of systematic literature review and PRISMA analysis. Ten key enabling technologies of I4.0 is discussed with their impact on the economic, social and environmental sustainability. Yadav et al. (2020a) proposed a sustainable framework for SMEs of developing nations and highlighted how sustainability can be achieved in I4.0 practices. Similarly, Jamwal et al. (2021e) adopted hybrid MCDM approach to propose a sustainability framework for MSMEs industries for I4.0 practices in which case study is done in the developing nation. It is found that I4.0 and sustainability adoption depends on the geographical as well as political issues. Luthra & Mangla (2018) highlighted the challenges for I4.0 and sustainable supply chain management in which Exploratory factor analysis and Analytical hierarchy process approach is used. (Varela et al., 2019) conducted the systematic literature review and discussed the relationship between lean tools and different I4.0 tools and their impact on sustainability. de Sousa Jabbour et al. (2018) discussed about the drivers for environmental conscious manufacturing for environmental sustainability in I4.0 era. Azizi & Hakl (2020) discussed the role of artificial intelligence and its applications to enhance the research opportunities in I4.0. Sung (2018) discussed difference between the terms I4.0 and fourth industrial revolution for Korean industries. The impact of I4.0 technologies on Korean industries in terms of sustainability is also discussed. Safar et al. (2020) discussed about the awareness regarding sustainability and I4.0 concepts among students and practitioners in India. Jamwal et al. (2021e) discussed how industries can achieve sustainability in manufacturing through the artificial and machine learning approaches and sustainable manufacturing (SM) concepts. A machine learning based SM is also proposed for the implementation of SM practices. Stock & Seliger (2016) discussed the both macro and micro perspective of SM practices in I4.0. The different opportunities for the SM is highlighted in the I4.0 context. Leng et al. (2020) discussed the challenges for blockchain enabled SM challenges for manufacturing industries. A blockchain enabled framework is proposed for the manufacturing industries to achieve sustainability in business practices.

Manufacturing industries are maximizing their outputs with minimum waste generation through SM technologies. I4.0 in manufacturing industries extends to the supply chain practices in which smart vehicles can be transmit the data to the cloud servers for analysis. In this process AI tools can be helpful to find the optimum route in which environmental impacts can be minimum. Smart filtration sensors can detect the rise in the chemical or pollutants can take actions automatically to minimize its impact on society. Business practices are now connected with the I4.0 technologies in which AI based energy systems and Industrial IoT are popular to achieve manufacturing sustainability.

2.2 Impact of Blockchain Technology on Manufacturing Sustainability

Manufacturing activities are adversely impacting the environment and natural resources are depleting at very fast rate due to comfort lifestyle demands of human. Industrialization, urbanization and depletion of natural resources are at the alarming rate (Elliott, 2012; Ahmadipourroudposht et al., 2015). Few studies claimed that earth is projected to be 2°C hotter by end of 2050. Due to these issues global manufacturing sustainability plays a crucial role to achieve 2030 UN SDG agenda (Sachs, 2012). In last few years many new technologies have been emerged with the revolution of I4.0. In these technologies, blockchain technology has an emerging role in sustainability. Blockchain technology have an emerging role to achieve manufacturing sustainability by helping foster collaboration between manufacturers and consumers, by assisting people in adopting more sustainable lifestyle (Leng et al., 2020). These practices can also improve the resources efficiency and recycling practices. The major benefits from the adoption of blockchain technology in organization is transparency in organization. It helps to provide a verifiable record as who buys and what from whom. This means that industries claim of being resource positive and minimizing their carbon emission as well as other environmental impacts can be counter checked and verified. The concept of circular economy is also crucial and its 3R concepts: reducing waste, reusing material and recycling material (Bal & Badurdeen, 2019; Enyoghasi & Badurdeen, 2021). Circular economy paradigm ensures that both services and products are traded in the cycles or closed loop supply chains (Rajput & Singh, 2019; De Marchi & Di Maria, 2020). Blockchain technology can help in this regard by ensuring traceability as well the transparency.

2.3 Challenges Related to Blockchain Enabled Sustainable Manufacturing for Organizations

Sustainability in the manufacturing activities in the organizations is very important to sustain the global market competition as well as lower carbon emission levels (Bhanot et al., 2017; Malek & Desai, 2019a). The adoption of the sustainability practices within the manufacturing depends on the many influencing factors (Jamwal et al., 2021d). However, if sustainability practices in I4.0 is adopted in the faulty manner then the industries can face loss in terms of investments and reputation (Bhanot et al., 2020). In last few years, increasing global competition and advancements in business models have changed the manufacturing practices. Now, it is necessary to identify and eliminate the critical challenges related to new technologies for manufacturing activities. Industries are now adopting I4.0 tools and practices which is facing by many critical challenges and barriers during the adoption of practices (Jamwal et al., 2021e). Many studies have highlighted the generalized set of challenges and barriers related to I4.0 adoption (Benias & Markopoulos, 2017; Luthra & Mangla, 2018; Raj et al., 2020; Yadav et al., 2020a) but these studies have limited perspective related to some technologies.

After, the comprehensive literature review related to blockchain technology articles total of 28 critical challenges have been found out which is discussed with their description in Table 1.

Table 1. Challenges for blockchain enabled sustainable manufacturing.

	Challenges	Description	Reference
C_1	Higher Implementation cost	The higher implementation cost of blockchain enabled manufacturing practices resist its implementation in manufacturing industries	(Lin & Qiang, 2018; Swan, 2019; Leng et al., 2020; Zhang et al., 2020)
C_2	Difficulty in hardware and software upgradation	Blockchain adoption requires upgraded software and hardware for information collection as well as for smart contracts	(Lin & Liao, 2017; Lu, 2018; Bao et al., 2020)
C_3	Lack of management support and awareness	Management support is a critical factor for the blockchain enabled SM practices	(Leng et al., 2020; Mnif et al., 2021; Fan et al., 2022)
C_4	Lack of continuous improvement culture	Continuous improvement culture in industry helps to sustain and improve the adoption of blockchain systems	(Kouhizadeh & Sarkis, 2018; Leng et al., 2020; Jamwal et al., 2021b)
C_5	Lack of sustainability practices	Industries needs to focus on the sustainability concepts and must aware about the performance metrics as well as measures	(Yadav et al., 2020a; Jamwal et al., 2021e)
C_6	Lack of effective collaboration	Effective collaboration helps to improve the implementation level of blockchain practices	(Leng et al., 2020; Barenji et al., 2021; Rejeb et al., 2021)
C_7	Complicated business models	Models in I4.0 are quite complex as compared to traditional business model and requires effective decision making	(Leng et al., 2020; Prewett et al., 2020)
C_8	Privacy protection	Blockchain enabled systems is also vulnerable to the leakage of transactional privacy because of public keys to everyone in the network	(Jia et al., 2018; Feng et al., 2019; Bao et al., 2020; Leng et al., 2020)
C_9	Quantum attacks	Quantum attacks can destroy the cryptographic principles of blockchain technology and can affect the manufacturing activities within the organization	(Kiktenko et al., 2018; Fernández-Carames & Fraga-Lamas, 2020; Leng et al., 2020)
C_{10}	Black box effect and efficiency	This can be referred as the challenge at the very core of machine learning in which some models are not completely predictable or understandable	(Tapscott & Tapscott, 2017; Babich & Hilary, 2020; Leng et al., 2020; Nassar et al., 2020)
C_{11}	Lack of system resiliency	Lack of system resiliency can lead to uncertainty in the system	(Fraga-Lamas & Fernández-Caramés, 2019; Mylrea & Gourisetti, 2017)
C_{12}	Retrieval on encrypted data	Retrieval of encrypted data is not suitable for the cloud information because cloud service provider is not able to retrieve the encrypted data	(Jiang et al., 2020; Leng et al., 2020)
C_{13}	Risk management and fraud detection	Risk management and fraud detection requires a good blockchain network which is still a major challenge for industry	(Fu & Zhu, 2019; Leng et al., 2020; Zhang et al., 2020)
C_{14}	Twinning blockchain with other systems	Cyber space includes multiple twins in the systems with can result in the interruption in the system	(Leng et al., 2020)
C_{15}	Multi-chain synchronization	Due to multi-chain synchronization there may be decrease in the speed of blocks within the system	(Li et al., 2019; Leng et al., 2020; Liu & Li, 2020)
C_{16}	Lack of effective self-adaptive coordination	Generally blockchain network consumes large amount of energy and there is need of self-adaptive environment to balance the energy consumption	(Leng et al., 2020)
C_{17}	Lack of middleware solutions	Middleware layers in blockchain helps to create and manage the blockchain component and lack in middleware solutions affects the adoption of blockchain technology	(Jia et al., 2018; Liu et al., 2018; Leng et al., 2020)
C_{18}	Lack of employee training programs	Blockchain technology requires higher skilled labour which requires regular training of employees. Lack in skills affects the adoption of blockchain enabled practices	(Lu, 2018; Fachrunnisa & Hussain, 2020; Sahebi et al., 2020)
C_{19}	Lack of communication between departments	Lack of communication between departments results in the transparency and trust issues in organization which resist the blockchain implementation	(Lin & Liao, 2017; Lu, 2018; Leng et al., 2020)
C_{20}	Lack of awareness about sustainability tools	Sustainability is the continuous improvement journey and lack in sustainability concepts resist the adoption blockchain enabled SM practices	(Jamwal et al., 2021b; Leng et al., 2020; Yadav et al., 2020a)

Table 1 continued…

C_{21}	Lack of consideration in human factors	Human factors plays an important role in blockchain adoption. Ignorance of human factors resist the blockchain enabled practices in organization	(Lin & Liao, 2017; Leng et al., 2020)
C_{22}	Lack of resistance in culture change	Rigid structure and culture of organization resist the blockchain enabled practices	(Leng et al., 2020; Yadav et al., 2020a)
C_{23}	Ineffective sustainability measurement systems	Unavailability and lack of knowledge about the sustainability measurement systems for practices resist the blockchain enabled practices	(Leng et al., 2020; Yadav et al., 2020a; Jamwal et al., 2021c)
C_{24}	Lack of sustainable energy adoption	Sustainability practices requires continuous training and awareness trend in the organization. Lack of sustainable energy adoption resist the blockchain enabled SM practices	(Leng et al., 2020; Yadav et al., 2020a)
C_{25}	Complexity within sustainable supply chain practices	Supply chains are now complexed in I4.0 era than the traditional supply chain. Complexity within the supply chains resist the adoption of new technologies	(Lin & Liao, 2017; Luthra & Mangla, 2018; Bao et al., 2020; Leng et al., 2020)
C_{26}	Lack of standardized tools and reference architecture	I4.0 tools and technologies are new and requires a standard reference or architecture for the new organizations. Lack in the standardization tools resist the adoption of blockchain technology	(Lin & Liao, 2017; Mittal et al., 2019; Bao et al., 2020)
C_{27}	Lack of updated auditing standards	Lack of updated auditing standards results affect the implementation of blockchain technology and hence affect the blockchain enabled SM	(Lu, 2018; Leng et al., 2020; Jamwal et al., 2021b)
C_{28}	High energy consumptions due to activities	Blockchain networks consumes large amount of energy for operations which results in higher carbon emissions as well as high energy costs	(Leng et al., 2020)

2.4 Solution Measures with the Industry 4.0 Technologies and Circular Economy Practices

In the last few years due to digitalization in manufacturing practices role of I4.0 have become more important (Asdecker & Felch, 2018; Mittal et al., 2019). However, few studies have discussed and argued that circular economy and I4.0 are the future of industries which will have a significant impact on sustainability as well as sustainable development goals (Bressanelli et al., 2018; Chauhan et al., 2019; Romero et al., 2021). Rajput & Singh (2019) pointed out the relationship between circular economy and I4.0 and analyse the factors related to both these two concepts with DEMATEL approach. In this principal component analysis is also used to find the factors related to I4.0 and circular economy. (Rosa et al., 2020) presented the systematic review to find the relationship between circular economy and I4.0 practices. It is found that circular economy and I4.0 practices have a positive impact on the life cycle management of products. The combination of big data analytics and IoT can improve the resource efficiency. de Sousa Jabbour et al. (2018) proposed future research agenda for circular economy and I4.0 for sustainable production in manufacturing industries and found that digital transformation in industries able to unlock the circularity of resources within the supply chain activities. Romero et al. (2021) stated that industries are now moving from the linear economy to circular economy by the use of different I4.0 technologies. However, there are few challenges which industries may face during the transition. Overcome from these challenges will help the industries to achieve sustainability and achieve sustainable development goals. There are few studies which discuss the opportunities for sustainability with circular economy and I4.0 technologies. However, limited studies have explored the area of sustainability with the help of blockchain technology. The studies by Leng et al. (2020) and Jamwal et al. (2021b) discussed how industries can achieve the manufacturing sustainability with blockchain technology. These studies were utilized to find the solution measures for the blockchain enabled SM issues. The solution measures for the blockchain enabled SM based on circular economy and I4.0 measures have presented in the Table 2.

Table 2. Solution measures for Blockchain enabled sustainable manufacturing with circular economy and Industry 4.0 measures.

	Solution Measure	Description	Reference
SM_1	Supplier commitment for sustainable materials and sustainability practices	Assurance of sustainable material supply and sustainability practices from the supplier through the entire supply chain	(Machado et al., 2020; Sharma et al., 2020; Yadav et al., 2020a)
SM_2	Green packaging and green purchasing initiatives	Green packaging and green purchasing initiatives helps to minimize the environment impacts as well improve economic sustainability	(Guirong et al., 2010; Yadav et al., 2020a; Wandosell et al., 2021)
SM_3	Adoption of sustainable manufacturing (6R) practices	Adoption of SM or 6R initiatives helps to improve the manufacturing sustainability in terms of economic, social and environmental sustainability	(Bag & Pretorius, 2020; Enyoghasi & Badurdeen, 2021)
SM_4	Rewards related to sustainability initiatives	Any rewards related to sustainability practices helps to encourage the employees and organizations to promote the sustainability initiatives	(Malek & Desai, 2019a; Bhanot et al., 2020; Jamwal et al., 2021e)
SM_5	Proper communication and coordination between the supply chain members and organization	Proper communication channel among the organization and different supply chain members helps to establish the smart information sharing systems which enhances the organization as well as resource efficiency	(de Sousa Jabbour et al., 2018; Cioffi et al., 2020; Yadav et al., 2020a)
SM_6	Organization commitment for sustainability adoption	Employees and management needs to be aware about the benefits from sustainability adoption and then strengthen their commitment towards the sustainability adoption in the organization	(Bag et al., 2018; Varela et al., 2019; Sharma et al., 2020)
SM_7	Advanced optimization algorithms such as: machine learning and AI	Advanced optimization algorithms such as machine learning and AI tools helps the industries to extract relevant information and use this for the future decision making	(Machado et al., 2020; Yadav et al., 2020a; Jamwal et al., 2021c)
SM_8	Smart factory components	Adoption of smart factory components helps the industries to enhance the adoption level of I4.0 technologies in the manufacturing organizations	(Dassisti et al., 2018; Mehrpouya et al., 2019; Varela et al., 2019; Chen et al., 2020a)
SM_9	Availability of reference frameworks related to circular economy and Industry 4.0	Availability of reference framework related to I4.0 technologies and circular economy will help the industries to adopt and enhance the reverse logistic practices	(de Sousa Jabbour et al., 2018; Bhanot et al., 2020; Sharma et al., 2020)
SM_{10}	Effective measures for life cycle analysis	Product designing with the environmental and economic aspects and their life cycle analysis helps to enhance the sustainability practices	(Luthra & Mangla, 2018; Leng et al., 2020)
SM_{11}	Continuous improvement culture	Continuous improvement culture in the organization helps to sustain the market position as well as improve the current state of industry	(Bag et al., 2020; Leng et al., 2020; Yadav et al., 2020a)
SM_{12}	Linkage between the various departments through advanced information technologies	Linkage between the various departments of organizations helps to share the information effectively and maintain the transparency in the manufacturing activities. The advanced information technologies available in I4.0 can be used for this purpose.	(Stock & Seliger, 2016; Varela et al., 2019; Machado et al., 2020; Jamwal et al., 2021b)
SM_{13}	Digitalized supply chains	Digitalization in supply chain activities helps to optimize the supply chain activities	(Mittal et al., 2018; Nica, 2019; Diaz et al., 2020)
SM_{14}	Sustainability practices in resource management	Sustainability practices in resource management helps to reduce the high power/energy consumption and helps to maintain economic and environmental sustainability	(Ahmadi et al., 2017; Gladysz et al., 2020; Hu et al., 2020)
SM_{15}	Industrial ecology	Industrial ecology practices helps to adopt circular economy and sustainability concepts	(Herrmann et al., 2014; Bours et al., 2017; Jamwal et al., 2021a)
SM_{16}	Advanced predictive maintenance techniques	Adoption of advanced predictive maintenance techniques helps to reduce the down-time as well as unwanted failures of system	(Bersani et al., 2020; Çınar et al., 2020; Jamwal et al., 2021b)
SM_{17}	Production process planning	Efficient production process planning helps to utilize the available resources in a better way	(Wang et al., 2015; Baki et al., 2020; Eccher & Geraghty, 2020)

Table 2 continued…

SM_{18}	Safety standards	Adoption of advanced safety modules and standards helps to maintain social sustainability	(Kamble et al., 2018; Bragança et al., 2019; Damiani et al., 2020)
SM_{19}	Awareness about sustainability benefits	Awareness about the circular economy and sustainability benefits helps in adoption of these practices and hence improve overall adoption	(Malek & Desai, 2019b; Bag et al., 2020)
SM_{20}	Brand image based on sustainability and circular economy	Brand image based on these concepts helps in the global acceptance of the products	(Rajput & Singh, 2019; De Marchi & Di Maria, 2020)
SM_{21}	Education 4.0 concepts	Education 4.0 concepts helps to improve the awareness about the new advances in sustainability as well as prepare the workforce for future industries	(Agrawal et al., 2021)
SM_{22}	Man-machine interaction	Man-machine interaction helps to facilitate the supply chain activities within the minimum response time	(Barenji et al., 2018; Angelopoulos et al., 2020)

3. Research Gaps in Literature

After the extensive literature review on articles related to manufacturing sustainability and blockchain technology following research gaps were observed which are:

(i) There are few studies in literature which discuss about the role of manufacturing sustainability with the blockchain technology. However, these studies are more theoretical rather than a practical industrial case.

(ii) There are very limited studies which discuss about the challenges related to blockchain technology for SM and these studies don’t discuss about the influence and intensity of challenges.

(iii) However, few studies have reported about the challenges related to blockchain technology for SM and developed the frameworks. However, it is noticed that none of these studies has established the linkage between the solution measures and challenges for the blockchain enabled SM.

(iv) Majority of proposed frameworks related to blockchain technology for manufacturing sustainability are not verified which raised a question about their applicability in the actual industrial scenario.

(v) There are few studies which reports about the I4.0 and sustainability related challenges with the multi-criteria decision making (MCDM) approaches but very few studies portray their relationship between the blockchain enabled SM.

The above discussed literature gaps clearly shows that there is a strong need for blockchain enabled SM framework which can link the challenges with circular economy and I4.0 based solution measures. Also, these research gaps demand for the application of hybrid MCDM approaches for computation of challenges and ranking of solutions. This clearly justifies the need of present study.

4. Research Methodology

The flow for the research methodology for blockchain enabled SM is shown in the Figure 1. In the initial stage of the study systematic literature review technique is adopted to find out the relevant articles related to blockchain technology and its applications in SM. However, few articles related to blockchain and sustainability were also included during the study. The article collection was done with the appropriate search string which were: “blockchain” AND “manufacturing sustainability” OR “sustainability” OR “sustainable manufacturing”. Total of 52 articles were finalized after the full text read and these articles were used to identify the challenges for blockchain enabled SM. Later, all the challenges were presented in the tabulated form and discussed with the experts for their inputs. Based on the expert inputs regarding these challenges a framework is developed and tested in the case organization by the application of hybrid BWM-ELECTRE MCDM approach. In this study BWM approach is used to compute the weights for challenges related to blockchain enabled SM. The consistency of the matrix is checked and in case of consistency more than 0.1 the responses were considered as reliable. ELECTRE approach is used to pairwise comparison of challenges and solution measures. With the steps followed by the ELECTRE approach the priority was identified and solutions were ranked. Further, relationship between the solution is established to investigate how these solutions will assist the organization to overcome the challenges in blockchain enabled SM practices. Finally, the findings of the case study is discussed with its implications for policymakers and practitioners.

4.1 Framework Development and Case Study Description

It is important to investigate the importance of factors related to blockchain enabled SM are linked with each other and form an implementation framework. It is also important to test the developed framework in the case organization to know its applicability in actual industrial scenario. Few studies reported that implementation frameworks developed based on MCDM approaches are robust and have more advantages during the implementation phase. In the next sections, case organization, problem statement and steps involved in the framework development have discussed.

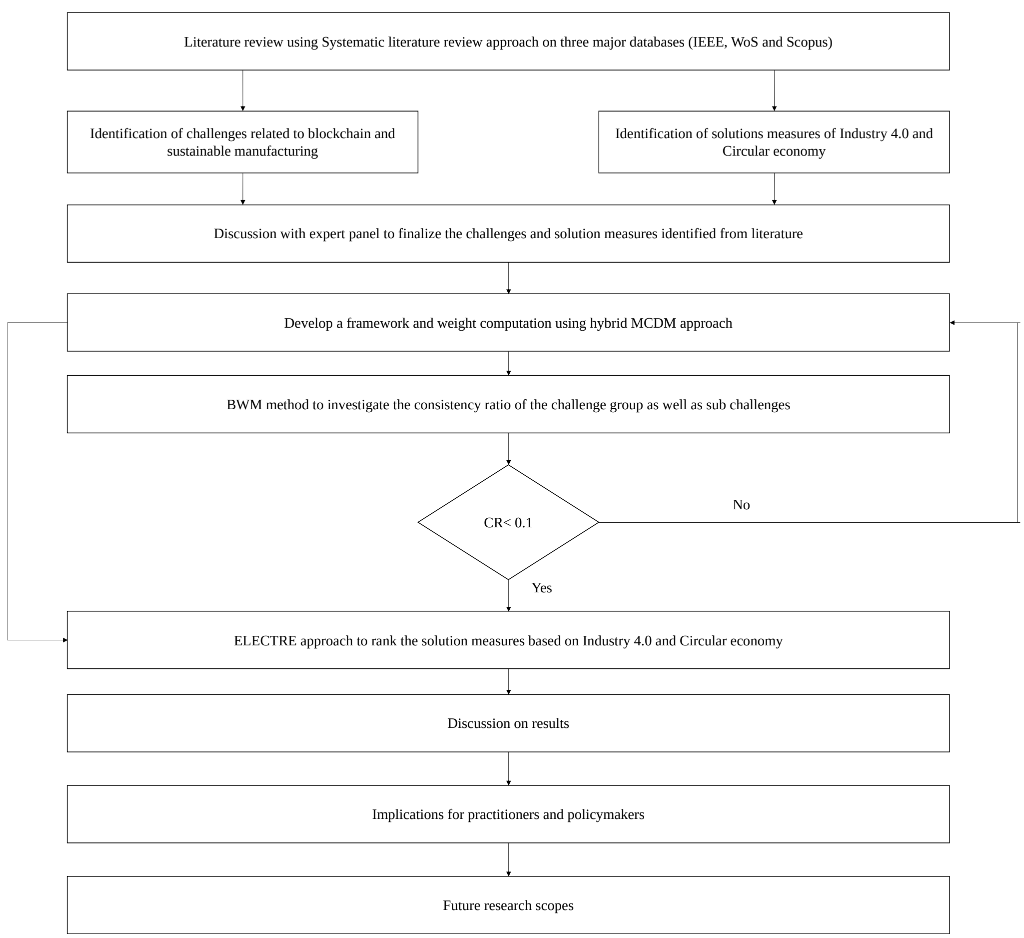

Figure 1. Flow of present research work.

4.2. Problem Description and Case Organization

Industries are now focusing on the adoption of I4.0 technologies in their manufacturing practices. However, the adoption of blockchain enabled SM is limited in developing nations due to some challenging factors.

In the present study an electronics manufacturing industry from Northern region of India is selected as the case organization. The organization started their manufacturing in the 2005 and in the area of 16000 square meter situated in North India. The industry works on the automated and flexible unit which manufactures the outdoor units of split air conditioners coupled with the tube heat exchanger coil manufacturing setup. The company is leading industry working on air conditioning with an annual turnover more than $700 million and holds more than 2000 employees. The organization has already implemented the IIoT based manufacturing facilities in industry and now planning to implement blockchain enabled solutions for manufacturing sustainability. The case organization was selected and a panel of eight experts from the case industry which includes two managers, three supervisors, three assistant managers. All the experts from the case organization have an exposure to the manufacturing area more than 15 years. However, three of experts have the strong background and experience of handling global manufacturing activities and holds the master degree in engineering and management.

4.3 Collection of Data and Development of Framework

Before the data collection from case organization an approval from the both institute and case organization that data collected during the study from organization will be only used for research and framework development purpose only. Further, findings of study is shared with the case organization in the form of report and presentation. Three different brainstorming sessions was conducted with the expert panel from the case organization. Before the analysis of challenges, a list of challenges which found out after extensive literature review is shared with the experts in tabulated form. In the 1st phase of brainstorming session challenges related to blockchain enabled SM is finalized which is required for the framework development. In the 2nd phase of session all the challenges were categorized into the different groups.

Further, a hybrid multi-criteria-based evaluation approach is used to develop a framework. In the study, an online based survey is shared with the expert team to obtain the inputs for hybrid Best worst method-ELECTRE approach. In the 2nd phase of brainstorming session inputs for pairwise comparison in BWM approach is taken from the experts. Finally, in the 3rd phase of study inputs for the ELECTRE method were obtained for the analysis. The framework developed for the present study is shown in Figure 2.

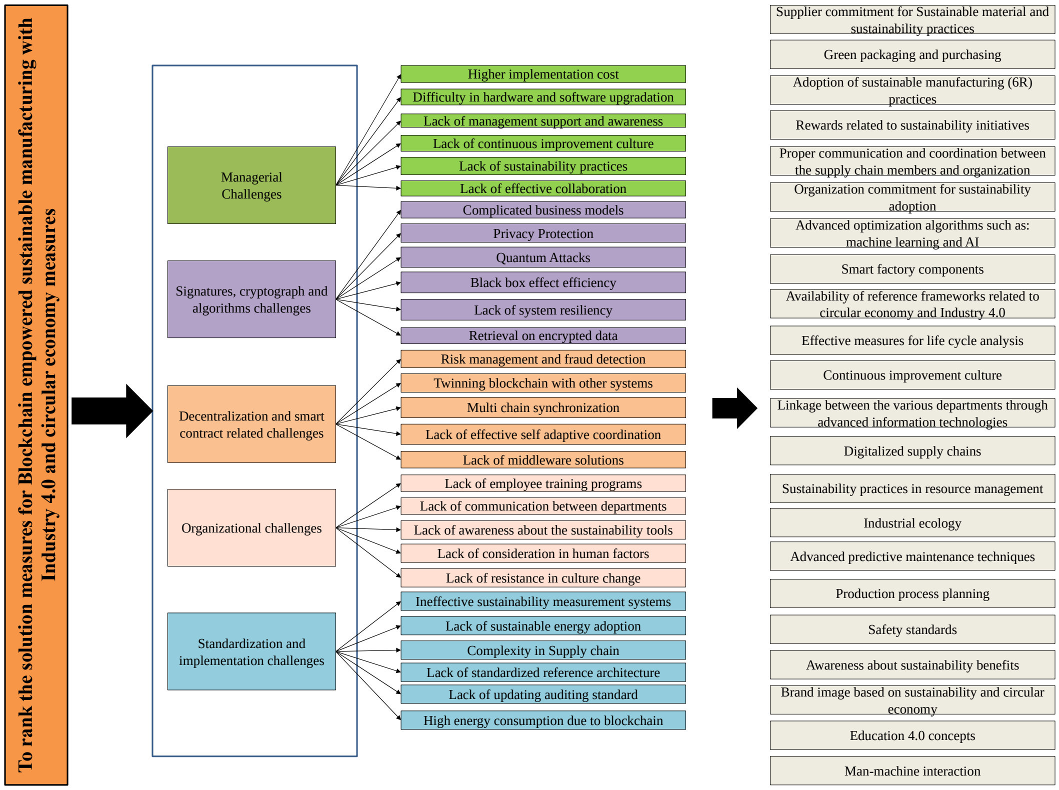

Figure 2. Framework to overcome challenges from blockchain enabled SM practices.

4.4 Analysis of Challenges

The proposed framework in this study for the implementation of blockchain enabled SM practices was tested in the case organization in two different stages. In the 1st stage of computation of weights for the challenges is done and in the second stage rank of challenges is calculated. The solution based on the ranking of challenges is highlighted which helps to improve the implementation of blockchain enabled SM practices. The details for both stages are discussed as below:

4.5 Computation of Weights for Challenges Related to Blockchain Enabled Sustainable Manufacturing Practices

In the past few review studies related to MCDM approaches have discussed about the different methods for the computation of weights for decision making problems (Kumar et al., 2017). In these studies, analytical hierarchy process, TOPSIS approach, DEMATEL, BWM, PROMETHEE and ELECTRE based approaches were discussed in detail (Antucheviciene et al., 2015). Jamwal et al. (2021d) argued that selection of MCDM approach for decision making problems depends on the nature of problem. Govindan et al. (2014) stated that some methods require a large number of respondents for weight computation which makes the decision-making problems complex in nature. Each method has its own limitations and advantages over the other MCDM approach (Meena et al., 2019; Prajapati et al., 2020). Hence to deal with the biasness and complexity issues related to decision making approaches Best worst method can deal with the complex decision-making problems (Rezaei, 2015). In the past few studies, BWM approach have used in various application areas such as manufacturing sector (Yadav et al., 2020a), sustainability (Malek & Desai, 2019b) and, supply chain practices (Ahmadi et al., 2017).

In the present study, weights of challenges related to blockchain enabled SM were computed by BWM approach. The steps involved in the BWM approach is as follows:

Step 1: In the initial step set of decision-making criteria is identified which can be represented as: $\{C_1, C_2, C_3, C_4, C_5, \dots \dots . C_n\}$ for the decision making process.

Step 2: In the second step best criteria (most important or most desirable) and worst criteria (least important or least desirable) is identified or finalized by the group of experts.

Step 3: The preference of best criteria is calculated over the other remaining criteria in which Likert scale 1-9 is considered. Here, 1 rating means equal importance and 9 rating means extreme importance of best criteria over the other criteria. The vector of Best-to-others can be represented as: $A_B = (a_{B1}, a_{B2}, a_{B3}, a_{B4}, \dots \dots, a_{Bn})$. Here a_{BB} represents the preference of best criteria *B* over the criteria *j* which can be deduced that a_{BB}=1.

Step 4: In this step, preference of all criteria is calculated over the worst criteria based on the Likert scale inputs. The Other-of-worst can be represented as:

$$A_w = (a_{1w}, a_{2w}, a_{3w}, a_{4w}, \dots \dots, a_{nw})^T \quad (1)$$

Here, a_{jw} represents the preference of *j* criteria over the *W* criteria which represents the worst criteria among all criteria. It can be deduced that a_{ww}=1

Step 5: In this step weights can be calculated which can be represented by:

$$w_1^*, w_2^*, w_3^*, w_4^*, \dots \dots, w_n^* \quad (2)$$

The weights of criteria considered in the decision making process should satisfy following requirements:

i. For each pair of w_B/w_j the ideal solution can be w_B/w_w, and $w_j/w_w = a_{jw}$ (3)

ii. For the best ideal solution minimize the maximum set of:

$$\{|w_B - a_{Bj}w_j|, \ |w_j - a_{jw}w_w|\} \quad (4)$$

In this case problem can be formulated as:

$$\min max_j \{|w_B - a_{Bj}w_j|, \ |w_j - a_{jw}w_w|\} \quad (5)$$

Subject to

$$\sum_j w_j = 1 \quad (6)$$

Here, $w_j \geq 0, for\ all\ j$

The equation 1 can be transferred to the linear programming problem as:

$$min \xi^L$$

Subjected to

$$|w_B - a_{Bj}w_j| \leq \xi^L, for\ all\ j \quad (7)$$

$$|w_j - a_{jw}w_w| \leq \xi^L, for\ all\ j \quad (8)$$

$$\sum_j w_j = 1 \quad (9)$$

Here, $w_j \geq 0, for\ all\ j$

After, solving equation 9 weights: $w_1^*, w_2^*, w_3^*, w_4^*, \dots \dots, w_n^*$ and ξ^{L*} can be considered as the indicator for calculating consistency.

However, studies by Yadav et al. (2018) and Chen et al. (2020b) found that weight computation in the decision-making problems are not sufficient for effective decision making. There is need to investigate the consistency of assigned weights. ξ values were calculated in the decision-making process to ensure that the judgements made by expert panel are consistent. In case of inconsistency in weights expert panel is again recalled to revise the weight computation process. From the BWM approach the best and worst criteria from each group is investigated and two types of comparison were made in later stages. In the first stage best criteria among the all criteria is compared with the rest of criteria. In the second stage worst criteria is compared with all the criteria. These two types of comparisons were made to ensure that there should be minimum inconsistency in the judgement made by experts. Here, ξ represents the level of consistency in the responses of decision makers. If the value of ξ is near to 0 then judgements made by experts can be considered as consistent in nature. These two comparisons were made during the decision making process to investigate whether the comparisons made by expert panel are consistent or any revision is required. The major comparison done during the decision-making process is shown in the Table 3 which represents both the worst and best criteria. It is found that ξ value is near to zero which shows that judgements made by experts related to blockchain enabled SM is consistent in nature.

Table 3. Ranking of the challenge group and sub challenges for blockchain enabled sustainable manufacturing.

Major Challenge Group	Weight of Challenge group	Criteria weight	Sub-Challenge	Local weight	Local Rank	Global Weight	Global Rank
Managerial Challenges	0.02259	0.0555	C_1	0.1834	2	0.041	7
			C_2	0.2682	1	0.0613	1
			C_3	0.1477	4	0.0327	13
			C_4	0.1396	5	0.0313	20
			C_5	0.1485	3	0.0331	15
			C_6	0.1173	6	0.0274	23
Signature, cryptograph and algorithm challenges	0.2434	0.0632	C_7	0.2246	2	0.0536	3
			C_8	0.2458	1	0.06	2
			C_9	0.1261	5	0.0298	19
			C_{10}	0.1371	4	0.034	16
			C_{11}	0.1429	3	0.0354	12
			C_{12}	0.1253	6	0.0296	21
Decentralization and smart contract Challenges	0.1809	0.058	C_{13}	0.2359	2	0.0434	5
			C_{14}	0.235	1	0.0434	4
			C_{15}	0.1272	5	0.0224	28
			C_{16}	0.1697	4	0.0314	18
			C_{17}	0.2251	3	0.0412	9
Organizational Challenges	0.1689	0.0767	C_{18}	0.2478	1	0.0414	6
			C_{19}	0.2434	2	0.0415	8
			C_{20}	0.1533	3	0.0253	24
			C_{21}	0.1429	4	0.0252	26
			C_{22}	0.2123	5	0.0345	11
Standardization and implementation Challenges	0.1809	0.062	C_{23}	0.2185	1	0.0394	10
			C_{24}	0.1859	2	0.0338	14
			C_{25}	0.1327	6	0.0243	27
			C_{26}	0.1775	3	0.0318	17
			C_{27}	0.1349	5	0.024	25
			C_{28}	0.1514	4	0.0278	22

4.6 Ranking of Solution Measures to Blockchain Enabled Sustainable Manufacturing
In the past few studies many researchers have argued about the relevancy of PROMETHEE decision making approach for multi-criteria decision-making problems over the ELECTRE approach (Kumar et al., 2017; Jamwal et al., 2021d). However, few studies observed that in PROMETHEE approach the relation between two factors can be represented by 0 or 1 (Govindan et al., 2014; Brans & De Smet, 2016). But, in actual decision-making problems it is not possible to have such relations in real life industrial case studies. Hence, Figueira et al. (2016) highlighted the advantage of ELECTRE approach in these case in which percentage of relationship between two factors can be identified to find more optimum results. For ranking of solution measures of blockchain enabled SM standard procedure for the ELECTRE approach is considered in this study which is as follows (Figueira et al., 2016, Yadav et al., 2020b):

Step 1: In the first step pairwise, comparison is done for the solution measures related to challenges of blockchain enabled SM. This helps to develop the hierarchical structure of decision-making problem.

Step 2: In this step weights of challenges calculated in the BWM approach is used as the inputs for ELECTRE approach.

Step 3: Formulation for concordance matrix: In decision making problems it is necessary to find out the beneficial and non-beneficial variables. In case of beneficial variables higher value is required and for the non-beneficial variables lower value is required. In this problem, all the challenges related to blockchain enabled SM are non-beneficial in nature. Hence, all the values need to minimized. Here, for every function of $f(b1), b1$ represents the alternative score and wj represents the weight for the j attribute. The concordance matrix can be represented by $C(b1, b2)$ and can be calculated as:

$$C(b_1, b_2) = \sum_{j=1}^{M} wj^* c_j\left(b_{1,}b_2\right) \tag{10}$$

The $c_j(b_1,b_2)$ can be calculated as:

$$C_j(b_1, b_2) = \begin{Bmatrix} 1, & if\ f_j(b_1 +\ q_j \geq f_j(b_2) \\ 0, & if\ f_j(b_1 +\ q_j \geq f_j(b_2) \\ \frac{f_j(b_1 + p_j - f_j(b_2)}{p_j - q_j} & if\ else \end{Bmatrix} \tag{11}$$

Step 4: In this step, discordance index is calculated which can be represented as: $d_j(b_1,b_2)$ and calculated as:

$$D_j(b_1, b_2) = \begin{Bmatrix} 1, & if\ f_j(b_1 +\ p_j \geq f_j(b_2) \\ 0, & if\ f_j(b_1 +\ v_j \geq f_j(b_2) \\ \frac{f_j(b_2 + p_j - f_j(b_1)}{v_j - p_j} & if\ else \end{Bmatrix} \tag{12}$$

Step 5: In this step credibility index is calculated which represents the intensity of influence i.e., "first solution measure is at least good as solution measure 2" can calculated as:

$$S(b_1, b_2) = \begin{matrix} C(b_1, b_2) & if\ C(b_1, b_2) \geq d_j(b_1, b_2) \forall j \\ C(b_1, b_2)^* \prod j \in (b_1, b_2) \frac{1 - d_j(b_1, b_2)}{1 - (b_1, b_2)} & else \end{matrix} \tag{13}$$

Step 6: In this step superiority ratio is calculated which can be calculated by:

$$Superiority\ ratio = \frac{Discordance\ credibility}{Concordance\ credibility} \tag{14}$$

Based on the decrease in the values of superiority ratio, discordance credibility, concordance credibility and final rank for the solution measure is calculated and presented in Figure 3. Further, Table 4 shows the final ranking of solution measures for blockchain enabled sustainable manufacturing.

Table 4. Final ranking of solution measures for blockchain enabled sustainable manufacturing.

Solution Measure	Rank
Advanced optimization algorithms such as: machine learning and AI	1
Sustainability practices in resource management	2
Man-machine interaction	3
Advanced predictive maintenance techniques	4
Proper communication and coordination between the supply chain members and organization	5
Education 4.0 concepts	6
Linkage between the various departments through advanced information technologies	7
Availability of reference frameworks related to circular economy and Industry 4.0	8
Organization commitment for sustainability adoption	9
Industrial ecology	10
Digitalized supply chains	11
Continuous improvement culture	12
Supplier commitment for sustainable materials and sustainability practices	13
Safety standards	14
Brand image based on sustainability and circular economy	15
Effective measures for life cycle analysis	16
Adoption of sustainable manufacturing (6R) practices	17
Production process planning	18
Green packaging and green purchasing initiatives	19
Awareness about sustainability benefits	20
Smart factory components	21
Rewards related to sustainability initiatives	22

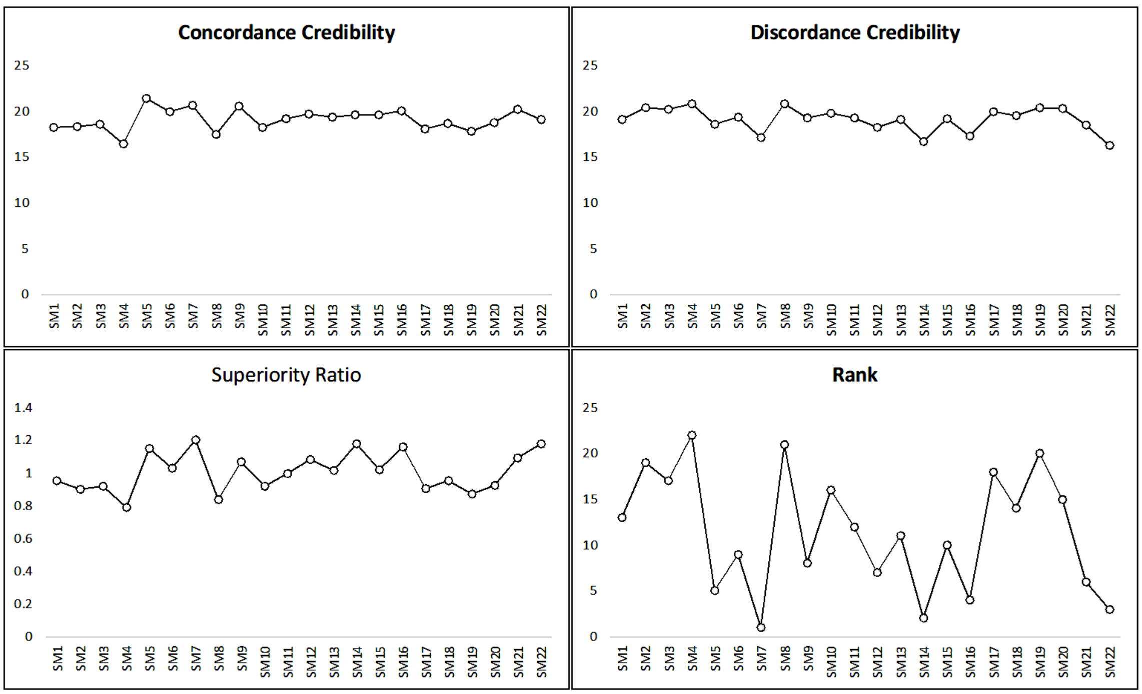

Figure 3. Values of superiority ratio, discordance credibility, concordance credibility and final rank for the solution measures.

5. Case Discussion

In this study Best and Worst method is used to evaluate the challenges related to blockchain enabled SM. The results obtained after the evaluation of decision-making process reveals that major criterion such as: Organizational challenges have the highest weights of 0.0767 which is followed by Signature, cryptograph and algorithm challenges (0.0632) and Managerial challenges (0.0555). Abeyratne & Monfared (2016) and Li et al. (2018) stated that organizational related challenges are crucial for the blockchain technology adoption in manufacturing industries. However, few studies reported about the impact of these challenges in I4.0 practices also (Kim, 2017; Alcácer & Cruz-Machado, 2019). Leng et al. (2020) stated that managerial issues in blockchain technology affects the sustainability. Managerial decision and role of management is very important for the implementation of blockchain enabled practices. de Sousa Jabbour et al. (2018), Raj et al. (2020) and Sharma et al. (2020) also suggested in their studies that managerial decision and organizational activities are important in the industries and it strongly obstructs the adoption of SM practices. Similarly, Yadav et al. (2018) suggested that role of organizational challenges should be considered as failure to overcome from these challenges may lead to economic loss in the industry. Whereas, the managerial challenges i.e., higher implementation cost, difficulty in the software or hardware upgradation due to economic constraints, continuous improvement culture and lack of sustainability practices due to lack of financial resources are the main influencing challenges which are associated with the economic challenges.

Decentralization and smart contracts related challenges have the weight of 0.058 and includes the challenges such as: Risk management and fraud detection, Lack of middleware solutions, Twinning blockchain with other systems and Multi chain synchronization. According to Mohamed & Al-Jaroodi (2019) many manufacturing organizations have a strong belief that lack of middleware solution affects the blockchain technology performance and degrades the blockchain network performance.

Standardization and implementation challenges related to blockchain adoption have the weight of 0.062 and includes the challenges such as: complexity issues within the supply chain practices, Lack of updated auditing standards, Ineffective sustainability measurement systems. Bhanot et al. (2015) suggested that theories and concepts related to sustainability measurement are same at the global level. However, there is requirement for the standardized measurement system for sustainability measurement and it can affect the sustainability practices. Higher energy consumption due to blockchain network is also a major challenge for the industries. Monrat et al. (2019) stated that blockchain network requires a high computation power for the operations which needs high amount of energy. This can affect the environment as well as economic sustainability conditions of the manufacturing organization. Figure 4 shows the rank of solution measures ranking of the challenges related to blockchain enabled SM with I4.0 and circular economy solution measures. These solution measures will help the manufacturing organizations to overcome the blockchain enabled SM issues.

6. Implication for Practitioners and Researchers

In the present study total of 28 challenges were discussed related to blockchain enabled SM which possess both practical and theoretical contribution towards the sustainability and blockchain implementation. The main implications for both practitioners and researchers can be as follows:

(i) The changing market demands and human lifestyle have forced manufacturing industries to adopt the I4.0 practices. Identification of challenges related to I4.0 technologies such as: blockchain technology and its impact on sustainability will be helpful for the effective implementation of blockchain enabled SM in the industries. In the present study exhaustive list of challenges related to blockchain enabled SM is provided in Indian context.

(ii) The practitioners in India are constantly looking for the innovative solutions related to I4.0 to improve the manufacturing sustainability and business performance. For this, knowledge about the I4.0 technologies and circular economy has become more crucial for practitioners. However, many of I4.0 have now gained the adequate maturity level but still many technologies are struggling with the effective implementation. In literature, few studies such as (Machado et al., 2020; Stock and Seliger, 2016) discussed about the role of I4.0 technologies for SM applications but very limited case studies reported which shows the practical validation of these concepts in actual industry scenario. In this study, solutions measures related to I4.0 and circular economy have been presented which will help the researchers to develop the new frameworks in the similar research area.

(iii) The existing literature discuss about the theoretical concepts related to blockchain technology and SM. However, few studies have discussed about the role of blockchain technology to enhance the manufacturing sustainability. These studies have a limited perspective related to challenges for the manufacturing sustainability with I4.0 technologies. A framework with the solution measures related to I4.0 technologies as well as circular economy was limitation. So, the framework with the help of solution measures developed in this study will be helpful for the practitioners to improve the blockchain enabled SM practices.

(iv) The outcomes of present study will provide the managers of manufacturing organizations with the in-depth solution measures related to blockchain enabled SM with an application of hybrid BWM-ELECTRE approach.

(v) Majority of the frameworks proposed related to I4.0 technologies in the previous studies were validated with the case studies. However, in the present study an MCDM based approach is utilized in the developing nation context which will help to boost the applicability of framework in emerging economies.

(vi) In the actual industry scenario, it is difficult to execute all the solution measures related to blockchain enabled SM at the same time. So, prioritization of solution measures is done with ELECTRE approach. This will help the managers to focus towards the high intensity solution measure in the priority.

6.1 Proposed Blockchain Enabled Sustainable Manufacturing Framework for Manufacturing Organizations

In this study we have proposed a blockchain enabled sustainable manufacturing framework for manufacturing organizations presented in Figure 4. The framework consist of four main layers: Infrastructure layer, blockchain service layer, blockchain application layer, client layer. The infrastructure layer consist of four main levels: (1) Source level: extraction phase, separation phase and refining phase (2) Production level: manufacturing processes, assembly operations and packaging operations (3) Distribution level: warehouse management, suppliers, dealers and customers (4) Usage level: use phase, disposal phase and recycling phase. All these levels are connected with each other through intelligent sensors. The main requirements for information sharing are hardware which include: smart sensors, wide area network, data storage and local servers; and software which include: operating systems. Data is transmitted and shared through the local servers to the service layer in which sustainable manufacturing operations performed. Water, energy and resources are the inputs and GHG, material waste and water waste are the output which is optimized and traced through the machine learning and deep learning tools. Further, the application layer includes the waste management, energy waste management, life cycle management, product information management, and liquid waste management. In the end layer or client layer applications can be used by clients such as: manufacturing organizations, government and non-government organizations, customers and society.

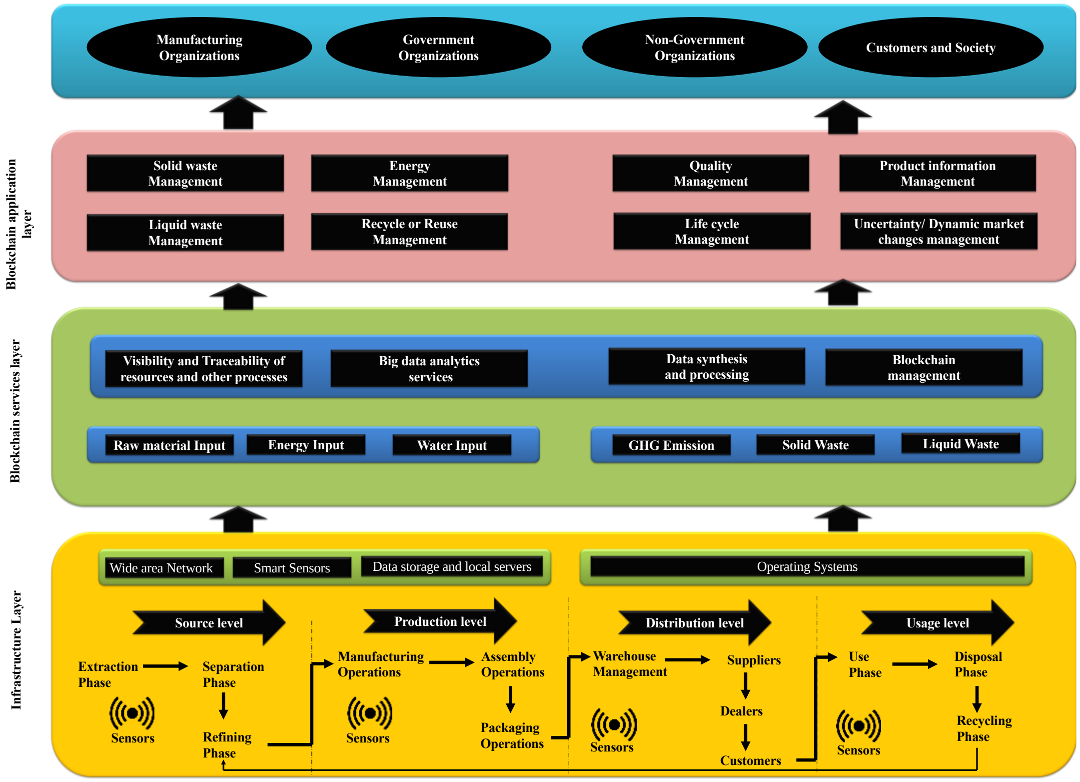

Figure 4. Proposed framework for Blockchain-enabled sustainable manufacturing practices.

6.2 Recommendations for Policymakers

The adoption of blockchain enabled SM practices will help the industries to enhance their organizational performance as well the traceability in the manufacturing activities. Other, emerging I4.0 technologies and circular economy will help the industries to produce sustainable and smart products which will help to achieve economic and environmental sustainability. Therefore, the government should develop the favourable policies to promote I4.0 initiatives. There is need to subsidies for the organizations to adopt both I4.0 technologies as well as sustainability practices. These initiatives will help the organization to create the sustainable value creation. The policymakers from emerging economies are advised to conduct sustainability training as well as awareness programs to educate their employees and customers. This will help to enhance the recyclability practices. The ranking obtained for the solution measures can be utilized by the policymakers as well as government officials to develop the strategies for the effective implementation of blockchain enabled SM.

7. Conclusion

In the present study, initially exhaustive literature review is conducted to find out the challenges related to blockchain enabled SM as well the I4.0 technologies and circular economy to improve the sustainability practices in I4.0 context. Total of 28 critical challenges related to blockchain enabled SM were finalized after expert opinions. A hybrid MCDM approach based on BWM-ELECTRE method is proposed to analyse the challenges as well as solution measures which is majorly responsible for the adoption failures of practices. All the 28 challenges were grouped into five major groups which are: managerial challenges, signature, cryptograph and algorithms challenges, decentralization and smart contracts related challenges, organizational challenges and standardization challenges for blockchain implementation. The ranking of solution measures related to blockchain enabled SM indicates that 6R concepts with the industry are at the top rank which can help the industries to overcome the implementation of blockchain practices. When compared with the previously published studies ranking of challenges were found to be meaningful. Practitioners need to focus higher ranked challenges and remove these challenges for the effective implementation of blockchain enabled SM practices. In the future studies a large scale survey can be conducted in the different industry sectors for the challenges listed in this study. Further, other techniques such as structural equation modelling, DEMATEL and analytical hierarchy process can be adopted to compare the results presented in this study.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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