

## Article

# Industry 4.0 to Accelerate the Circular Economy: A Case Study of Electric Scooter Sharing

Trang Thi Pham <sup>1</sup>, Tsai-Chi Kuo <sup>1,2,\*</sup> , Ming-Lang Tseng <sup>3,4</sup>, Raymond R. Tan <sup>5</sup>, Kimhua Tan <sup>6</sup> , Denny Satria Ika <sup>1</sup> and Chiuhsiang Joe Lin <sup>7</sup> 

<sup>1</sup> Department of Industrial and Systems Engineering, Chung Yuan Christian University, Taoyuan 32023, Taiwan; trangpham211.ars@gmail.com (T.T.P.); dennysatria014@gmail.com (D.S.I.)

<sup>2</sup> R&D Center for Membrane Technology, Chung Yuan Christian University, Taoyuan 32023, Taiwan

<sup>3</sup> Institute of Innovation and Circular Economy, Asia University, Taichung 41354, Taiwan; tsengminglang@asia.edu.tw

<sup>4</sup> Department of Medical Research, China Medical University Hospital, China Medical University, Taichung 110122, Taiwan

<sup>5</sup> Chemical Engineering Department, De La Salle University, Manila 00000, Philippines; raymond.tan@dlsu.edu.ph

<sup>6</sup> School of Business, University of Nottingham, Nottingham NG7 2QL, UK; kim.tan@nottingham.ac.uk

<sup>7</sup> Department of Industrial Management, National Taiwan University of Science and Technology, Taipei 10607, Taiwan; chiuhsiangjoelin@gmail.com

\* Correspondence: tckuo@cycu.edu.tw; Tel.: +886-3-265-4421

Received: 23 October 2019; Accepted: 14 November 2019; Published: 25 November 2019



**Abstract:** To achieve sustainability, the circular economy (CE) concept is challenging traditional linear enterprise models due to the need to manage geographically distributed product life cycle and value chains. Concurrently, Industry 4.0 is being used to bring productivity to higher levels by reducing waste and improving the efficiency of production processes via more precise real-time planning. There is significant potential to combine these two frameworks to enhance the sustainability of manufacturing sectors. This paper discusses the fundamental concepts of Industry 4.0 and explores the influential factors of Industry 4.0 that accelerate the sharing economy in the CE context via a case of electric scooters in Taiwan. The result shows Industry 4.0 can provide an enabling framework for the sharing economy in CE implementation.

**Keywords:** Industry 4.0; circular economy; interpretive structure modelling; sustainable development; sharing economy

## 1. Introduction

Humanity is currently faced with the challenges of poverty, inequality, climate change, environmental degradation, violence, and injustice [1,2]. Sustainability is the integration of economic growth, social equity, and environmental resilience to the benefits of future generations [3,4]. The circular economy (CE) is a conceptual framework that seeks to balance human consumption with the capacity of the Earth to provide resources; it focuses on closing the loop in industrial networks through business models that incentivize firm-level sustainability enhancement [5,6]. Geissdoerfer, Savaget, Bocken and Hultink [3] argue that both CE and sustainability are overlapping and mutually supporting concepts. These similarities include intra- and intergenerational commitments, global models, integrating non-economic aspects into development, and multi-disciplinary scope.

CE is currently being promoted in several developed and developing countries and regions, including the EU, China, Japan, UK, France, Canada, and Taiwan [7,8]. CE represents a systemic shift that aims to reduce short- to medium-term gains to increase the probability of preserving resources

for future generations. These resources include, but are not limited to, economic and business opportunities, environmental preservation, and other social benefits [9]. The origins of the concept of CE can be traced to the work of Pearce and Turner [10]. However, the most well-known definition was given by the Ellen Macarthur Foundation [9], which states that CE is “a framework for an economy that is restorative and regenerative by design”. Critics have pointed out that there is a lack of consensus on the definition of CE [11,12]. In addition, the clear differentiation of CE from the earlier related concept of industrial ecology (IE) was discussed by Walmsley et al. [13]. The latter paper also proposed that engineering tools such as process integration (PI) could be used to implement CE.

CE can be seen as the optimization of the triple bottom line (TBL), and could be of use in the creation of new business models and job opportunities. CE can also be used to save cost, soften the price volatility of resources, and improve resource security for the supply chain, while reducing the environmental pressure and impact [11]. The European Commission’s CE Roadmap argues that “closing the loop” [12–14] on linear product life cycles of make, use, and discard, and transforming them into varying loops of re-use, repair, refurbish, and recycle is a key strategy for Europe’s competitive growth into this century [15]. The Japanese government introduced a material-cycle society vision, based on the 3R (reduce, reuse, and recycle) principle [16]. Elia, et al. [17] suggested different actions for a CE, such as circular product design and production, business models, cascade/reverse skills, and cross-cycle and cross-sector collaboration. However, for enterprises, the transition to CE still brings a lot of difficulties, including sustainable production–consumption, systems, closed-loop supply chains, and product service system [18]. CE also faces many unsolved methodologies and limitations, e.g., those concerning the common methods of environmental life cycle assessment (LCA) and system dynamics (SD) [19,20]. In other words, its implementation is still in the early stages, since few available implementation tools have been developed [11,21].

To implement newer technologies in CE, it is important for the barriers to be overcome with emerging technological improvements and concepts, such as Industry 4.0. Industry 4.0 itself is a set of tools in data management that uses automation and data exchange in the setting of smart manufacturing and production through the use of cloud service, Internet of Things (IoT), Big Data and its analytic tools, and artificial intelligence (AI) to reduce over-consumption and production errors. The efficiency gains can contribute to sustainability. In itself, Industry 4.0 brings a new perspective to the industry on how manufacturing can utilize new technologies to create value with maximum output and minimum resource utilization [22,23].

Industry 4.0 starts from data-driven analysis that can potentially be pursued to optimize existing infrastructure to bring sustainable solutions, reducing usage and emissions. The vertical and horizontal integration of manufacturing processes in Industry 4.0 can optimize the performance of firms and supply chains. There is a lot of recent research that is beginning to explore the connection of CE and Industry 4.0 [22,24,25]. However, few studies have focused on how the influential factors of Industry 4.0 could accelerate the circular economy. In this study, first a framework of Industry 4.0-supported CE is constructed. Second, interpretive structural modeling (ISM) is used to illustrate the details of the influential factors of Industry 4.0 that could accelerate the sharing economy in a circular economy. In addition, a case study of the electric scooter manufacturer has shown a new innovated business model with the embedded technologies of IoT and cloud computing in Industry 4.0 to accelerate the sharing economy aspect of the circular economy. Finally, conclusions and prospects for future research into Industry 4.0 and CE are given.

## 2. Literature Review

There is abundant research related to sustainability because of its importance [26–30]. Papers were selected by a structured keyword search on major databases and publisher websites (Ebsco, Springerlink, Wiley Interscience, Elsevier ScienceDirect, Emerald Insight, and Open Access Journals). The keywords “circular economy”, “sustainability”, “Industry 4.0”, and “review” were used to find and analyze the barriers to the CE.

## 2.1. Barriers of CE

A paper by de Jesus and Mendonça [31] identified the barriers that includes hard (technical, economic/financial/market) and soft (institutional/regulatory, social/cultural) factors. Korhonen et al. [8] identified six challenges in CE, including thermodynamic limits, spatial and temporal system boundary, rebound effect, path dependencies and lock-in, intra-organization and inter-organization strategies, and physical flows. Among these barriers, Kircherr et al. [21] identified sequences on CE barriers that include a lack of data; due to technological limitations, both designing and implementation-wise, high upfront investments and a lack of support for circular resource processing are the next problems that are considered predominant issues. This and the continued subsidy for raw virgin material have prevented growth of CE at least from the point of view of Kircherr et al. [21]. The next obstacle is the outdated and less flexible laws and regulations, which prevented other countries in either bilateral or multilateral corporations to process and use recycled materials from each other. Finally, there is also the factor of consumer awareness and interest, where differences in cultural views prolonged the time needed for implementation to run sustainably, increasing the need for support both by government and local communities. Furthermore, because of data quality and security, most of these companies at some point will revise their data, which blocks full data transparency. Table 1 shows the barriers for the enterprises moving toward CE.

**Table 1.** Gap of the enterprises toward the circular economy (CE).

Barriers	Description	Authors
Technology	<ul style="list-style-type: none"> <li>• Inappropriate technology, lag between design and diffusion, lack of technical support and training</li> <li>• Ability to deliver high-quality remanufactured product, circular design, too few large-scale demonstration projects, lack of data, e.g., on impacts</li> <li>• Incorporate digital technology</li> </ul>	
Economic/Financial/Market	<ul style="list-style-type: none"> <li>• Large capital requirements, significant transaction costs, high initial costs, asymmetric information, uncertain return and profit</li> <li>• Low virgin material prices, standardization, high upfront investment costs, limited funding for circular</li> <li>• Rethink the business model</li> <li>• Collaborate to create joint value of the products, material, and resources</li> </ul>	Kalmykova, Sadagopan and Rosado [11] de Jesus and Mendonça [31] Kircherr et al. Kirchherr, Piscicelli, Bour, Kostense-Smit, Muller, Huibrechtse-Truijens and Hekkert [21] CE [32]
Institutional/Regulatory	<ul style="list-style-type: none"> <li>• Misaligned incentives, lacking of a conducive legal system, deficient institutional framework</li> <li>• Limited circular procurement, obstructing laws and regulations, lacking global consensus</li> </ul>	
Social/Cultural	<ul style="list-style-type: none"> <li>• Rigidity of consumer behavior and businesses routines</li> <li>• Company, collaboration of value chain, consumer awareness and interest, operating in a linear system</li> </ul>	

Several research studies address the enabling factors of the transition to the circular economy. Table 2 shows the management indicators of the transition to the circular economy

**Table 2.** Management indicators of the transition to the CE.

Manage Indicators	Descriptions	Authors
Innovative and smart system	To produce innovative policy; to provide the subjects of innovative activity with the necessary resources; commercialization; and the practical use of new knowledge	[33,34]
Collaborative consumption	To control capacity planning directly with customers and suppliers To implement integration approaches between these processes To participate directly in the process of creation	[35]
Measurement and optimization	To optimization of waste management in industrial processes	[36,37]
Service- and function-based business models	Service-based business models provide transparency for customers about the costs of the whole use phase, whereas uncertainties exist about the costs of maintenance, repair, and replacement in purchase-based models	[38,39]

## 2.2. Innovations in Industry 4.0

The fourth industrial revolution—also named Industry 4.0—is one of the most trending topics in both professional and academic fields [40,41]. Industry 4.0 starts with customer requirements and integrates the different systems, such as connected technologies. The main goal of Industry 4.0 is to create value by connecting resources, services, and humans in real time. The basic technologies of Industry 4.0 are described as follows.

- (1) IoT: Ashton coined the term IoT in 1999. The fundamental idea of IoT is to use a number of distributed sensors or gadgets (i.e., “things”) lying in an unpredictable vast environment (a house, a large urban area, or a greater region) [42]. These things could collect a massive amount of raw data (structured or unstructured) and translate them into relevant information.
- (2) Cloud computing (CC): CC could be accessed by using web-based technologies, combining internet connectivity and pay-per-use systems in a new business model for IT provisioning [43,44]. Normally, three different types of service models are categorized as: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS).
- (3) Cyber physical systems (CPS): CPS was first proposed by the US National Science Foundation in 2006. The original purpose of CPS is to reveal cross-cutting fundamental scientific and engineering principles that underpin the integration of cyber and physical elements across all application sectors [45,46].
- (4) Data-driven analytics (DDA): DDA involves the analysis of large volumes of heterogeneous and multi-source data generated along the life cycle of industrial production [47]. The common predictive techniques that are often used by data scientists include regression modeling, decision trees, Bayesian networks, Artificial Neural Networks (ANNs), Support Vector Machine (SVM), and nearest neighbor algorithms [48].
- (5) Artificial intelligence (AI): Artificial intelligence according to Mayr et al. [49] is a commonly used term for engineered learning tools or perception-based modeling, as well as a problem-driven solution-making system that could be used to derived certain problems. AI are also well defined as a focus on human performance or rationality, where their implementation could be to the benefit of the users. Nowadays, AI are used from research facilities to marketing departments, and from large manufacturing industries to small farms, producing a high yield per dollar spent on using traditional equipment.

### 2.3. Industry 4.0 in Support of CE

A lot researchers have pointed out we could use data-driven Industry 4.0 to solve the problems of CE [24,48,50–53]. They claimed that the benefits of Industry 4.0 are vertical integration, virtualization, automation, traceability, flexibility, and energy management. Kamble et al. [54] proposed a sustainable Industry 4.0 framework. Shubhangini [24] proposed finding the connection of CE and Industry 4.0 in the context of a supply chain. Stock, et al. [55] mentioned using Industry 4.0 as an enabler for sustainable development. Rajput and Singh [24] pointed out there are 15 challenging factors to link CE and Industry 4.0: data analysis, a collaborative model, CPS (cyber physical system) standards and specifications, CPS modeling and modeling integration, smart device development, investment cost design, compatibility, infrastructure standardization, interfacing and networking, semantic interoperability, process digitization and automation, automation system virtualization, cloud computing, and sensor technology.

- (1) Smart circular systems. IoT changes the way to create value in the business sector as the information that is generated by the interconnected devices, machines, and products evolves in a fundamental component in value creation, such as maintenance, re-use, repair, and recycle. Through IoT, there is a capability to foster CE through the connection of people and things by mobile devices, which derives significant economic opportunities for both individuals and businesses in multiple domains [56–60].
- (2) Cloud manufacturing (CM) and sustainable process manufacturing. CM increases in sustainability are identified: (1) collaborative design; (2) greater automation; (3) improved process resilience; and (4) enhanced waste reduction, re-use, and recovery [61]. By using the CC model in mobility and transportation management systems, managers can reduce the total cost of provided services for residents, carbon footprint, and remanufactured WEEE [62–65].
- (3) Data-driven analysis can be used to help enterprises understand their sustainability performance [66–69] and create value (value proposition, value creation and delivery, and value capture [70,71]). It refers to all the tools and techniques that analyze the vast and varied business data management to generate useful insights for decision making. The analytical tools include mathematics, optimization, simulation, statistics, and other techniques.
- (4) There is a lot of research related to energy and cyber physical systems. Ma, Zhang, Lv, Yang and Wu [45] presented architecture of energy cyber physical system-enabled management for energy-intensive manufacturing industries to promote the implementation of a cleaner production strategy. Lu et al. [72] provided an energy-efficient CP production network.
- (5) AI has been implemented in both renewable energy and electrical energy to achieve better efficiency [73–75].
- (6) Sharpe et al. [76] demonstrated the implementation of cyber physical systems with the end-of-life (EOL) processing of WEEE. In addition, some research applied the CPS in energy management [45,77].

### 3. Industry 4.0-Supported CE

The concept of using Industry 4.0 tools to support CE is still in its infancy. In this study, first the framework of Industry 4.0-supported CE is constructed. Second, the interpretive structural modeling (ISM) is used to illustrate the factors through which Industry 4.0 can accelerate the sharing economy in the circular economy.

#### 3.1. Framework of Industry 4.0-Supported CE

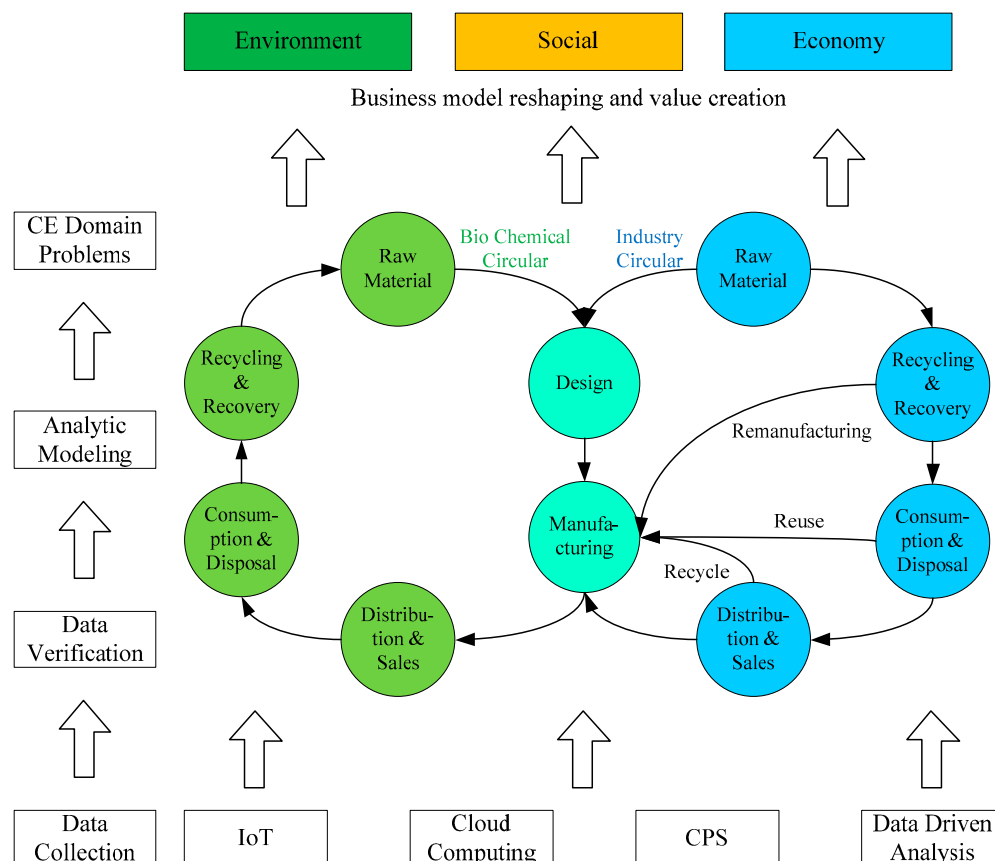
Industry 4.0 is a data-driven concept that addresses automation within information and communication technologies. It includes cyber physical systems, data science, the IoT, cloud computing, and modeling techniques [22]. With systems thinking, Industry 4.0 could overcome some barriers of

CE to promote more sustainability. Figure 1 shows how Industry 4.0 can accelerate the CE. The data could be collected through the IoT, such as structured or unstructured data types.

- (1) To help the transition from linear production to circular production, the collected data should be screened and cleaned based on the expert's domain knowledge. In a real system, a large amount of big data will be collected; however, most of the data could be considered noise data. Therefore, the data have to be analyzed by using cluster methods. However, most of the time, it will take a lot of time to clean and verify the data.
- (2) In order to store and analyze the data, the enterprises should consider building their private cloud or public cloud for computing. With Industry 4.0, high computing speed is needed to deal with vast amounts of real-time data. Sometimes, this technology is also based on the supply chain requirements.
- (3) For some special scenarios that have a probability of happening, finding possible solutions through CPS could also help, especially those in the circular economy situations.
- (4) The core value is the data-driven analysis that drives the analysis of resource/process, asset/utilization, labor, inventories, quality, supply/demand match, time to market, and service/after-sales [78,79].

### 3.2. Interpretive Structural Modeling

ISM is a process that transforms unclear and poorly articulated mental models of systems into visible, well-defined models that are useful for many purposes. ISM generally has the following steps based on the previous research [80,81]:



**Figure 1.** Framework of Industry 4.0-supported circular economy (CE).



#### 4. Electric Scooter Case of Industry 4.0-Supported CE

Traditionally, fossil oil is used to generate energy power for vehicles. However, the tradeoff is the side environmental impacts of carbon dioxide (CO<sub>2</sub>) emission and particulate matters (PM 2.5). There are 14 million electric scooters in Taiwan. As the climate change problem is serious, the electric vehicle has been developed and replaced previously Taiwan authority. The subsidy fee is around USD 1000; however, its effect is small. The electric vehicle is still not widely accepted by the public. These problems include that the battery charging time is longer compared with the refill time of fossil oil, battery-charging stations are not easily and widely accessible, and so on.

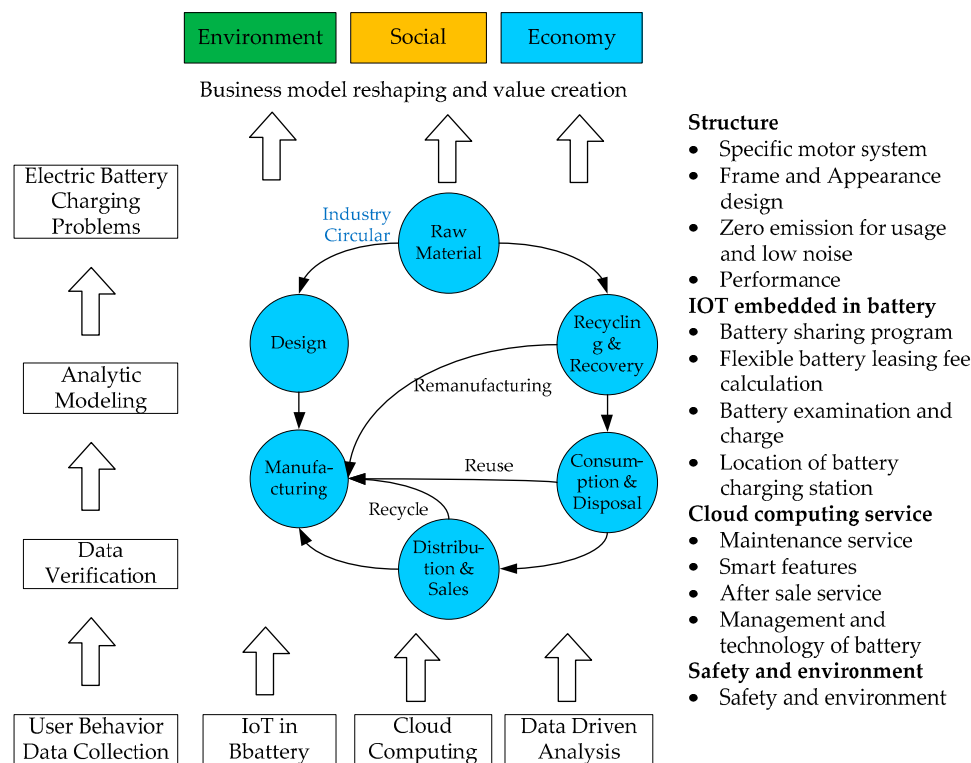
In order to overcome the above problems, a Taiwanese electric scooter manufacturer has innovated a new business model with the embedded technologies of IoT and cloud computing in Industry 4.0 to accelerate the sharing economy aspect of the circular economy. This innovative business model is not only to provide a swapping battery with IoT technology but also to analyze the user behavior by using the technology of big data and cloud computing. This new model has accelerated the amount of electric scooters to increase 10 times from 2016 to 2018 (18,942 (2016), 39,025 (2017), 78,676 (2018), and 113,828 (2019)). First, the aging battery is the most difficult challenge for promoting electric cars. Therefore, the life cycle of the battery should be monitored. To overcome this problem, the real-time performance of the battery is collected and monitored via IoT technology. Second, the battery is replaced easily. The user could have checked and replaced the battery very conveniently via the battery platform. Third, all the battery information is collected, calculated, and simulated via cloud computing. Therefore, the electric scooter manufacturer could conduct the battery predictive maintenance to increase the battery quality. Fourth, the company could monitor the replaced time to determine the battery-charging station location and the number of batteries.

In addition, the appearance design and service of electric motorcycles is also improved to attract consumers. Through the IOT technology and cloud computing technologies, the marketing of electric motorcycles increased. In this research, we try to use ISM to identify the problems.

##### 4.1. Factors of Accelerating the Sharing Economy in Circular Economy via Industry 4.0

In this research, several factors for the electric scooter manufacturer are identified to find the how Industry 4.0 can support the CE. It includes the systems related to the structure, energy, business platform, safety, and environment. More details are listed as follows (adopted from the smart scooter spec sheet). Figure 2 shows the Industry 4.0-supported sharing economy in the CE regarding electric scooter practices.

The factors were identified by three experts. The first expert is an engineer of the electric scooter manufacturer who has worked for five years with the firm. He suggested revising the structural factors to be more detailed. The second expert is the marketing manager of the electric scooter manufacturer who has worked for four years in the firm. He identified the factors pertaining to the customers' needs. The third expert is a professor with more than 10 years of experience in product service systems. He suggested clarifying the research purpose and making it more specific. Table 3 shows the factors of accelerating the sharing economy within the circular economy via Industry 4.0.



**Figure 2.** Industry 4.0-supported sharing economy in the CE regarding electric scooter practices.

**Table 3.** Factors of accelerating the sharing economy in the circular economy via Industry 4.0. IoT: Internet of Things.

	Structure
R1	Specific motor system. It includes the motor, motor control, and cooling system, especially for the liquid cooled permanent magnet synchronous system.
R2	Frame and appearance design. It includes a personalized spectrum edgeless dashboard, changeable faceplate, extra-large luggage compartment for full-size helmet storage with a trunk light and USB charge port, and so on.
R3	Zero emission for usage and lower noise.
R4	Performance. It includes acceleration, maximum speed, and maximum riding range per battery swap.
	IoT embedded in the battery
R5	Battery-sharing program. The battery could be leased and shared instead of purchasing. User could swap the two batteries in one minute.
R6	Flexible battery-leasing fee calculation. The user could pay the basic fee plus extra cost for extra Amp/Hr.
R7	Battery examination and charging stations. The health of the battery could be monitored and predicted for recycling.
R8	Location of battery-charging stations. Since the IoT is embedded in each battery, the optimization problem related to the numbers and locations of charging stations is the user's focus.
	Cloud computing service
R9	Maintenance service. The maintenance shop location could be analyzed based on the battery exchange stations.
R10	Smart features. It includes smart sensors and wireless communication technology. All the data could be collected for the analysis of big data.
R11	After sale service. The strategies could be determined based on the big data analysis, such as the maintenance policy, battery fee calculation, and so on.
R12	Management and technology of battery. Each battery has its own specific number as its profile. The security is also a very important issue.
	Safety and environment
R13	Safety and environment. Zero emission for our environment.





**Table 7.** Transformation of the reachable matrix (2).

	<i>R1</i>	<i>R2</i>	<i>R3</i>	<i>R4</i>	<i>R5</i>	<i>R6</i>	<i>R7</i>	<i>R8</i>	<i>R9</i>	<i>R10</i>	<i>R11</i>	<i>R12</i>	<i>R13</i>
<i>R1</i>	1	0	0	0	0	0	0	0	0	0	0	0	0
<i>R2</i>	0	1	0	0	0	0	0	0	0	0	1	0	0
<i>R3</i>	0	0	1	1	1	1	1	0	1	0	1	0	1
<i>R4</i>	0	0	1	1	1	1	1	0	1	0	1	0	1
<i>R5</i>	0	0	0	0	1	1	1	0	0	0	0	0	0
<i>R6</i>	0	0	0	0	1	1	1	0	0	0	0	0	0
<i>R7</i>	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>R8</i>	0	0	0	0	0	0	0	1	0	0	0	0	0
<i>R9</i>	0	0	0	0	0	0	0	0	1	0	1	0	0
<i>R10</i>	0	0	0	0	0	0	0	0	0	1	1	0	0
<i>R11</i>	0	0	0	0	0	0	0	0	0	0	1	0	0
<i>R12</i>	0	0	0	0	0	0	0	0	0	0	0	1	0
<i>R13</i>	0	0	1	1	1	1	1	0	1	0	1	0	1

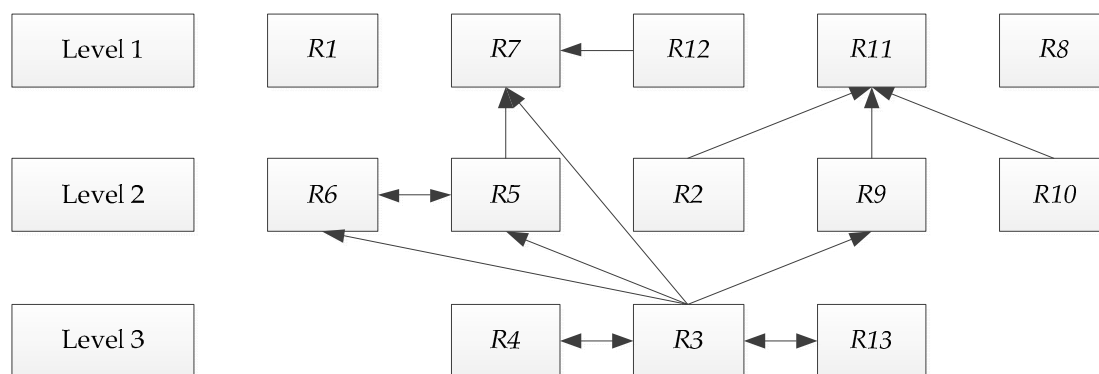
The last step is to transform the reachability matrix into a hierarchical matrix, as shown in Table 8. From the final reachability matrix, for each factor, the reachability set and the antecedent set are derived. The reachability set consists of the factor itself and the other factors that it may influence, whereas the antecedent set consists of the factor itself and the other factors that influence it. Then, the same process is repeated to find out the factors in the next level. This process is continued until the level of each factor is found. These levels help in building the digraph and the ISM model.

**Table 8.** Partition of electric scooter factors.

Level	Si	Reachability Set ( $R_i$ )	Antecedent Set ( $A_i$ )	$R_i \cap A_i$
1	<i>R1</i>	1	1	1
	<i>R2</i>	2.11	2	2
	<i>R3</i>	3.4.5.6.7.9.11.13	3.4.13	3.4.13
	<i>R4</i>	3.4.5.6.7.9.11.13	3.4.13	3.4.13
	<i>R5</i>	5.6.7	3.4.5.6.13	5.6
	<i>R6</i>	5.6.7	3.4.5.6.13	5.6
	<i>R7</i>	7	3.4.5.6.7.13	7
	<i>R8</i>	8	8	8
	<i>R9</i>	9.11	3.4.9.13	9
	<i>R10</i>	10.11	10	10
	<i>R11</i>	11	2.3.4.9.10.11.13	11
	<i>R12</i>	12	12	12
	<i>R13</i>	3.4.5.6.7.9.11.13	3.4.13	3.4.13
2	<i>R2</i>	2	2	2
	<i>R3</i>	3.4.5.6.9.13	3.4.13	3.4.13
	<i>R4</i>	3.4.5.6.9.13	3.4.13	3.4.13
	<i>R5</i>	5.6	3.4.5.6.13	5.6
	<i>R6</i>	5.6	3.4.5.6.13	5.6
	<i>R9</i>	9	3.4.9.13	9
	<i>R10</i>	10	10	10
3	<i>R3</i>	3.4.13	3.4.13	3.4.13
	<i>R4</i>	3.4.13	3.4.13	3.4.13
	<i>R13</i>	3.4.13	3.4.13	3.4.13

The above table is transformed in Figure 3. Figure 3 shows that the *R3* in level 3 (zero emission for usage and lower noise) is the most important critical factor that influences the success of electric scooters. It means that the electric scooter could solve the problem by developing the technology of Industry 4.0. *R5* (Battery-sharing program), *R6* (Flexible battery leasing fee calculation), and *R9*

(Maintenance service) are effective methods to reach zero emission for usage and lower noise. *R11* (Management and technology of battery) should be supported by *R2* (Frame and Appearance design), *R9* (Maintenance service), and *R10* (Smart features). *R7* (Battery examination and charge) should be supported by *R3* (Zero emission for usage and lower noise) and *R5* (Battery-sharing program).



**Figure 3.** Hierarchy of electric scooter factors.

#### 4.3. Summary of Case Studies

After studying the electric scooter case provided above, the following is a brief summary of what this research provides. These key points represent general principles that can be adopted for implementation in other countries and regions. The result shows that Industry 4.0 could accelerate the sharing economy within a CE framework. However, it should start from the customer needs. The benefit of Industry 4.0 is that it started from data analysis. Therefore, to promote CE, data related to user behavior should be collected and analyzed first.

### 5. Conclusions

In this work, we have discussed the potential of Industry 4.0 for implementing the CE to enhance the sustainability of firms. This approach integrates human workers with autonomous machines to approach a scenario of highly efficient operations. A framework for CE based on Industry 4.0 is proposed, where the technologies of Industry 4.0 (IoT, CPS, CC, and data-driven analysis) provide a powerful set of tools to overcome barriers to implementation. In order to find the detailed influential factors of Industry 4.0 that could accelerate the sharing economy in the circular economy, interpretive structural modeling (ISM) is used. An electric scooter case study also illustrated how this unified framework can provide clear benefits, and revealed important directions for the further research.

In Industry 4.0, there are also barriers and problems that still require extensive research. These barriers include the cultural feasibility of the proposed models and the required support by the governments. Dalenogare et al. [79] concluded that Industry 4.0 innovations tend to be cherry-picked by enterprises, especially in developing countries. Businesses in those countries prefer the use of low-end technologies (e.g., tracking and management technology), and not the full suite of support tools (e.g., data analytics) that comes with Industry 4.0. This reluctance creates situations where data is collected but not optimally used to support decisions. Government support may be needed to influence firms to go beyond such partial implementations.

Government support through the provision of infrastructure is important. In the EU, the implementation of big data infrastructure played an important role in the readiness of big data analytics and the implementation of Industry 4.0; differences in infrastructure quality (e.g., internet connection speed) directly affect the capacity to utilize Industry 4.0 in different countries [81]. Clearly, barriers to implementing Industry 4.0 as an enabler of CE can be overcome through government investments in ICT infrastructure.

To reiterate, the main challenges to the CE that need to be solved are:

- (1) Legislative and policy landscape. Research toward CE and Industry 4.0 have shown that inflexible or outdated laws are a big barrier to implementation, and that without strong legal and financial support by the government, such policies may create insurmountable inertia against CE.
- (2) Socio-cultural limitations. More advanced nations have developed human and knowledge capital that are capable of supporting the implementation of both Industry 4.0 and the CE.
- (3) Corporate culture. Research has shown that firms that have adopted more sustainable business practices outperform their peers. However, the fundamental problem for the implementation of Industry 4.0 is data collection and analysis, which can potentially improve the management of material flow in conjunction with various CE tools such as material flow accounting (MFA).
- (4) Inter-firm co-dependencies. The final challenge is to create a co-value chain for the circular economy. This challenge can only be solved by creating and maintaining mutual trust between firms, and by creating venues where the use of Industry 4.0 tools can be expanded.

CE must be implemented with a holistic, policy-oriented approach focusing on the use of Industry 4.0 to achieve the resource-efficient production of manufactured goods. From the challenges mentioned above, future research should focus on how to address the multi-dimensional barriers that occur. Furthermore, more research is needed to develop a more flexible approach to implementing CE technology. An approach to this could be seen in BS 8001:2017 [82] and in a recent work by Walmsley et al. [13]. Such techniques can also provide key insights into CE implementation at a globally significant scale.

**Author Contributions:** R.R.T., K.T., T.T.P., T.-C.K. and M.-L.T. designed the research structure; T.T.P. and T.-C.K. performed the research; finally, R.R.T., K.T., D.S.L., and C.J.L. revised the study. All authors have read and approved the final manuscript.

**Funding:** This research was funded by Ministry of Science Technology of the Republic of China, Taiwan, grant number 107-2621-M-033-001 and 107-2221-E-033-051.

**Conflicts of Interest:** The authors declare no conflict of interest.

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