A SAP-LAP linkages framework for integrating Industry 4.0 and circular economy

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Abstract

Purpose – In the recent years, the two increasingly popular topics, namely, Industry 4.0 and circular economy (CE) have attracted the attention of many academicians and practitioners. However, the connection between CE and Industry 4.0 has not been much investigated in the literature. Motivated by this gap, the purpose of this paper is to integrate these two streams and attempt to understand the new paradigm of Industry 4.0 for resolving the issues pertaining to CE principles.

Design/methodology/approach – The study uses situation, actor, process, learning, action, performance (SAP-LAP) linkages framework to analyze the applications of Industry 4.0 mechanisms in realizing the issues of current CE business models. This is done through the interpretation of the cross-interaction and self-interaction relationships among the different interfaces/elements of SAP-LAP.

Findings – The results suggest that top managers are the most essential actors for integrating the use of Industry 4.0 to achieve sustainability, in the light of CE. In addition, advanced technologies such as Internet of Things and cyber-physical systems are the most important Industry 4.0 actions that help in improving the CE performance parameters.

Research limitations/implications – This qualitative study is an attempt to analyze and assess the strategic issues pertaining to Industry 4.0 standards in CE. The study identifies learnings (challenges/opportunities) and the corrective actions which are imperative toward achieving CE principles. This study will guide managers and policymakers to understand the importance of implementing Industry 4.0 for accomplishing CE principles.

Originality/value – This study integrates two important streams of literature – Industry 4.0 and CE. Thus, this paper offers insights about the importance of Industry 4.0 standards in achieving CE principles.

Keywords Circular economy, Industry 4.0, SAP-LAP linkage framework

Paper type Research paper

> The 4th Industrial Revolution and what it means in terms of a new economy, the circular one, demands a society oriented in the creation of resources instead of generating wastes. (Atilio Savino, the Board Member of International Solid Waste Association, 2017)

1. Introduction

In the recent years, circular economy (CE) has received much attention from researchers and practitioners globally as a solution to problems posed by sustainability concerns (Genovese *et al.*, 2015; Ghisellini *et al.*, 2016; Granger, 1969; Lieder and Rashid, 2016; Lopes de Sousa Jabbour *et al.*, 2018; Merli *et al.*, 2018). For example, China has been heavily promoting regulations to incentivize organizations for pursuing CE principles such as material circularity, life-cycle assessment, eco-efficiency, carbon footprint, cleaner production,

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collection and recycle rates and other sustainable practices, etc. China has also incorporated CE as the central objective of their 11th and 12th five-year plans for National Economic and Social Development (Qi *et al.*, 2016). Several studies view CE as a necessary condition for sustainability (Bakker *et al.*, 2014; Rashid *et al.*, 2013). CE principles offer hands-on solutions to reduce the pressure on natural ecosystems and achieve sustainability (Allwood, 2014; Bocken *et al.*, 2014; Evans *et al.*, 2009; Garetti and Taisch, 2012). The recent studies on CE have also started to integrate all the three dimensions of sustainability, namely, economic, environment and social.

However, there are certain barriers to the adoption of CE business models. For example, the organizations suffer from lack of information on the lifecycle of their products, lack of technological know-how in product design and integration into product processes, institutional and regulatory burden such as lack of government support, misaligned incentives, and socio-cultural issues such as risk aversion behavior of managers in adopting CE because of the customer's rigidity with the traditional products (de Jesus and Mendonça, 2018; Ritzén and Sandström, 2017; Rizos *et al.*, 2016). Nevertheless, with the rising technologies from Industry 4.0, it may now be possible to overcome these barriers and adopt Industry 4.0 mechanisms for achieving CE principles. For instance, CE business models can be used in recycling the electronic scraps with the help of integration of web technologies, smart production systems, additive manufacturing and 3D printing (Nascimento *et al.*, 2019). Furthermore, according to the survey report of International Solid Waste Management World Congress (2017), the use of innovations such as fully robotic sorting, the revolution of sensors, artificial intelligence (AI), digitalization, big data solutions, etc., will play a major role in affecting the CE of plastics and solid waste management.

Industry 4.0 standards are the keystone to realize the future of manufacturing industries (Lee *et al.*, 2015). Industry 4.0 standards are based on modern-day digitalization technologies that include cloud computing, cyber-physical systems (CPS), additive manufacturing and Internet of Things (IoT). The applications of these technologies rely upon the data gathered by the distributed smart objects and the communication infrastructure for the transmission of information (Ahmadov and Helo, 2018; Li *et al.*, 2018; Sinha *et al.*, 2017). Industry 4.0 integrates manufacturing assets with sensors, actuators, computing platforms, communication technology, control, simulation, data-intensive modeling and predictive engineering (Abed, 2016; Kusiak, 2018; Qu *et al.*, 2016; Tang *et al.*, 2015). A gradual transition toward Industry 4.0 standards will help the manufacturing firms to improve operations with respect to cost, quality, flexibility, speed and so forth (Ferrer *et al.*, 2010; Karjagi Nigappa alias Shridhar and Selvakumar, 2016; Offodile and Abdel-Malek, 2002). It is argued that Industry 4.0 technologies have the potential for paving the way for CE principles. For instance, manufacturers can track products post-consumption for the recovery of components (Lopes de Sousa Jabbour *et al.*, 2018). Also, the manufacturers can directly release environmental information through network platforms in which way consumers can acquire information quickly and select more environmentally friendly products (Du *et al.*, 2018). Industry 4.0 tools can contribute to all the three dimensions of sustainable operations management decisions through data-driven mechanisms (de Man and Strandhagen, 2017; Stock and Seliger, 2016). There exist various quantitative tools, indicators and matrices that can be utilized for the application of CE principles. But, these methods are often restricted by the non-availability of data, data inconsistencies and other gaps. This is where Industry 4.0 technologies can provide the necessary solutions by removing such obstructions. Nonetheless, the relationship between the CE and Industry 4.0 technologies has not been widely studied in the literature, and the two topics have been analyzed separately in the extant literature.

In the extant literature, there are very limited studies that examine the connection between CE and Industry 4.0. One of the recent works is the study of Lopes de Sousa Jabbour *et al.*

(2018), where the authors explore and expand the ReSOLVE framework of CE business model by linking it with the contributions of smart technologies of Industry 4.0 to it. Still, to the best of our knowledge, there are insignificant numbers of studies that consider the qualitative factors to understand the overall view of integrating Industry 4.0 technologies into current CE practices. In this context, the situation-actor-process (SAP)-learning-action-performance (LAP) (SAP-LAP) linkages framework can be a very important tool to develop a systematic theoretical framework to provide a holistic view for the managerial inquiry of the issues of CE principles and implementing Industry 4.0 mechanisms for the same (Sushil, 2009, 2017). It is a qualitative and interpretive approach for developing models of managerial inquiry (Sushil, 2000). SAP-LAP framework first analyses the given context through understanding the present "situation" of it, identifying the relevant "actors" or participants involved in it, and how the situation is being handled or "processed" by the identified actors. The second step involves the synthesis of SAP and deriving the key "learnings" from the existing situation, and formulating the necessary "actions" for improving the "performance" of actors, processes and situational factors. The final step is to develop the SAP-LAP linkages, i.e., the self-interaction and cross-interaction matrices among the different interfaces of SAP-LAP to establish the inter-relationships among them.

In sum, the present study identifies the call for a need to analyze and integrate the issues of sustainability with Industry 4.0, in the light of CE. This integration will require a critical analysis of present CE situations, various CE actors, CE activities and CE performance indicators. Therefore, the objectives of this study are:

- to understand the present status of academic and practitioners' perspectives on Industry 4.0 and CE and hence underline the significance of integration of Industry 4.0 and CE; and
- to define the elements of SAP-LAP and develop the SAP-LAP linkages framework to analyze the importance of Industry 4.0 standards in achieving CE principles

The major contribution of the paper lies in the development of theoretical framework by using SAP-LAP linkages approach, for illustrating the integration of Industry 4.0 mechanisms for achieving CE principles.

The remainder of this paper is organized as follows. In Section 2, we discuss the selective and related literature review on CE, Industry 4.0 and the literature that talks about these two topics together. Section 3 describes the SAP-LAP linkages framework. Based on the identified elements of SAP-LAP and interpreting the SAP-LAP linkages, Section 4 builds the integrated conceptual framework for Industry 4.0 and CE. Section 5 discusses the inter-relations between the various elements of SAP-LAP. Finally, Section 6 concludes with the managerial implications, limitations of this study and future research directions.

2. Literature review

2.1 Circular economy

The concept of CE has emerged as one of the building blocks of discourse in sustainability. A large number of studies, for example, Geissdoerfer *et al.* (2017), Ghisellini *et al.* (2016), Merli *et al.* (2018) and Su *et al.* (2013) accredit the introduction of the CE to Boulding (1966). Boulding (1966) visualizes CE as a prerequisite for the preservation of the sustainability of life on Earth. In an early study on CE, Pearce and Turner (1990) elucidate how natural resources influence the economy by providing inputs for production and consumption and serve as a sink for outputs. The study further investigates the linear and open-ended features of contemporary economic systems and explains the shift from the traditional economic system to the circular economic system. Murray *et al.* (2017) conceptualize and

origin of the CE by drawing its meanings, and investigating the antecedents in economics and ecology, and present the operational perspective of CE in business and policy. An increasing number of scholars have carried out the analysis of the extant literature in the field to shed light on the nuances of CE. Ghisellini *et al.* (2016), De Angelis *et al.* (2018), Govindan and Hasanagic (2018), Masi *et al.* (2017), Ormazabal *et al.* (2018), Prieto-Sandoval *et al.* (2018) underline the main features, basic principles, advantages, disadvantages, implementation issues and modeling of CE at the different levels. CE is understood as a juncture of different fields of research such as sustainable product design, reverse logistics and sustainable supply chains. A large number of studies in the field such as Genovese *et al.* (2015), Nasir *et al.* (2017), Geissdoerfer *et al.* (2018), Kazancoglu *et al.* (2018) compare the performances of traditional and circular production systems across several indicators. The studies on the sustainability performance of the circular business models affirm that the integration of CE principles with sustainable supply chain management will deliver clear advantages from the environment point of view (Yang *et al.*, 2018). Bocken *et al.* (2016) suggest that for implementing the principles of the CE, it is indispensable to evolve toward a circular business model where the manufacturing processes and the utilized resources are able to regenerate. The transition toward CE can be done by the involvement of all actors of the society and creating suitable cooperation patterns. Simultaneous consideration of the economic, environmental, technological, economic and social aspects of a process as well as of the interaction among all these aspects has to be taken into account for the transition (Birat, 2015).

The growing importance of CE has been well elucidated by the extant literature. The scholars in the field of CE advocate that the companies must harness full potential of the CE value drivers for bringing economic and environmental benefits. New research in the field of CE is expected to illustrate the utilization of its capability with the help of Industry 4.0 technologies for the achievement of sustainability standards (Lopes de Sousa Jabbour *et al.*, 2018; Nascimento *et al.*, 2019). In the subsequent sections, we emphasize the application of Industry 4.0 tools and techniques for the successful implementation of CE.

2.2 Industry 4.0

Industry 4.0 concept was first announced at the "Hannover Messe 2011" in Germany. The report specified that it would create new values, build new business models and pose solution to various social problems through communication networks based on IoT, Internet of Services and CPS (Kang *et al.*, 2016). In light of the changing business trends, organizations are required to embrace this forthcoming change not only in operations but also in the broad supply chain networks where they operate (Geerts and O'Leary, 2014; Ivanov *et al.*, 2016; Lin *et al.*, 2017). Several authors have presented a detailed review of the meanings and the implications of the Industry 4.0. (Ben-Daya *et al.*, 2017; Büyüközkan and Göçer, 2018; Costabile *et al.*, 2017; Filho *et al.*, 2017; Lu, 2017; Oesterreich and Teuteberg, 2016; Thibaud *et al.*, 2018; Wu *et al.*, 2016; Xu *et al.*, 2014) in their detailed review highlight Industry 4.0 concept as a fundamentally new approach that will bring together the digital and physical worlds. Industry 4.0 synergizes the growth of big data analytics with these key enabling technologies to provide insight toward greater value proposition, analytical powers and decision-making process (Lee *et al.*, 2018; Rajput and Singh, 2018).

Porter and Heppelmann (2015) identified a set of four managerial capacities aligned with the concept of Industry 4.0 which include monitoring, optimization, control and autonomy. According to Rüßmann *et al.* (2015), Industry 4.0 technologies and methods can be summarized in nine main groups, namely, big data and analytics simulation, IoT, CPS, cloud computing, virtual reality, cyber security, collaborative robots and machine-to-machine communication. These technologies in combination with the

above-mentioned managerial capacities offer an opportunity for sustainable business models through the transformation toward circular economies by harnessing their potential. Industry 4.0 tools can play a vital role in controlling the three aspects of sustainability by energy transformation, developing a sustainable logistics sector, providing enhanced health care and securing a competitive position for the leading manufacturing industry (Kagermann, 2015). In the subsequent section we highlight the importance of integrating Industry 4.0 with CE and its implications.

2.3 Industry 4.0 in conjunction with circular economy

It is estimated that in India, a CE trail for vehicle manufacturing in a digitally enabled model of development can create annual benefits of $482bn by 2050, compared with the current set-up (Macarthur, 2013). Several scholars in the field of Industry 4.0 have reflected upon the impact of Industry 4.0 on the dimensions of sustainability (Bag *et al.*, 2018; Bonilla *et al.*, 2018; Luthra and Mangla, 2018; Strandhagen *et al.*, 2017). Industry 4.0 technologies can help to coordinate the product, material, energy and water flows throughout the product lifecycles as well as between different factories (Stock and Seliger, 2016). It is expected that Industry 4.0 will encourage the introduction of new business models which can produce value, innovation and well-being (Majeed and Rupasinghe, 2017; Rajput and Singh, 2018; Sundarakani *et al.*, 2019; Yin *et al.*, 2018). Industry 4.0 paradigm drifts into the concept of CE, as it entails the potential of reduction and elimination of waste, makes consumer products durable, enhances traceability and ability to remanufacture, maximizing their value in use (Garcia-Muiña *et al.*, 2018; Lopes de Sousa Jabbour *et al.*, 2018; Nascimento *et al.*, 2019). Industry 4.0 technologies can contribute to the three dimensions of sustainable operations management decisions through data collection, and information sharing (Bag *et al.*, 2018; de Man and Strandhagen, 2017; Stock and Seliger, 2016). Industry 4.0 enables smart factories and products, with the result that components, machines and digital devices can communicate with each other in order to self-manage production lines and provide high performance in terms of product design, production and logistics systems (Trentesaux *et al.*, 2016). Several quantitative tools, indicators, metrics that rely on data have already been developed to monitor the sustainability at various levels. These methods are often delimited by non-availability of data, data inconsistencies, security issues and other gaps. Industry 4.0 technologies can be used to provide the necessary solutions by removing these barriers. Industry 4.0 standards that include CPS, the IoT and cloud manufacturing can further drive the deployment of new CE initiatives by providing data-driven optimization solutions for logistics networks in CE to achieve sustainability. There are huge potential values of Industry 4.0 technologies that remain unearthed in new product development (Zhan *et al.*, 2018). The new business models assisted by Industry 4.0 technologies will also support data-driven design and thus assist the development of CE products. The exponentially growing amount of data and the convergence of different affordable technologies can help in the systematic transition to CE (Garcia-Muiña *et al.*, 2018; Lin, 2018).

Despite a vast potential of integrating the CE principles with Industry 4.0 perspective, till date very few studies have looked into this dimension. Table I presents a brief review of the literature on CE and Industry 4.0. Most of these studies are conceptual models and bibliometric analysis of the extant literature.

3. Methodology: SAP-LAP linkages

3.1 Background of SAP-LAP framework

The SAP-LAP framework was developed by Sushil (2000) which is a flexible system managerial approach. This is an interpretive method that was developed in two phases,

Table I.
Review of literature on integration of CE and Industry 4.0

Dimension	Authors	Brief description	Methodology
Roadmap to circular economy	Lopes de Sousa Jabbour *et al.* (2018)	The study proposes a pioneering roadmap to enhance the application of CE principles in organizations by means of Industry 4.0 approaches and highlights potential contributions of smart production technologies to the ReSOLVE model of CE business models	ReSOLVE (Regenerate, share, optimize, loop, virtualize, exchange) matrix
Product lifecycle management	de Oliveira and Soares (2017)	A circular economy product lifecycle management (PLM) strategy is defined. The strategy encompasses of sharing of data, information and knowledge of all the product lifecycle phases among all the stakeholders; encourage collaboration between customers, designers, producers and suppliers; and to enable sustainability through IoT and big data	Conceptual model
Product lifecycle management	Reuter (2016)	The analyses how different "product stewardship" and "end-of-life" strategies can support the circular economy and what the challenges and benefits are from an original equipment manufacturer perspective. The study concludes that integration of environmental information into the EIS can digitalize and generate new business value to actors across the value chain	Conceptual model
Literature review	Nobre and Tavares (2017), Song *et al.* (2017)	The application of Industry 4.0 technologies as enablers of CE has been showing a consistent growth interest on recent years but still there is a scarcity of studies in the field	Bibliometric analysis
Literature review	Davis *et al.* (2017)	The study points the way for using Big Data to suggest novel pathways for implementing the circular economy	Bibliometric analysis
Performance indicators for circular economy	Ouyang and Ma (2014)	The authors design a measure platform for the circular economy based on the cloud computing and IOT for real-time monitoring of economic indicators, early warning value, the critical value, to guide the implementation of related management action	Conceptual model
Integrative framework	Jabbour *et al.* (2019)	The study presents an integrative framework to enhance the understanding of the CE and large data nexus; a relational matrix which illustrates the complexity of large-scale data and stakeholders' management	Conceptual model
Roadmap for digitization of circular economy	Kantola *et al.* (2018)	The study introduces a concept model for utilizing Industry 4.0 as a business and innovation driver to facilitate the transition toward the circular economy	Conceptual model
Holistic view on CE and Industry 4.0	Reuter (2016)	The study provides framework for smart integration of tools and methods that quantify RE and deliver circular economy engineering in metallurgy industry	Lecture article
Holistic view on CE and enabling technologies	Sarkis and Zhu (2008)	The paper focuses on the developing circular economy policy within China and its relationship to enabling technologies. The authors conclude that proposed governmental policy can greatly influence sustainability in the IT industry	Literature review

namely, analysis and synthesis. In the first step, a given context is analyzed under three broader interfaces, namely, situation (S), actor (A) and process (P). These are together called SAP. The "situation" describes the present state or status of what is existing out there in the given system. The "actor" represents who are all the individual or group participants, organizations and stakeholders that are dealing with the situation. The "process" represents how the situation is being handled by the actors. In the second step, the synthesis of SAP leads to another three broader interfaces, namely, learning (L), action (A) and performance (P). These are together named as LAP. Based on the synthesis of SAP, "learning" represents the key issues that answer why the given context is in its currently existing form. Furthermore, based on the insights gained from learning leads to decision making on when (time frame) and where (location) the appropriate "action(s)" has to be taken. Finally, actions lead to "performance" which represents what is intended to improve in the situation, actor and process of the given context.

The SAP-LAP has widely attracted the attention of many researchers in the recent two decades. The SAP-LAP framework has been largely applied to various fields, for example, supply chain coordination (Arshinder *et al.*, 2007; Pramod and Banwet, 2010), strategic management (Kak, 2004; Likhi and Sushil, 2013) and management information system (Suri and Sushil, 2008, 2012). The SAP-LAP framework has predominantly been used as a case research (Charan, 2012; Palanisamy, 2012). It has been also used for the theory building in humanitarian supply chain (Kabra and Ramesh, 2015) and disaster management (Sushil, 2017).

3.2 SAP-LAP linkages

The SAP-LAP framework has been further enhanced to "SAP-LAP Linkages" framework that considers the interaction and inter-relationships among the different interfaces of SAP-LAP (Sushil, 2009). To the best of our knowledge, Sushil (2017) is one of the earliest work to use SAP-LAP Linkages as a generic framework for the purpose of theory building. Inspired by this approach, in this paper, we attempt to integrate Industry 4.0 and CE by using SAP-LAP linkage framework. The linkages are developed by enquiring the influence of one interface over the other. The basic steps that are involved in establishing the SAP-LAP linkages framework are as follows:

- develop SAP-LAP framework;
- identify the various elements of SAP-LAP;
- develop cross-interaction linkage matrices among the SAP-LAP interfaces and establish the binary and interpretive matrices between the elements of the corresponding interfaces;
- develop self-interaction matrices for a chosen SAP-LAP interface and establish the binary and interpretive matrices among its individual elements; and
- finally, interpret the interactions.

Following the same route as Sushil (2017), we establish the SAP-LAP linkages, as shown in Figure 1. We also establish the binary and interpretive matrices for each of the linkage, respectively. The Linkages 1 and 2 demonstrate the influence of situation on the various actors and processes involved. The Linkage 3 depicts the role of these actors in the process. The Linkages 4–6 exhibit the interpretations from what existing, who all are the key players and how it is happening, respectively, to further learn why it is in such state. After answering this, the Linkage 7 further leads to the suitable actions that will be taken to combat such state. Next, the impact of actions on the performance is shown by Linkage 8. Finally, Linkage 9 provides the feedback from the performance to further advance the learnings.

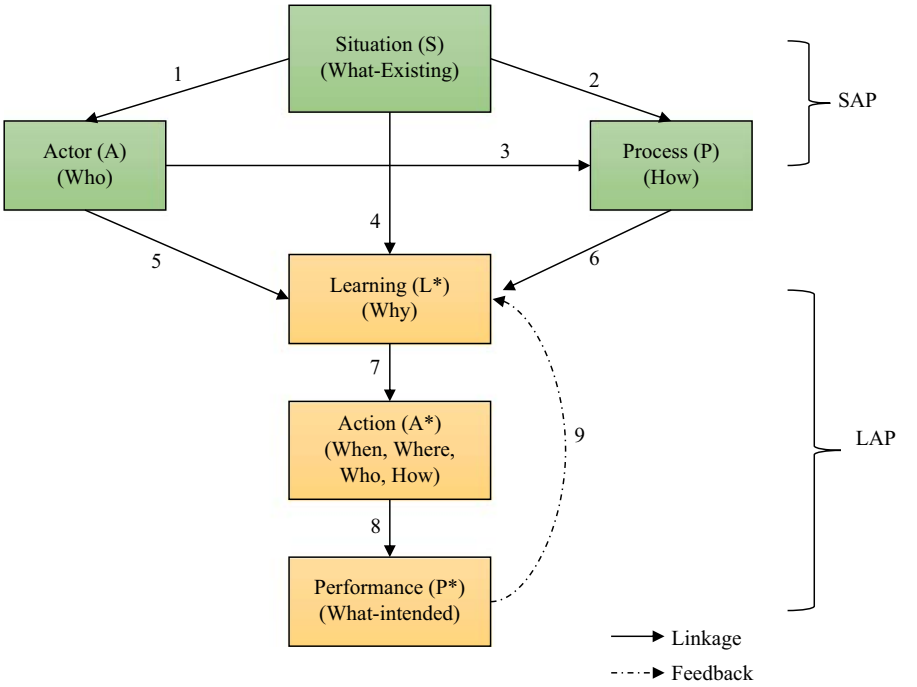

Figure 1.
Generic SAP-LAP linkage framework to integrate Industry 4.0 and CE

Source: Based on Sushil (2017)

Furthermore, we develop the self-interaction matrices (including both binary and interpretive matrices) for "action" and "performance," respectively. The matrices are as shown in Tables AI–AXI. To develop these matrices, the expert's opinion is very crucial. For that, a 1-h workshop with five experts including two professors/academicians and three practitioners/consultants, all with at least ten years of experience in smart technologies and waste management has been conducted. The participants shared their practice and knowledge over the adoption of various Industry 4.0 mechanisms in obtaining CE principles. In this way, given the thoughts, comments and insights from the experts on the use of Industry 4.0 in CE business models, the links between the different interfaces of SAP-LAP were developed.

4. Development of theoretical framework for the integration of Industry 4.0 and CE

Considering the concept of sustainable operations management, the SAP-LAP framework of CE is proposed. The current study proposes that CE performance indicators can be achieved successfully by the implementation of Industry 4.0 tools and techniques. Table II presents the interfaces of SAP-LAP, which are derived from the extant literature.

We now briefly define the SAP-LAP elements for enabling CE through Industry 4.0 as follows.

4.1 Situation

The key question "what" for the existing process or system is answered in "Situation." The existing scenario which needs to be managed is represented as situation. In the absence of

Element	Description	Related literature
S1	Consumption of excessive resources in traditional CE business models	Geissdoerfer *et al.* (2018), Genovese *et al.* (2015), Nasir *et al.* (2017), Kazancoglu *et al.* (2018), Yang *et al.* (2018)
S2	Excessive energy losses in shipping and other logistics activities	
S3	Deficit in the availability of advanced technologies for material circularity, sustainable production and less emissions	
S4	Lack of flow of information along the different links of supply chains	
S5	Lack of customer satisfaction regarding the quality of circulated and refurbished products	
A1	Top management	Heck (2006), Ji *et al.* (2018), Sarkis and Zhu (2008), Bressanelli *et al.* (2018)
A2	Industry employees	
A3	Government/policymakers	
A4	Consumers	
P1	The circular production processes lack in the sufficient information on life-cycle of products	Bressanelli *et al.* (2018), Jabbour *et al.* (2019), Lopes de Sousa Jabbour *et al.* (2018), Nascimento *et al.* (2019)
P2	Industry employees lack on technological know-how in product design and integration of products	
P3	Ambiguity among the top managers for providing proper infrastructure in CE business models	
P4	Lack of trust for new technologies	
L*1	Growing attention for digitization and connected manufacturing in CE business models	Bauer *et al.* (2015), Rashid *et al.* (2013), Ghisellini *et al.* (2016), Lopes de Sousa Jabbour *et al.* (2018)
L*2	Government's policies for enhancing CE principles in various industrial activities	
L*3	Increasing emphasize on the use of data-driven technologies due to peer competition in CE business model innovation	
L*4	Rising customer's awareness and expectations for CE products	
A*1	Use of Internet of Things (IoT) and cyber-physical systems (CPS) to facilitate decision making through the real-time data availability	Shrouf and Miragliotta (2015), Zhong *et al.* (2017), Dweekat *et al.* (2017), Lopes de Sousa Jabbour *et al.* (2018), Müller *et al.* (2018), Nascimento *et al.* (2019)
A*2	Using cloud manufacturing for facilitating connections between different stakeholders, such as buyers, suppliers and customers	
A*3	Use of additive and smart manufacturing, 3D printing in CE business models to re-use and re-design products	
A*4	Introduction of sensors and robotics in waste sorting and recycling	
A*5	Employing big data, digitalization and artificial intelligence to understand customer requirements and improve CE business models	
A*6	Use of robots, driverless cars and drones to improve collection rates and enhancing circularity	

(*continued*)

Table II.
Summarizing SAP-LAP interfaces

Element	Description	Related literature
P*1	Maximizing material circularity	Ellen MacArthur Foundation (2015), Franklin-Johnson *et al.* (2016), Huysman *et al.* (2017), Lopes de Sousa Jabbour *et al.* (2018), Zhao and Zhu (2017)
P*2	Product's life-cycle assessment	
P*3	Eco-efficiency, carbon footprint and cleaner production	
P*4	Improved collection rate and recycle rate	
P*5	Improved sustainable practices such as: reusability, remanufacturability, refurbishment and restoration	
P*6	Reduced losses and increased profitability	

Table II.

technologies that help the managers to monitor and optimize the consumption of resources, the traditional CE business models in manufacturing cannot be expected to give the desired results. The logistics decisions in the CE business models can be complied by utilizing the data from smart technologies such as cloud manufacturing and CPS. The traditional business landscape is also marked by excessive energy losses in shipping and other logistics activities due to the unavailability of mechanisms for monitoring. The Industry 4.0 technologies can support circularity of materials and energy (Lopes de Sousa Jabbour *et al.*, 2018). In the scenario where technologies such as IoT, CPS and cloud manufacturing are absent, the material circularity, sustainable production and energy utilization are not efficacious. Traditional businesses are also marked by lack of flow of information along the different links of supply chains. Additionally, Industry 4.0 technologies can enable the companies to collect information on consumers' behavior. The lack of these technologies leads to inferior product design for use or replacement of the product, and thus decreases customers' satisfaction (Rymaszewska *et al.*, 2017).

4.2 Actor

In SAP-LAP, the question that "who" are the central actors responsible for handling the situation is answered by understanding the "actors." The actors of Industry 4.0 in CE can be classified into two types: internal and external. The internal members constitute the management team and employees of the organization, whereas the external actors include government and consumers. The environmental initiatives by the government should reconcile economic and environmental development by fostering technological innovation (Lopes de Sousa Jabbour *et al.*, 2018). Apart from improving the firm operations, CE is expected to create value for the consumers. Top management has major role to play in embracing and adapting CE. The realization of the CE over a sustained period requires joint efforts from the top management along with pro-active participation from employees. Also, the government can ensure transparency and predictability in the administrative as well as economic policies. The government should ensure enforceability of legislation and provide economic incentives (Su *et al.*, 2013).

4.3 Process

The "Process" answers the "how" question while handling the situation. The sustainable design of processes addresses the holistic resource efficiency approach by designing appropriate manufacturing process chains. However, these processes lack in the sufficient trust from the stakeholders. Industry employees lack on technological know-how in product design and integration of products. The top managers experience uncertainty while

investing in the infrastructure for CE business models. The powerful analytical capabilities, inherent in Industry 4.0, together with virtual prototyping can help the management to understand the current position of their organization as well assist them to better understand the CE principles.

4.4 Learning

The learning (challenges) for the use of Industry 4.0 in CE tells us "why" the current state of system exists. These provide a foundation to define action points so as to alleviate these challenges. Government policies should enhance the implementation of CE principles in various industrial activities. In developing countries such as China, CE has been introduced as a novel development model to help China advance along a sustainable economic structure. Increasing emphasis on the use of data-driven technologies due to rising competition will further drive CE business model innovation. The enforcement of the CE regulation will help to encounter both environmental degradation and resource scarcity issues (Bressanelli *et al.*, 2018). With the rising market competition, the managers have started to acknowledge the need for digitization and connected manufacturing for the successful implementation of CE business models in the organizations (Nascimento *et al.*, 2019). The extant literature argues that the organizations that implement data-driven technologies foster higher barriers for competitors, create strong revenue streams and foster sustainability (Spring and Araujo, 2017).

4.5 Action

According to Sushil (2017), the actions arise from the learning which should be defined in terms of "when" the actions are to be carried out and "where" to be implemented. Responsibility for answering "who" and "how" the actions need to be taken are also defined. Industry 4.0 will lead a transformation in CE business practices. Bressanelli *et al.* (2018) in their detailed review of literature shed light on the set of functionalities enabled by Industry 4.0 technologies which include better product design, attracting target customers, monitoring and tracking product activity, technical support, maintenance plan, optimization of product usage, upgradation of product, enhancing renovation and end-of-life activities. Cloud manufacturing will help in facilitating connections between different stakeholders, such as buyers, suppliers and customers. Big data, digitalization and AI will help to understand customer requirements and improve CE business models. The use of supporting databases, geo-location/decision support/integrated environmental information systems will provide a huge contribution to e-waste management, saving resources from material's use (Wang *et al.*, 2015). The use of sensors and robotics will enhance the efficiency of waste sorting and recycling. IoT and CPS can facilitate decision making through the real-time availability of data and improve the optimal use of resources. This will also help to reduce wastage by identification and mitigation of possible failures. Additive manufacturing, 3D printing in the context of CE business models would assist the re-use and re-design of products. The use of robots, driverless cars and drones will improve collection rates and enhance material circularity.

4.6 Performance

Performance answers the question of "what" is to be achieved for the attainment of the final objective. The performance objectives for the final objective of attaining sustainability could be an enhancement of material circularity, eco-efficiency and overall performance (see Table AXI). The actual performance on these indicators would tell the effectiveness of implementing Industry 4.0 tools. CE is an amalgamation of two interrelated ideas, the closed-loop economy and "design to re-design" thinking (Murray *et al.*, 2017). In an Industry 4.0 setup, factory and value chains will become distributed. Responsive manufacturing will

enable mass customization of products and services through collaborative processes (Santos *et al.*, 2017). A product that is designed for environment faces competitive forces. Customer may find sustainable substitutes attractive if customized smart products can be delivered with customized services in a shorter time with the application of Industry 4.0. Moreover, products designed using smart technologies should last longer, and maintenance should be available to allow re-use and extend product life. The availability of information from all the links in the supply chain will optimize the usage of natural resources, assist the re-use of energy and eliminate waste. This will enhance the overall productivity, profitability and sustainability of the business (de Man and Strandhagen, 2017). According to the vision of Industry 4.0, these interconnected systems will cooperate closely and strive for the maximum value creation. For example, IoT technologies support material tracking, thus playing a crucial role in the collection of end-of-life products and waste management, thus helping to close the loop (Nobre and Tavares, 2017). Additionally, Industry 4.0 technologies enable the organizations to collect information on consumers' expectations and therefore improve the product design and development thereby helping in the enhancement of the circularity potential.

5. Discussion

In this section, we discuss the cross-interaction matrices and self-interaction matrices, derived from SAP-LAP linkages. Under each of these matrices, we define two matrices, i.e., a binary (1,0) matrix and interpretive matrix. In a binary matrix between any two interfaces of SAP-LAP, 1 is assigned if the two components of SAP-LAP interfaces are interrelated, otherwise, it is assigned 0. The interpretative matrix in addition illustrates the reason for the inter-relation.

5.1 Cross-interaction matrices

The cross-interaction matrix shows "between-the-elements" interaction among the various elements of SAP-LAP framework. The cross-interaction matrices of the given SAP-LAP framework are shown in Tables AI–AIX. Tables AI–AIII show the matrices corresponding to the SAP linkages between the elements of situation and actor, situation and process, action and process, respectively. Table AI shows that there is a strong inter-relation of S3 with Tables AI–AIII (1,1,1,0), which means that lack of investment by top management into advanced technologies, lack in advanced skills of workers, and governmental regulations leads to insufficiency in the availability of advanced technologies for better material circularity and CE. This possibly due to the risk aversion behavior of managers in adopting Industry 4.0 technologies, as there is lack of technical skills among the employees. Also, the government should facilitate the incorporation of advanced technologies into CE business models by formulating appropriate policies and incentives. Table AII shows that in the current CE business models, there is a lack of trust among the customers regarding the quality of recycled and refurbished products. This is inter-linked with the lack in technical know-how of industry employees on product re-design and product integration strategies, as per the customer needs. It is also observed from Table AII that S1 is strongly linked with P1, P2 and P3 (1,1,1,0). This implies that due to the insufficient knowledge of product life-cycle assessment, unskilled workers and ambiguity among the top managers leads to the excessive use of resources, like labor and material. For example, tooling and assembling of products leads to the consumption of high number of man-hours and material wastage. Table AIII shows how different actors like top management, industry employees, government and consumers handle various processes. These interlinks broadly suggest that actors such as managers and other employees in current CE business models have limited knowledge on the product life-cycle and technical know-hows in product design and integration of products.

Tables AIV–AVI show the linkages between situation and learning, actor and learning, process and learning. In sum, these linkages imply the learnings from the analysis of all the elements of SAP. From Table AIV, S4 is linked with L*1 and L*3 (1,0,1,0), which suggests that the lack of flow of information along the supply chain can be mitigated by the adoption of digitization and advanced data-driven technologies. The link between S5 and L*1, L*4 (1,0,0,1) suggests that customer's database management plays a crucial role in the better understanding of customer requirements. In addition, from the same table, we see that the use of digitization and connected manufacturing reduces the amount of resources used in CE models. From Table AV, we see that the actors like top managers are now realizing the importance of integrating advanced technologies into their CE business models due to peer pressure. This also results in managers starting skill development programs for their employees to learn new data-driven technologies and standardization of processes. Furthermore, Table AVI shows that realizing the potential of data-driven technologies will actually mitigate the issues related to the ambiguity among the top managers for technology adoption.

Tables AVII and AVIII show the linkages between learning and action, action and performance. From Table AVII, it can be seen from the connection between L*1 and A*1, A*2, A*3, A*5 (1,1,1,0,1,0) that the adoption of Industry 4.0 technologies like IoT, CPS, cloud manufacturing, additive manufacturing, connected manufacturing, big data, etc., will lead to the feasibility of meeting the goals of CE models. For example, the use of sensors and robotics in waste sorting can result in meeting the environmental norms and hence a very efficient CE model. Further, we see that L*4 is also linked with A*1, A*2, A*3, A*5 (1,1,1,0,1,0), i.e., with Industry 4.0 technologies like big data, digitalization, 3D printing and virtual manufacturing, the customer's needs and requirements can be well understood and the product can be provided at their place, as per their choice. Table AVIII shows that certain actions like the adoption of various Industry 4.0 technologies will improve the performance parameters of CE models, like material circularity, product life-cycle, eco-efficiency, and carbon footprint, collection rate and recycle rate, reusability, remanufacturing, refurbishment and restoration, etc. To reduce the wastage and enhance the material circularity, the top managers should ensure the proper exchange of information and uniform standards for data transfer and utilization. The stronger commitment to strengthen Industry 4.0 will foster the industrial development in a more sustainable fashion. Table AVIII also suggests that almost all the actions, i.e., various Industry 4.0 technologies have a positive influence on all the CE principles. However, among all the actions, we observe that A*1 (i.e. IoT and CPS) has the highest number of links (1,1,1,1,1,1) with performance parameters. Thus, we find that these two technologies are the most crucial for meeting CE principles. This is possibly because these technologies enhance the degree of connection between the machines and production lines through real-time data availability. The instant sharing of data through IoT provides better information about the physical systems, which can be further analyzed through big data analysis. Finally, Table AIX shows the feedback linkage between performance and learning. The better performance in terms of accomplishing CE principles gives feedback for future corrective actions. Understanding the causes of weak performance of the suggested actions will guide the managers on developing future actions. We see that the performance parameter P*5 (improved sustainable practices) is linked with all the learning elements (1,1,1,1). In sum, we can say that the measurement of sustainable practices like reusability, remanufacturing, refurbishment and restoration will act as the most important feedback parameter to our learnings for the better corrective actions in future.

5.2 Self-interaction matrices

The self-interaction matrix reflects "within-the-elements" interaction among the various elements of the SAP-LAP framework. According to the given SAP-LAP framework, we

focus on the self-interaction matrices within the elements of action and performance, respectively. These are shown in Tables AX and AXI. Table AX shows the linkage between various mechanisms of Industry 4.0 technologies. We see that the actions such as A*1 has connection with all the other actions. This suggests that IoT and CPS, together with additive manufacturing, 3-D printing, big data and digitalization will help in meeting the CE goals such as improving waste sorting, collection rate and computational redesigns of products as per the customer needs, etc. Table AXI demonstrates the linkage between the components of performance. It shows that better material circularity will enhance the collection rate and recycle rate, eco-efficiency and carbon footprint. The products designed using smart manufacturing should last longer and maintenance should be available to permit their re-use and extend the product life.

6. Conclusion

The present study aims to analyze the current systems of CE business models and how the integration of Industry 4.0 mechanisms to these models will help in achieving the CE principles. For this, we use SAP-LAP linkages framework to develop a theoretical framework for the managerial inquiry of integration of Industry 4.0 and CE business models and to emphasize the importance of enabling technologies in achieving sustainability, in the light of CE. Through this methodology, we examine the current situation of CE business models, various actors involved in it, and how these actors handle/process those situations. Based, on the analysis of these situations, actors and processes, we identified several opportunities (learnings) and necessary actions (Industry 4.0 technologies) that will improve the performance parameters of CE business models. From the analysis of cross-section and self-interaction matrices between various elements of SAP-LAP, we find that top managers are the most important actors in imparting Industry 4.0 mechanisms in current CE business models. From the interpretive matrix between the actors and situations, it is clear that the unwillingness among the top managers to adopt new technologies, lack of infrastructure provided by them, and their lesser investment in data-driven technologies are some of the critical reasons for the current stated situations of CE business models (refer Table AX). However, the growing realization of the potential of digitization, smart manufacturing, data-driven technologies, government's policies for cleaner production, and consumer awareness are the key drivers to integrate Industry 4.0 technologies into CE models (refer Table AIV). Further from Table AVIII, we find that action A*1 (i.e. IoT and CPS) is interacting with all the performance elements. This suggests that IoT and CPS are among the most important Industry 4.0 mechanisms to meet CE goals.

6.1 Managerial implications

This qualitative research is an attempt to analyze and assess the strategic issues pertaining to Industry 4.0 integration in CE. This study will guide managers and policymakers to understand the value addition of implementing Industry 4.0 mechanisms for accomplishing CE principles. The proposed framework will help the managers and policymakers to understand the advantages and disadvantages of different actions (Industry 4.0 technologies) and further help to define the responsibilities of different actors. Successful implementation of Industry 4.0 calls for the coherence between desired actions. The different course of actions identified in the analysis will contribute toward driving the transformation toward CE. Management has to be committed to standardizing the process, meet compliances, and drive the transformation by training and educating the employees for Industry 4.0. The employees need to upgrade their skill-set and embrace the change. These activities need to be streamlined and that would require the commitment of top management. As evident from the learning and action interpretive matrix, all the actions simultaneously contribute to eliminate the challenges related to management unwillingness for the adoption of Industry 4.0 mechanisms. The

guidelines for implementation and best practices sharing contribute maximum for driving the transformation toward a sustainable organization.

6.2 Limitations and future research directions

The current study is a nascent step toward the application of Industry 4.0 to achieve CE principles. Besides the contribution toward the literature of Industry 4.0 and CE, there are certain limitations to the study. The first limitation is regarding the identification of links between various elements of SAP-LAP, as it is based on the judgments of experts which is open to personal bias. Due to the limited scope of the paper, the second limitation is the empirical validation of the results in the real world and the ranking or prioritization of the elements of SAP-LAP on the basis of their relative importance. Future studies can be carried out to make a hierarchy model for existing challenges. Further work can be carried out to rank the suggested actions by using multi-criteria decision-making techniques such as interpretive ranking process, analytic hierarchy process, TOPSIS, ELECTRE, etc. We also suggest conducting case studies to understand the roles of digitization and data-driven technologies in achieving the goals of CE.

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Appendix 1

	A1	A2	A3	A4
Binary matrix				
S1	0	1	0	0
S2	1	0	0	0
S3	1	1	1	0
S4	1	0	0	0
S5	0	0	0	1
Interpretive matrix				
S1	–	Excess use of labor and material in current CE models. For example, tooling and assembling, material losses	–	–
S2	Top management unwillingness to upgrade current CE technologies for achieving higher values of energy savings	–	–	–
S3	Lack of investment on CE infrastructure by top management	Industry employees lack in skills to handle advanced technologies	Government's environmental regulation policies to limit the amount of emissions	–
S4	Lack of investment on data-driven mechanisms by top management	–	–	–
S5	–	–	–	Understanding consumers requirements and awareness

Table AI. Cross-interaction matrix for situation (S)×actor (A) – Linkage 1

	P1	P2	P3	P4
Binary matrix				
S1	1	1	1	0
S2	0	0	1	0
S3	1	0	0	0
S4	0	0	0	1
S5	0	1	1	1
Interpretive matrix				
S1	Lack of product life-cycle information leads to its losses	Inadequate technical capacities	Lack of infrastructure for the efficient use of available limited resources	–
S2	–	–	Inappropriate infrastructure for eco-designs	–
S3	Inaccurate life-cycle assessment with current technologies	–	–	–
S4	–	–	–	Lack of trust on smooth information flow
S5	–	Insufficient knowledge of customers for designing and integrating new products	Managers are risk averse in adopting technologies as per the customer requirements	Lack of trust in current CE technologies which leads to ambiguity regarding the quality of recycled products

Table AII.
Cross-interaction matrix for situation (S)×process (P) – Linkage 2

	P1	P2	P3	P4
Binary matrix				
A1	0	0	1	0
A2	1	1	0	0
A3	0	0	1	0
A4	0	0	0	1
Interpretive matrix				
A1	–	–	Top management's unwillingness for investing in cleaner production	–
A2	Workers lack in accurate information about the product's life-cycle	Workers lack in skills for the target products	–	–
A3	–	–	Insufficient incentives by government for practicing cleaner production	–
A4	–	–	–	Consumer unawareness and lack of trust in new technologies

Table AIII.
Cross-interaction matrix for actor (A)×process (P) – Linkage 3

	L*1	L*2	L*3	L*4
Binary matrix				
S1	1	0	0	0
S2	1	1	0	0
S3	0	0	1	0
S4	1	0	1	0
S5	1	0	0	1
Interpretive matrix				
S1	Digitization and connected manufacturing reduces the amount of resources used in CE models	–	–	–
S2	Reduces energy losses	Government's strict policies for reducing emissions in environment	–	–
S3	–	–	Adaptation of advanced technologies due to peer pressure	–
S4	Information flow can be mitigated through digitization	–	Data-driven technologies for less interruption in the flow of materials	–
S5	Customer database management for the better understanding of their requirements	–	–	Better understanding of customer's behavior

Table AIV. Cross-interaction matrix for situation (S)×learning (L*) – Linkage 4

	L*1	L*2	L*3	L*4
Binary matrix				
A1	1	0	1	0
A2	1	0	1	0
A3	0	1	0	0
A4	0	0	0	1
Interpretive matrix				
A1	Top management realization for digitization and connected manufacturing	–	Peer pressure to top management decision-makers	–
A2	Developing skills for employees to work on new technologies	–	Employees training for data-driven technologies and standardization	–
A3	–	Government's guidelines	–	–
A4	–	–	–	Customer perception and expectations

Table AV. Cross-interaction matrix for actor (A)×learning (L*) – Linkage 5

	L*1	L*2	L*3	L*4
Binary matrix				
P1	1	0	0	0
P2	1	0	1	0
P3	0	1	0	0
P4	0	0	0	1
Interpretive matrix				
P1	Life-cycle assessment	–	–	–
P2	Product integration and connected manufacturing	–	Employee trainings due to peer competition	–
P3	–	Realization of the potential of data-driven technologies will mitigate ambiguity among top managers for technology adoption	–	–
P4	–	–	–	Lack of trust in new technologies by managers will affect customer's requirements

Table AVI. Cross-interaction matrix for process (P)×learning (L*) – Linkage 6

	A*1	A*2	A*3	A*4	A*5	A*6
Binary matrix						
L*1	1	1	1	0	1	0
L*2	0	0	0	1	0	0
L*3	1	0	0	1	1	1
L*4	1	1	1	0	1	0
Interpretive matrix						
L*1	IoT and CPS for digitization	Cloud manufacturing facilitates connected manufacturing	Additive manufacturing and connected manufacturing	–	Big data and digitalization helps in digitization and smart manufacturing	–
L*2	–	–	–	Helps in waste sorting and hence meets environmental norms	–	–
L*3	IoT and CPS for data-driven technologies	–	–	Enhanced waste management	Big data and data-driven technologies	Enhanced waste collection
L*4	CPS integrates users and internet	Virtual manufacturing by users	Additive manufacturing and 3D printing is targeted to the customer's needs	–	Big data and digitalization helps in identifying needs of different clusters of customers	–

Table AVII. Cross-interaction matrix for learning (L*)×action (A*) – Linkage 7

	P*1	P*2	P*3	P*4	P*5	P*6
Binary matrix						
A*1	1	1	1	0	1	1
A*2	1	0	1	0	0	1
A*3	1	0	1	0	1	0
A*4	1	0	1	1	0	1
A*5	1	1	1	0	1	0
A*6	1	0	0	1	1	1
Interpretive matrix						
A*1	IoT and CPS will enhance material circularity	Life-cycle assessment	Increasing eco-efficiency and carbon footprint	–	Guides for sustainable practices	Implementing IoT and CPS will reduce losses and may result in long-term profits
A*2	Facilitating connections will enhance material circularity	–	Decreases decentralization	–	–	Connections and links will reduce losses by promoting supply chain coordination
A*3	Closed-loop supply chains	–	Minimized losses and hence lesser carbon footprints	–	Modules for guiding product reusability and restoration	–
A*4	Enhances material circularity	–	Waste sorting will increase eco-efficiency	Sensors and robotics will increase collection rate and recycle rate	–	Recycling through robotics and sensors will reduce material losses
A*5	Improves circularity	Life-cycle assessment	Big data and digitalization will help in developing standards for eco-efficient products	–	Product refurbishment as per the customer's choice	–
A*6	Improved collection rates and hence circularity	–	–	Improvised collection rate and recycle rate	Sharing practices for reusability and recycling	Higher collection rates will cut on losses

Table AVIII. Cross-interaction matrix for action (A*)×performance (P*) – Linkage 8

	L*1	L*2	L*3	L*4
Binary matrix				
P*1	1	1	1	0
P*2	0	0	1	1
P*3	1	1	0	1
P*4	0	0	1	1
P*5	1	1	1	1
P*6	1	0	1	1
Interpretive matrix				
P*1	Digitization and connected manufacturing will enhance material circularity	Strategically meeting state policies	Active response to competition	–
P*2	–	–	Product differentiation	Matches customer expectations regarding product quality
P*3	Eco-efficient designs	Helps in gaining brand image	–	Customer awareness
P*4	–	–	Improves market image	Better customer service by facilitating collection
P*5	Improved sustainable practices	Support and involvement from policymakers	Motivates further to use highly advanced data-driven technologies	Sets benchmark among eco-conscious customers
P*6	Economic advantage	–	Competitive advantage	Market potential

Table AIX. Cross-interaction matrix for performance (P*)×learning (L*) – Linkage 9

Appendix 2

	A*2	A*3	A*4	A*5	A*6
Binary matrix					
A*1	1	1	1	1	1
A*2		1	1	1	1
A*3			1	0	0
A*4				1	0
A*5					0
Interpretive matrix					
A*1	Supply chain links improve with real-time data availability	Guidelines for training programs	Guidelines for sharing best practices	Guidelines for setting standards	For the ease of managers
A*2		University support for conducting trainings	University support for sharing best practices	University's involvement in setting standards	Employee engagement
A*3			Training modules will help in sharing best practices		
A*4				Setting standards by sharing best practices	
A*5					

Table AX. Self-interaction matrix for action (A*)× action (A*)

	P*2	P*3	P*4	P*5	P*6
Binary matrix					
P*1	1	1	1	1	1
P*2		1	0	0	1
P*3			1	1	1
P*4				1	1
P*5					1
Interpretive matrix					
P*1	Material circularity will enhance product lifecycle	Material circularity will increase eco-efficiency	Material circularity will improve collection rate and recycle rate	Product reusability improves with material circularity	Overall performance improvement
P*2		Eco-efficient products will have longer product life-cycle			Higher profitability
P*3			Collection rate and recycle rate improves eco-efficiency	Reusability will enhance eco-efficiency	Profitability will improve
P*4				Collection rate and recycle rate improves reusability	Increase in profit
P*5					Enhances profitability

Table AXI. Self-interaction matrix for performance (P*)×performance (P*)

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