DRIVERS OF INDUSTRY 4.0-ENABLED SMART WASTE MANAGEMENT IN SUPPLY CHAIN OPERATIONS: A CIRCULAR ECONOMY PERSPECTIVE IN CHINA

Journal:	*Production Planning & Control*
Manuscript ID	SI-TPPC-2019-0042.R3
Manuscript Type:	Research paper for Special Issue
Date Submitted by the Author:	06-Nov-2019
Complete List of Authors:	Zhang, Abraham; Auckland University of Technology (AUT) Business School, AUT University, Private Bag 92006, Auckland 1142, New Zealand; Lumen Research Institute, Excelsia College and Indiana Wesleyan University, 69-71 Waterloo Road, Macquarie Park, NSW 2113 Australia Venkatesh, V G; Ecole de Management Normandie - Campus du Havre Wang, Jason X. ; Huddersfield Business School, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, the United Kingdom Venkatesh, Mani; Montpellier Business School, Wan, Ming; School of Management, Jinan University, 510632, Guangzhou, PR China; Institute of Physical Internet, Jinan University (Zhuhai Campus), 519070, Zhuhai, PR China Qu, Ting; School of Intelligent Systems Science and Engineering, Jinan University (Zhuhai Campus), 519070, Zhuhai, PR China; Institute of Physical Internet, Jinan University (Zhuhai Campus), 519070, Zhuhai, PR China
Keywords:	Circular economy, Industry 4.0, Smart waste management, Supply chain sustainability, Sustainable waste management

DRIVERS OF INDUSTRY 4.0-ENABLED SMART WASTE MANAGEMENT IN SUPPLY CHAIN OPERATIONS: A CIRCULAR ECONOMY PERSPECTIVE IN CHINA

Abraham Zhang[a, b]

[a] Auckland University of Technology (AUT) Business School, AUT University, Private Bag 92006, Auckland 1142, New Zealand (E-mail: abraham.zhang@aut.ac.nz)

[b] Lumen Research Institute, Excelsia College and Indiana Wesleyan University, 69-71 Waterloo Road, Macquarie Park, NSW 2113 Australia

V G Venkatesh[c],

[c] Ecole de Management de Normandie, 30 Rue de Richelieu, 76087 Le Havre, France. (E-mail: vgv1976@gmail.com)

Jason X. Wang[d]

[d] Huddersfield Business School, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, the United Kingdom (E-mail: J.Wang2@hud.ac.uk)

Mani Venkatesh[e]

[e] Montpellier Business School, Montpellier, France. (E-mail: m.venkatesh@montpellier-bs.com)

Ming Wan[f, g]

[f] School of Management, Jinan University, 510632, Guangzhou, PR China

[g] Institute of Physical Internet, Jinan University (Zhuhai Campus), 519070, Zhuhai, PR China. (E-mail: wanming@stu2018.jnu.edu.cn)

Ting Qu[h,g*]

[h] School of Intelligent Systems Science and Engineering, Jinan University (Zhuhai Campus), 519070, Zhuhai, PR China

[g] Institute of Physical Internet, Jinan University (Zhuhai Campus), 519070, Zhuhai, PR China (Corresponding author: quting@jnu.edu.cn)

Abstract

Increasingly, circular economy (CE) has been adopted globally to operationalise supply chain sustainability. The development of industry 4.0 technologies provides a new opportunity to improve the effectiveness and efficiency of adoption of CE, in particular, from the waste management perspective. More recently, scholars acknowledge the need for more studies on industry 4.0 and CE-driven sustainability aspects in supply chains. This research aims to fill the literature void and make a contribution from the perspective of smart waste management in supply chains using industry 4.0-based CE operations. Eleven key drivers were identified through semi-structured interviews, administered to experienced supply chain practitioners in China. A fuzzy DEMATEL method was used to analyse the interrelationships among these key drivers. The results show that the most fundamental causal drivers of smart waste management are overcoming operational challenges, recovering value, speeding up operations, saving cost and improving profit. There is a virtuous cycle between market demand and the improving price-performance ratio of industry 4.0 technologies. Our findings are part of the development of a bottom-up approach to adopting smart waste management in supply chains. The interrelationships identified in this research provide valuable insights into driving forces. Organisations, policy makers and technology providers can apply these insights when utilising industry 4.0 technologies to improve supply

chain waste management in line with the CE principle, and to achieve supply chain sustainability.

Keywords: Circular economy; Industry 4.0; Internet-of-Things; Smart waste management; Supply chain sustainability; Sustainable waste management

Article Classification: Research article

1. Introduction

Circular Economy (CE) proposes a paradigm shift and a new vision for firms for operationalizing supply chain sustainability (Farooque et al., 2019a). CE signifies a circular material flow in the economy (Su et al., 2013). From a waste management perspective, CE employs circular thinking about how to regenerate biological materials and to increase the reuse, remanufacturing and recycling of technical materials through innovative product design and waste management, thereby producing zero waste (de Sousa Jabbour et al., 2018; Farooque et al., 2019a; Veleva et al., 2017). The rapid development of industry 4.0 concepts and technologies equips firms to adapt, moving from the present linear supply chain operations to the circular model (Batista et al., 2018b; Fatorachian & Kazemi, 2018), enabling 'smart waste management' (Chowdhury & Chowdhury, 2007). The interplay between industry 4.0 and CE offers a promising way to achieve supply chain sustainability (Mangla et al., 2018b). This paper adopts the smart waste management perspective to address industry 4.0-enabled CE operations in supply chains.

The CE principle is to change the linear production pattern in the traditional business model (i.e., take, make, use, and dispose) to a circular system, wherein the resources circulate in the supply chain up- and downstream. This flow is facilitated by innovative logistics and supply chain ecosystems (Batista et al., 2018a). From the viewpoint of environmental and social sustainability, CE is desirable for business firms and society. From an environmental perspective, eco-design and waste management address concerns in the early stage of product development and reduce the negative impact of final products. Also, from a social perspective, CE contributes towards reducing poverty and improving living conditions through positive changes to ecological systems, for example, reduction in the risk of shortages of natural resources (Mangla et al., 2018a).

The trade-off between environmental/social and economic performance has been long debated in the supply chain sustainability literature (Tang, 2018). CE seems to offer a solution to the synergy issue (Genovese et al., 2017). The restorative and regenerative nature of CE solves the problem of rising procurement costs or shortage of raw materials/components and extends the product life cycle, thus creating economic value (Mangla et al., 2018a). Within the present business models, supply chain sustainability is largely driven by economic motives (Masi et al., 2018). Because of all these advantages of the CE paradigm, it has become a driving force of sustainability (Hobson, 2016).

CE has been adopted by more and more economies in recent years (Farooque et al., 2019b). For example, the European Commission embraced it quickly and has continuously evaluated the relevant policies to maximize environmental and economic value (Govindan & Hasanagic, 2018). Japan and USA applied CE as a practical tool in the design of environmental and waste management policies (Ghisellini et al., 2016). CE is of paramount importance in China. As an emerging economy, it relies on energy-intensive and heavy manufacturing industries for its rapid economic growth (Govindan & Hasanagic, 2018). Therefore, the diminution of reserves of energy and natural resources is a real threat to that economic growth and to sustainability. Additionally, increasing pressure from the global community to implement sustainable operations is countered by different barriers in the arena of international competition. It is a challenge for Chinese firms which have not considered environmental factors such as waste management (Su et al., 2013). These looming challenges pushed China to embrace CE as part of its national development strategy. The Circular Economy Promotion Law was passed in 2009, making China one of the three countries that has legislated CE-related policies (Su et al., 2013), introducing CE through a top-down approach as a new development model to usher in a more sustainable economic structure (Yong, 2007).

Waste management is a core area in CE (Su et al., 2013). The circularity which CE is named for largely relies on effective and efficient waste management to create a closed-loop flow of materials in the economic system. CE takes the form of a closed material loop in both technical (e.g., restorative) and biological (e.g., regeneration) cycles (Batista et al., 2018b). In the technical cycle, waste management means transformation and recycling of waste back into production systems. In the biological cycle, waste management means utilization of the waste resources of other companies in the economic system. Thus, the understanding of waste management is critical in the implementation of CE practices.

Moreover, there are relatively explicit economic values (e.g., cost reduction) and environmental benefits (e.g., conservation of scarce resources) through appropriate waste management (Wen et al., 2016). The synergy of economic and environmental bottom lines in waste management provides firms, especially for-profit ones, with incentives and resources to implement the practices in the full range of CE areas (e.g., consumption and production). Therefore, the studies on waste management are vital in CE in order to develop ‘a balanced interplay of environmental and economic systems’ (Ghisellini et al., 2016).

To be in line with the CE principle, supply chain operations needs to have waste management integrated into them. In modern business, firms operate and compete all across the supply chain (Tate et al., 2012). The production and usage of materials – and, thus, waste generation – are carried out in a highly interdependent manner between supply chain partners. Waste management should be operationalised at the supply chain level to create a true circular system. Moreover, supply chain waste management provides an opportunity to maximise the retained values of waste. Supply chain partners are more likely to share critical knowledge and resources in operations and, therefore, are more likely to explore and learn about opportunities of waste regeneration from one another (Govindan & Hasanagic, 2018). For example, while some by-products have little value for the firms that generate them, they can be regenerated by partner firms that work in the same supply chains to create value.

The requirement of CE (circular operations in the supply chain waste management) goes beyond the capacity of the linear model in the traditional supply chain management (Mangla et al., 2018a). In recent years, researchers and practitioners have tried to apply industry 4.0 technologies to overcome the challenges in supply chain waste management. Industry 4.0 provides a conceptual model to facilitate the application of what is termed 'smart waste management'. Industry 4.0 is defined as 'smart manufacturing', which is an information technology (IT) driven manufacturing system (de Sousa Jabbour et al., 2018). Internet of Things (IoT) (e.g., Radio-Frequency Identification [RFID]), cloud manufacturing, cyber-physical systems, and additive manufacturing (such as 3D printing) are the core technologies of industry 4.0 (Kang et al., 2016), providing managers with real-time information on production, machines, and the flow of components/materials in order to optimise supply chain operations. Industry 4.0 technologies have been increasingly used by firms to improve operations. For example, Wal-Mart coerced its suppliers to integrate RFID systems in order to improve the efficiency and effectiveness of Wal-Mart's supply chain operations (Deitz et al., 2009). In the service industry, vehicle recovery service providers use a cloud platform to collect and share real-time operational data (on, for example, loading time) with the downstream supply chain partners so as to optimise towing service schedules and resources (Duong et al., 2017).

Smart waste management is the practice of using innovative waste management systems supported by industry 4.0 technologies. The real-time data collected and shared through the applications of IoT automates the recognition and categorisation of waste at different supply chain stages, and thus makes waste management activities more intelligent, effective and efficient. For example, Bin-e devices have been implemented in municipal waste management (Bodamer, 2017). The data collected by the sensors in rubbish bins are sent to remote servers, stored, processed and used to monitor the current waste level; to make intelligent decisions for collection routes, times, and container size; and, most importantly, optimise the overall waste management process. Hence, industry 4.0 is likely, in line with CE, to eliminate the technological barriers to waste management in supply chains. It is noteworthy that many firms have already been applying industry 4.0 technologies in manufacturing and logistics operations (Kang et al., 2016).

There is a lack of research from the smart waste management perspective on how business firms can utilise industry 4.0 concepts to do better at adopting CE and, thus, supply chain sustainability. The adoption of general CE practices has been widely studied as a new approach to developing sustainable supply chains. Su et al. (2013) reviewed the long-term development of CE concepts, practices and assessment in China and found that CE provides a way to ease the tension between economic development and environmental concerns at the macro level; yet there are substantial challenges. Ghisellini et al. (2016) explored CE applications in a broad range of cultural contexts (e.g., China, U.S., and Japan) and at multiple levels (macro-, meso-, and micro-) and confirmed the promising benefits of CE to overall society; yet the implementation is still at an early stage. Particularly, the authors found a significantly positive effect on waste management (e.g., improved waste recycle rates) when the CE concepts were integrated. The concepts of industry 4.0 have been rapidly developed and are found to substantially improve firms' operations (Fatorachian & Kazemi, 2018; Lee et al., 2015). However, the use of industry 4.0 technologies in improving the effectiveness and efficiency of CE adoptions is still a novel research field.

de Sousa Jabbour et al. (2018) provided a pioneer five-step roadmap connecting industry 4.0 technologies to CE applications for supply chains. Mangla et al. (2018b) called for research on the different aspects in the integration of industry 4.0 and CE in developing sustainable supply chains. In particular, the authors emphasised the importance of studies which explore drivers and barriers of such integration as major research themes, and provide practical answers on how business firms address industry 4.0 and CE-driven supply chain sustainability. In this study, we answered their call. Specifically, we focused on the interplay between industry 4.0 and CE from the perspective of waste management in supply chains, or 'smart waste management in supply chains'.

Smart waste management can be adopted at different levels in society (Ghisellini et al., 2016). The study of it includes add-on attributes that can be incorporated into an existing process, rather than a heavy change-over, thus providing a transition to other areas of CE (e.g., production and consumption). In the review of literature, we found that the previous research on smart waste management has remained at the macro- or meso –level. Scholars have mainly focused on smart waste management in municipalities (Binder, Quirici, Domnitcheva, & Stäubli, 2008; Glouche & Couderc, 2013; Omar et al., 2016; Binder et al., 2008; Catania & Ventura, 2014; Glouche & Couderc, 2013; Omar et al., 2016). Because of China's leading role in the adoption of CE at the national level, urban smart waste management has been widely researched in Chinese cities (Anagnostopoulos et al., 2017; Chi et al., 2011; Park et al., 2010). Other studies took a mainly technical perspective on smart waste management (Chowdhury & Chowdhury, 2007; Shyam et al., 2017). To the best of our knowledge, there is a lack of research from the operations management perspective on how smart waste management can be adopted at the corporate level and in supply chains. The previous studies provide a top-down approach to the implementation of smart waste management, which is more likely to be in line with the broad and macroeconomic concept of CE. Nonetheless, business firms may find it difficult to determine their individual role and develop daily operations within the broad principle of CE. Especially, because operations among supply chain partners are so highly interdependent, the supply chain scope should be covered for waste generation, which can create a truly circular model of smart waste management and contribute to true sustainable development. Thus, in this study, we covered the research gap by exploring the bottom-up approach to the implementation of smart waste management in supply chains, as a transition to industry-4.0 enabled CE. We opted to focus on Chinese firms. The long-term development of CE concepts and practices in China provides a big enough object for a valid and reliable study of the integration of industry 4.0 in waste management. Also, our study based on Chinese firms is likely to provide practical and confirmatory results for other emerging markets (e.g., India) that follow a similar CE pattern.

Specifically, we address the following two research objectives.

- To identify the key drivers of industry 4.0 in the supply chain operations of smart waste management for a transition to a circular economy
- To understand the cause-effect relationships between the key drivers of smart waste management

The contribution of this research lies in the novelty of exploring the drivers of smart waste management at the supply chain level, thus complementing the literature from the waste management perspective, deepening understanding for business firms about operationalising "industry 4.0 and CE driven sustainability aspects in the supply chains" (Mangla et al., 2018b). The identified drivers, and particularly cause-effect relationships, provide a clear road map to successful adoption of smart waste management in line with CE principles. Moreover, this study focuses on Chinese firms. The Chinese government has ambitiously embraced CE as part of its national development strategy and is a leading country among emerging economies using the CE principle to develop sustainably (Su et al., 2013). While our study provides timely guidance for managers in China, the findings in this research are likely to be applicable to other emerging markets (e.g., India), owing to the comparable CE context among emerging economies (e.g., government regulations and top management commitment to CE) (Yadav et al., 2019).

The rest of this paper is organized as follows. In the following section, we briefly cover the background literature. Methodology and data collection procedures are explained in Section 3. Section 4 presents the results, analysis, and findings. Section 5 discusses the managerial and policy implications. Section 6 concludes the research.

2. Background Literature

In the first step of understanding the background literature, we adopted the systematic literature review (SLR) procedure suggested by Tranfield et al. (2003). Articles with the combination of keywords *smart waste management, technology in waste management, circular economy waste management, waste technologies, smart technologies in waste management, waste recycling, Internet of Things (IoT), waste collection and handling,* and *waste monitoring systems* were retrieved from databases such as Scopus, EBSCO and JSTOR. We reviewed the collected literature using the forward and backward snowball technique to finalise a list of more relevant articles to our work (Yadav and Desai, 2016; Yadhav et al. 2018). Furthermore, this review is structured in three sub-sections.

2.1 Waste Management and Circular Economy

Traditionally, waste is generated from household, commercial and institutional processes, and effective management of it is a challenge in densely-populated cities (Sadaf et al., 2016; Kumar et al., 2017). Also, a huge amount of value has been lost, and waste generation poses a serious challenge to sustainability. In the CE literature, managing this waste is essential to maintaining the circularity of energy and resources and providing environmental and economic benefits (and the ensuing resource efficiency benefits).

Businesses see it as a mechanism to gain competitive advantage through integrating systems and cultivating partnerships with other stakeholders (Geng et al., 2009).

In addressing the challenge of waste treatment, the CE philosophy is to think innovatively about waste management, wherein waste is considered as a resource (Veleva et al., 2017). Also, only 30 percent of materials are used for recovery at the global level, of which 11 percent goes to material recovery and 19 percent to energy recovery (Singh and Ordonez, 2016). CE mimics the natural ecosystem by transforming the so-called waste into valuable feedstock through biological decomposition (such as reuse) and technical restoration (such as remanufacturing, repairing and recycling) (Genovese et al., 2017; The Ellen MacArthur Foundation, 2013). At present, waste-to-energy techniques are classified into four broad types: physical, thermal, chemical and biological. Among them, landfill is still a dominant physical waste disposal pattern worldwide (Ghisellini et al., 2016). The other prominent techniques are gasification (thermal), combustion (chemical), co-digestion, anaerobic digestion and fermentation (biological) (Pan et al., 2015). All these processes facilitate CE to directly or indirectly address the problem of energy demand and greenhouse gas (GHG) emissions.

Moreover, when waste is generated faster than traditional technology can deal with it, the negative environmental impact creates an obstacle for the long-term development of human society (Su et al., 2013). It is to address this that CE envisions always restoring value from used resources (that is, waste) and creating zero waste. Waste management in line with CE philosophy requires continuous exploration of the opportunities to decrease waste generation while increasing the rate of waste reclamation. Firms also embark on waste management strategy through specific initiatives such as Circular Economy 100 (The Ellen MacArthur Foundation, 2013).

In theory, waste management under the guidance of the CE principle offers promising environmental and economic benefits. However, in practice, waste management is always challenging, especially at the supply chain level, where it requires a considerable transformation of waste treatment in terms of the flow of procurement, production, logistics and consumption processes. Supply chain operations need to be extended to utilise by-products and waste. At the same time, they need to be cost-efficient and socially acceptable. Many factors, such as political governance, government regulations, taxes and support incentives also drive waste management strategy (Malinauskaite et al., 2017). To fulfil the CE vision of waste management, all the supply chain stages should be integrated, including product design, manufacturing procedures and restoration (Jensen & Remmen, 2017). Yet supply chain practices that take place beyond firm boundaries are extremely complex and difficult (Giunipero, Hooker, & Denslow, 2012). Firms do not always have the full information on products throughout their life cycle due to the multiplicity of production stages in supply chains, and technological challenges are a major barrier to integrating the information and managing the restoration of waste (Govindan & Hasanagic, 2018).

Moreover, waste management based on the CE principle at the supply chain level demands substantial financial investment in internal processes and coordination of supply chain partners, which discourages many firms from adopting the most effective waste management practices of a CE system (Sousa Jabbour et al., 2018). Furthermore, scholars have found, consumers have not always been fully aware of or had high regard for the restorative value of product waste (Govindan & Hasanagic, 2018; Hazen, Mollenkopf, & Wang, 2017). At the last stage of the traditional product life cycle, when consumers do not accept products remanufactured from waste, it decreases the potential value of waste management at the supply chain level. Additionally, Hazen et al. (2017) discussed how consumers' attitudes are an important factor of environmental and economic benefits from CE (Gaur et al., 2019). The transparent information flow facilitated by smart waste management is likely to change their attitudes toward using remanufactured products and their willingness to participate in waste management.

2.2 Smart Technologies in Industry 4.0 Realm

In the current environment, the challenge is to uphold the principles of sustainability along with the flexibility of supply chain operations. Industry 4.0 allows the systems to integrate a cyber-physical network of machines, sensors and facilities to streamline data management (Luthra et al., 2018a). Such a network involves technologies such as intelligent production, human-computer interaction, remote operations and data networks. These all help in real-time monitoring of waste management performance in terms of energy consumption and other operational parameters (Esmaeilian et al., 2018).

Table 1. Recent developments in smart waste management

Author (s) & year	**Major contribution in smart management**
Anganostopoulous et al. (2017)	Dynamic waste management model using sensors, RFID, and actuators
Saha et al. (2017)	Integrated web-based solution called smartbox, which optimises waste collection
Lu et al. (2017)	New bin scheduling algorithm using multi-restricted and multi-compartmental routing problem
Ramya et al. (2017)	Smart bin solutions
Aazam et al. (2016)	Cloud-based smart waste management monitoring system for all stakeholders
Ramasami et al. (2016)	Location decision algorithm to select suitable land for the landfill construction
Thakker et al. (2015)	Container screening system using near-infrared spectroscopy (NIR) to alert about the problems of dumps that are not cleaned on time.
Folionto et al. (2015)	Intelligent monitoring system
Wahab et al. (2014)	Smart system of trash recycling

From the technological perspective, the CE agenda is to move from the old-fashioned disposal procedures to the intelligent waste treatment technologies, which mainly involves linking physical waste with digital information (Glouche and Coudrec, 2013). Towards that purpose, industry 4.0 smart technologies have been increasingly used by firms to improve supply chain and operational performance along with the waste treatment process. The technologies are classified into four main groups: spatial (e.g. GIS), identification (e.g. Radio Frequency Identification and barcodes), data acquisition (e.g. sensors, imaging), and data communicating technologies (e.g. Wi-Fi) (Esmaeilian et al., 2018). These technologies act as intelligent control units to customise service by integrating the concept of Internet of Things (IoT) (Hong et al., 2014) and are discussed in detail by Pardini et al. (2019) (Table 1 provides a snapshot of smart waste management technologies). These innovations have led to the proposal of various frameworks within the realm of smart waste management. For example, Catania and Ventura (2014) provide a roadmap for applications of smart technologies in waste management, and Aazam et al. (2016) proposes a cloud-based arrangement. All these developments aim to reduce the waste management costs and make the process more transparent, starting from improving the quality of selective sorting of items to recycling them (Chowdhury and Chowdhury, 2007; Glouche and Coudrec, 2013; Pardini et al., 2019).

Along similar lines, the recent development of smart cities forces city administrators to have a ubiquitous waste management architecture with real-time information across various nodes. As a result, innovations like new sensor-based technologies and data analytics, along with social networking interactions, are integrated to effectively manage waste. They are mainly used for various applications within the waste treatment domain, such as waste recognition, collection and route optimisation , reduction of fuel costs and tracking of the performance of the garbage collectors and workers and of stolen or damaged containers (Glouche and Coudrec, 2013; Catania and Ventuura, 2014; Kansara et al., 2019). Recent works propose an IoT framework integrating the *Geographical Information System*

(GIS) to monitor waste bins daily through a new, optimised algorithm (Shyam et al., 2017). In addition, they apply add-on technologies and know-how that can be relatively easily incorporated into existing supply chain operations without investing in extensive changes (Malinauskaite et al., 2017). Thus, the financial investment required for smart waste management is reduced when the technologies to be invested in are similar to those already in use. In a similar context, it is interesting to investigate other managerial factors that impact the deployment of smart technologies.

2.3 Waste Management in China

China is now experiencing rapid urbanisation and industrialisation, which leads to challenges in managing both household and industrial waste (Gu et al., 2015). According to the World Bank estimate, the total amount of waste in China will be over 480 million tons in 2030 (Chen et al., 2014). In order to address this challenge, the Chinese government has been promoting CE initiatives through legislation since 2009. It is a growing concern for China, as it produces 30 percent of the world's solid waste (Gu et al., 2017). There is a special focus on recycling, treatment technologies and infrastructure in China's current 13th five-year plan, which was released in 2016. As a result, China has proposed high-level CE frameworks; however, their enforcement may vary due to regional practices (Ranta et al., 2018). The government has commenced CE initiatives in 27 provinces, coupled with smart technologies in key sectors such as metallurgy, textiles, transportation and pharmaceuticals (Li and Lin, 2016). The government also shows interest in developing eco-cities and industrial parks (Li qiang, 2019). In spite of the authorities steering sustained efforts and multiple initiatives to implement CE practices assisted by smart tools, the progress so far has been modest, and it is important to understand the factors that drive the adoption of technology in the current CE realm.

The above-structured review summarises the importance of smart technologies in the current CE environment. While studies such as that of Ranta et al. (2018) qualitatively explore the institutional CE drivers in the Chinese context, they point to and leave a scope for understanding those drivers and barriers – specifically, in regard to smart waste management applications in the Chinese CE context. Such understanding of drivers and barriers would accelerate CE implementation and inform the design of policy for further improvement. The present study adopts a mixed-methods approach to analyse, in two stages, the drivers and their interrelationships. A qualitative method was used in the first stage to identify key drivers: interviewing practitioners who were experienced and knowledgeable about the supply chain operations of smart waste management in China. We elaborate on various drivers of industry 4.0-enabled smart waste management in Section 4.1. At the second stage, fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) was applied to examine the cause-effect relationships among the identified drivers. The DEMATEL technique is a rigorous tool for disentangling the interrelationships between factors (Wu & Lee, 2007).

3. Methodology and Data Collection

3.1 A Mixed-methods Approach

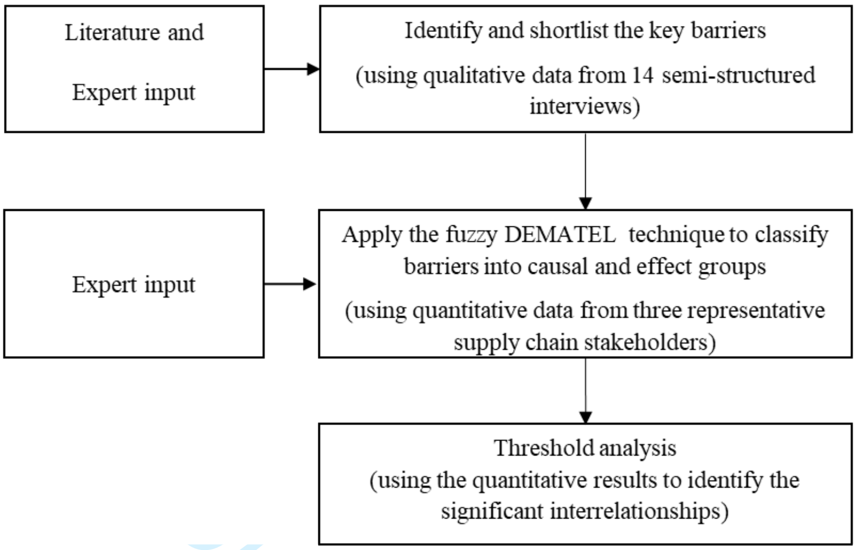


Figure 1. Research Framework

A combination of qualitative and quantitative methods has recently been advocated for investigating business-related issues (Gölcük & Baykasoğlu, 2016; Govindan & Chaudhuri, 2016; Shao et al., 2016). Figure 1 depicts the framework of the research procedures. Mixture of methods fits the nature of the research and its two objectives as outlined in Section 1. As a pioneering and exploratory work in smart waste management, this research requires a qualitative method first to identify the key drivers of industry 4.0 in the supply chain operations of waste management for a circular economy. After that, it employed a quantitative method, the fuzzy DEMATEL technique, to classify barriers as causal and effect. Additionally, a threshold analysis was conducted to identify the significant interrelationships among drivers, bringing to light the most impactful ones.

Semi-structured interviews were conducted in the qualitative phase. A semi-structured interview method provides enough structure to keep conversations focused. At the same time, it allows enough flexibility to take new directions and dig deeper into unexpected findings (Bell et al., 2018). An information sheet was provided to interview participants to explain the concepts of CE and smart waste management, and the possible application of industry 4.0 technologies (including internet-of-things) in the supply chain operations of waste management. The interview protocol that was used to guide the process is included as Annexure 1.

The information sheet also provided an initial list of factors. The list was compiled based on a survey of news reports and academic literature (Walker et al., 2008; Hsu et al., 2013; Giunipero et al., 2012; Govindan et al., 2015; Govindan & Hasanagic, 2018). These factors were the influences of market demand, regulatory pressure and organisational vision; the need good marketing image, cost saving, speed of operations and value recovery from waste; and concern about the amount of waste going to landfills, the environment and operational challenges encountered in waste management. The interviewees were advised that this list of factors was not exhaustive and was meant to prompt their thinking to identify more factors.

The quantitative phase of the research employed the fuzzy DEMATEL technique. This technique (Gabus & Fontela, 1972) supports multi-criteria decision-making through the creation and analysis of structural models of causal relationships between system components. It has been increasingly used in managerial studies, especially in the sustainable supply chain domain (Zhu et al., 2014; Seleem et al., 2016; Shao et al., 2016; Bai et al., 2017; Luthra et al., 2018b; Farooque et al., 2019b). Venkatesh et al. (2017) and Farooque et al. (2019b) made comprehensive comparisons of DEMATEL and other multi-criteria decision-making techniques. They suggested that DEMATEL is better for barrier studies than Interpretive Structural Modelling (ISM), Analytic Hierarchy Process (AHP), Analytic Network Process (ANP) and Structural Equation Modelling (SEM). This study employed a fuzzy set extension to the standard DEMATEL technique to handle the inherent subjectivity and vagueness in human judgments (Wu & Lee, 2007; Lin, 2013). Another variation is grey-based DEMATEL, which uses very similar methodological procedures but with grey numbers to handle subjectivity and vagueness in input data (Si et al., 2018). The researchers chose fuzzy DEMATEL because it is slightly more sophisticated, using triangular fuzzy numbers which have three dimensions (e.g., 0, 0, 0.25), while grey numbers have only two dimensions (e.g., 0, 0.25). The technical details of the fuzzy DEMATEL method can be found in Venkatesh et al. (2017) and Farooque et al. (2019b).

3.2 Data Collection

Research data were collected from the Pearl River Delta of China, which has a reputation as the factory of the world. The Chinese language was used in both data collection stages. In the first stage, an invitation to participate in research was emailed to 20 potential participants along with the interview information sheet. A purposeful sampling approach (Gentles et al., 2015) was taken, selecting organisations and their experienced staff members who had most to do with the practice of smart waste management. After follow-up communications with the potential participants, we were able to secure 14 interviews in August and September 2018, either face-to-face at a participant's organisation or over the phone. Each interview lasted about 30-50 minutes. The interviews involved organisations in both the public and private sectors and a variety of ownership types. Their industry types included government, healthcare, property development, logistics and manufacturing. Annexure 2 presents the profile of research participants.

In the second stage, we obtained quantitative data for DEMATEL analysis. We asked the participants to judge the cause-effect relationships among shortlisted driver factors by making pairwise comparisons. We surveyed three participants (Annexure 3 provides their profiles) from different organisations, each having a different perspective on the supply chain operations of waste management. We asked each to fill out a survey form on smart waste management in supply chain operations. Such a research design is more robust than one which obtains data from a single type of organisation. It helps to avoid the bias of a single type of supply chain stakeholder, rather providing a more holistic understanding of the research topic. These three organisations were as follows:

- A technology provider: a manufacturer which designs and produces smart waste management equipment/systems;
- A technology user in the private sector: a property development and construction business which has been using smart waste management equipment/systems;
- A technology user in the public sector: a local government agency which oversees waste collection and management activities.

4. Results, Analysis and Findings

4.1 Key Drivers of Smart Waste Management

The qualitative phase of the research arrived at a final list of 11 important drivers of the implementation of smart waste management in supply chain operations. The researchers shortlisted these 11 mainly because they were most frequently identified by the 14 interviewees. According to the research framework as illustrated in Figure 1, the researchers also took into consideration the important driver factors identified in the literature. Based on the input from both the literature and interviewed experts, the researchers had two meetings to discuss and shortlist the 11 drivers. The detailed description of individual drivers follows.

D1 – Profit maximisation: This driver is the overall financial benefit associated with the use of industry 4.0 technologies in waste management for improving the sustainability of supply chain operations. Smart waste management helps an organisation to increase its profit when its implementation cost is outweighed by monetary returns.

D2 – Cost saving: Industry 4.0 technologies can save organisations cost in waste management. For example, IoT sensors can be used to provide location intelligence on how full rubbish bins are, informing efficient use of waste collection vehicles (Gutierrez et al., 2015).

D3 – Value recovery from waste: Industry 4.0 technologies enable more effective value recovery. For example, an interviewee introduced his organisation's newly-invented smart bin that separates glass from other waste. The recycled glass is then used for making handicraft products.

D4 – Operational challenges in waste management that require smart solutions: Some challenges in the supply chain operations of waste management are insurmountable until a new industry 4.0 technology becomes commercially viable. For example, source separation is a best practice in sustainable household waste management. However, it has not been widespread in many developing countries due to a variety of infrastructural, cultural and behavioral obstacles. In China, a pilot project used two-dimensional (2D) barcodes to identify and trace each rubbish bag and hold residents accountable for not sorting rubbish. The implementation was proved to be very effective in enforcing source separation in a residential community (Xu, 2017).

D5 – Improved speed of operations in waste management: Many waste management activities are labor-intensive and time-consuming. Some industry 4.0 technologies can speed operations up through automation. For example, Apple Inc. uses robots to disassemble end-of-life iPhones to recover technical materials. It is much faster and more cost-efficient than manual operations.

D6 – Alignment with organisational vision/marketing image: An organisation is more likely to embrace industry 4.0 technologies for sustainable waste management if such an implementation is aligned with its vision and marketing image. For example, manufacturers including Cadbury, Mars Nestlé, Heinz, Premier Foods and Kerry Noon are committed to both

CE and industry 4.0 (Mangla et al., 2018). Therefore, they have a great incentive to apply industry 4.0 technologies for a CE transition in their waste management functions.

D7 – Market demand: Customers and consumers are important stakeholders of any organisation. As the public (and therefore the market) has become more environmentally-conscious in the past decade, there has been increasing demand for all supply chain stages, including waste management, to be more sustainable (Mangan & Lalwani, 2016). This trend drives the utilisation of the latest industry 4.0 technologies for more effective and sustainable waste management.

D8 – Regulatory pressure: Regulatory pressure is one of the key drivers of greening supply chain operations (Mangan & Lalwani, 2016). Increasingly, enterprises are influenced by regulatory norms to adopt industry 4.0 technologies for reducing harmful waste and meeting the environmental requirements.

D9 – Corporate social responsibilities (CSR) expectations of the public: The public and the media are now paying increased attention to the social responsibilities of enterprises. This change drives businesses to better protect the environment and to reduce the amount of waste going to landfills. Recent studies (Eccles, Ioannou, & Serafeim, 2014; Flammer, 2013) found that shareholders reward businesses which do better in CSR and penalise those that ignore it.

D10 – Top management's environmental values: Top management sets organisational directions, so its environmental values influence how the organisation manages waste. Giunipero et al. (2012) identified top management initiatives as the top-ranked driver in the context of broad sustainability management. Sroufe's (2003) work proved that top management's support for the environmental management system is positively linked to waste management practices.

D11 – Increasing price-performance ratio of industry 4.0 technologies: As technologies advance, they usually become more capable and cheaper. This translates into an improving price-performance ratio of industry 4.0 technologies, which has been a driving force behind their adoption worldwide. The same is true for their implementation in waste management.

4.2 Fuzzy DEMATEL Analysis Results

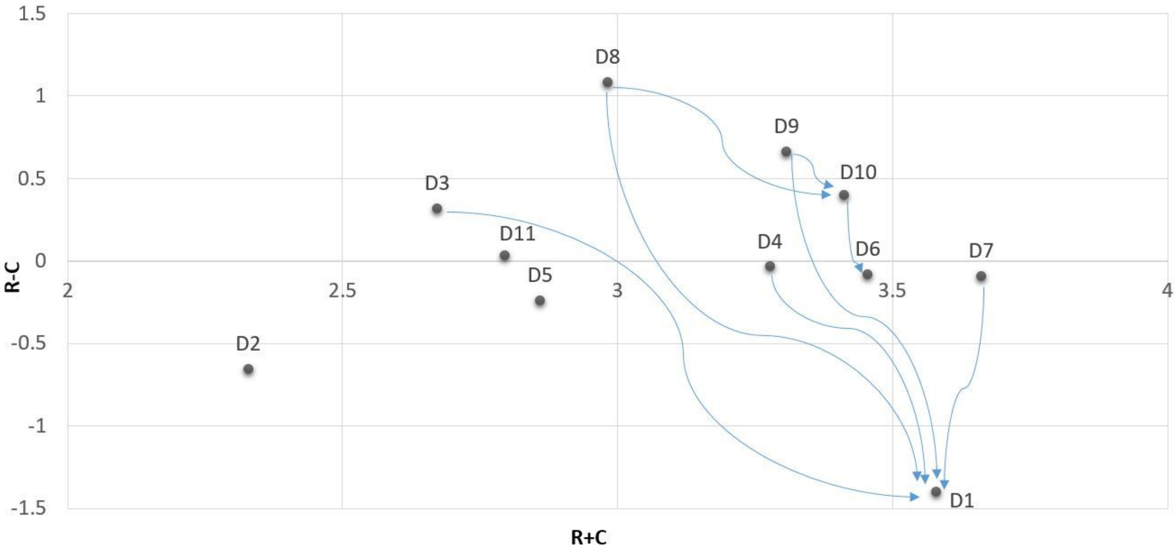
Fuzzy DEMATEL analysis yields a total relation matrix. From this matrix, it is easy to calculate the sum of rows (R) and of columns (C) for each driver factor, and their (R+C) and (R-C) values. The (R+C) value depicts the prominence (importance) of a driver factor for smart waste management in supply chain operations. It indicates the total effect, including both influenced and influential driver strength. The relation or influence (R-C) value represents the cause-and-effect relationship. If the (R-C) value is positive, the driver factor is in the causal category; otherwise, it is in the effect category (Wu & Lee, 2007; Lin, 2013). Based on the quantitative results, a prominence-causal relationship diagram is generated to visually classify driver factors. The diagram also maps significant relationships above a threshold value, which is calculated by adding 1.5 standard deviations to the mean of the total relation matrix (Fu et al., 2012; Zhu et al., 2014).

4.3 Results from the Technology Provider's Perspective

Table 2 shows the total relation matrix from the perspective of the technology provider. The threshold value is 0.229. The values greater than this are highlighted in bold in the table. They are also mapped in Figure 2 to indicate significant cause-effect relationships.

Table 2. Total relation matrix from the technology provider's perspective

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
D1	0.104	0.094	0.053	0.075	0.134	0.146	0.148	0.050	0.126	0.096	0.062
D2	0.218	0.050	0.038	0.077	0.056	0.089	0.134	0.032	0.049	0.050	0.043
D3	**0.278**	0.155	0.067	0.157	0.117	0.172	0.180	0.055	0.104	0.109	0.100
D4	**0.260**	0.167	0.173	0.100	0.161	0.176	0.189	0.058	0.081	0.110	0.146
D5	0.200	0.182	0.127	0.148	0.077	0.113	0.127	0.070	0.064	0.069	0.133
D6	0.228	0.122	0.106	0.176	0.109	0.122	0.254	0.135	0.161	0.176	0.098
D7	**0.298**	0.171	0.109	0.176	0.175	0.188	0.131	0.093	0.120	0.164	0.158
D8	**0.249**	0.120	0.127	0.200	0.197	0.171	0.206	0.083	0.209	**0.256**	0.216
D9	**0.244**	0.139	0.124	0.196	0.188	0.237	0.171	0.149	0.110	**0.252**	0.177
D10	0.204	0.137	0.158	0.193	0.181	**0.230**	0.167	0.145	0.200	0.118	0.172
D11	0.206	0.154	0.094	0.156	0.154	0.123	0.170	0.078	0.097	0.105	0.076



Significant relationships: D3-D1, D4-D1, D7-D1, D8-D1, D8-D10, D9-D1, D9-D10, D10-D6

Figure 2. DEMATEL prominence-causal relationship diagram from the technology provider's perspective

Results from the technology provider's perspective show that the two most fundamental causal drivers are D8 (Regulatory pressure) and D9 (CSR expectations of the public), which both arise from external stakeholders. The third most important causal driver is D10 (Top management's environmental values), which is highly dependent on the two aforementioned. The other causal driver is D3 (Value recovery from waste), which has a significant effect on D1 (Profit maximisation). These results suggest that external causal drivers are of greater importance than internal ones. This finding is consistent with a recent study by Farooque et al. (2019b) that identified the higher influence of external factors over internal ones in sustainable circular food supply chains in China.

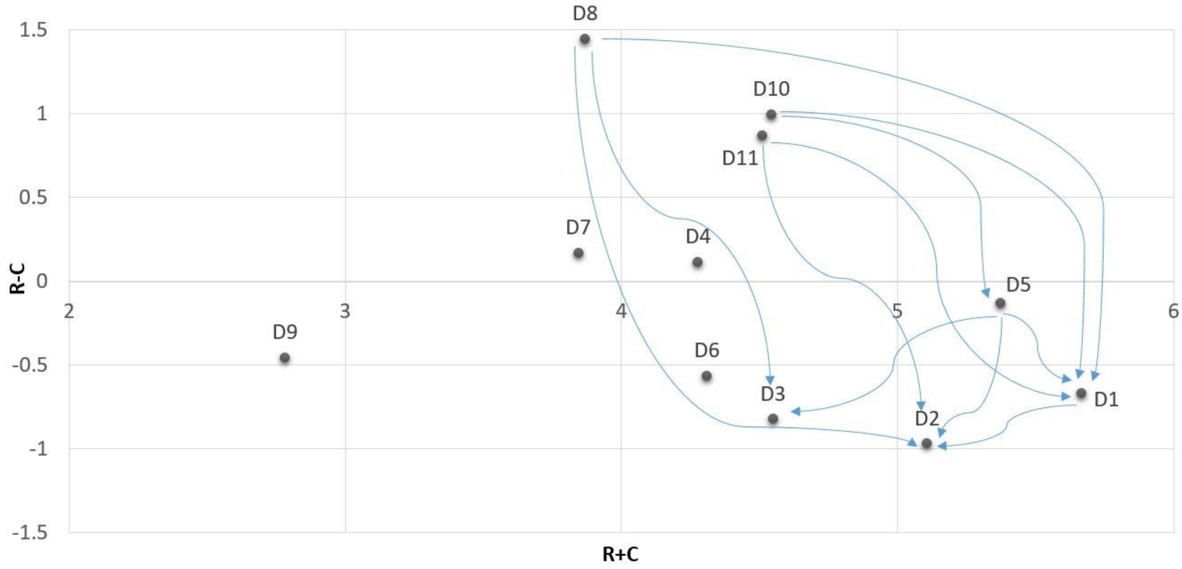
The most prominent drivers (those which have the greatest R+C values) are D7 (Market demand) and D1 (Profit maximisation). It is reasonable to see D7 (Market demand) being rated as the most prominent by the technology provider, given that their survival and growth depends on market demand. However, it is a surprise to find D1 (Profit maximisation) to be an effect driver, despite a high prominence score. Nevertheless, as can be seen in Figure 2, this is because D1 (Profit maximisation) is dependent on multiple drivers, including D3 (Value recovery from waste), D8 (Regulatory pressure), D4 (Operational challenges in waste management that require smart solutions), D9 (CSR expectations of the public) and D7 (Market demand). Based on an interview with the technology provider, D8 (Regulatory pressure) and D9 (CSR expectations of the public) have a good influence on D7 (Market demand), which in turn stimulates technological advancements to improve D1 (Profit maximisation). D3 (Value recovery from waste) and D4 (Operational challenges in waste management that require smart solutions) have a direct impact on D1 (Profit maximisation).

4.4 Results from the Private Sector Technology User's Perspective

Table 3 and Figure 3 show the results from the perspective of the technology user in the private sector. The threshold value is 0.316 for determining a significant relationship.

Table 3. Total relation matrix from the private sector technology user's perspective

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
D1	0.239	**0.327**	0.270	0.187	0.304	0.254	0.208	0.121	0.152	0.203	0.236
D2	0.296	0.188	0.234	0.195	0.240	0.253	0.148	0.108	0.126	0.138	0.143
D3	0.245	0.267	0.152	0.185	0.223	0.209	0.136	0.074	0.117	0.126	0.130
D4	0.276	0.269	0.277	0.138	0.280	0.230	0.193	0.110	0.133	0.143	0.148
D5	**0.377**	**0.369**	**0.340**	0.229	0.218	0.263	0.214	0.124	0.151	0.166	0.172
D6	0.279	0.203	0.181	0.144	0.224	0.137	0.174	0.140	0.120	0.132	0.137
D7	0.256	0.250	0.191	0.156	0.233	0.177	0.114	0.103	0.170	0.178	0.180
D8	**0.383**	**0.377**	**0.317**	0.237	0.289	0.230	0.151	0.097	0.155	0.209	0.215
D9	0.140	0.136	0.124	0.103	0.126	0.115	0.095	0.074	0.061	0.093	0.095
D10	**0.325**	0.312	0.287	0.270	**0.324**	0.300	0.224	0.132	0.234	0.145	0.216
D11	**0.349**	**0.340**	0.314	0.237	0.289	0.269	0.180	0.127	0.199	0.241	0.147



Significant relationships: D1-D2, D5-D1, D5-D2, D5-D3, D8-D1, D8-D2, D8-D3, D10-D1, D10-D5, D11-D1, D11-D2

Figure 3. DEMATEL prominence-causal relationship diagram from the private sector technology user's perspective

Results from the private sector user's perspective show three important causal drivers: D8 (Regulatory pressure), D10 (Top management's environmental values), and D11 (Increasing price-performance ratio of industry 4.0 technologies). It should be noted that this user firm is a medium-sized enterprise with about 300 employees. It is privately owned and not publicly listed. This explains why D9 (CSR expectations of the public) was not rated as a causal driver for this user, although it was rated as a key causal driver by the technology provider. This is coherent with the reality in China: the public has been paying more attention to CSR issues, but the focus has been mainly on publicly-listed large enterprises. This firm therefore does not face much CSR pressure on its supply chain sustainability. This finding affirms the importance of regulatory pressure, which was identified by Zhu et al. (2014) and Mangla et al. (2018) in their studies of sustainability barriers in two different developing countries.

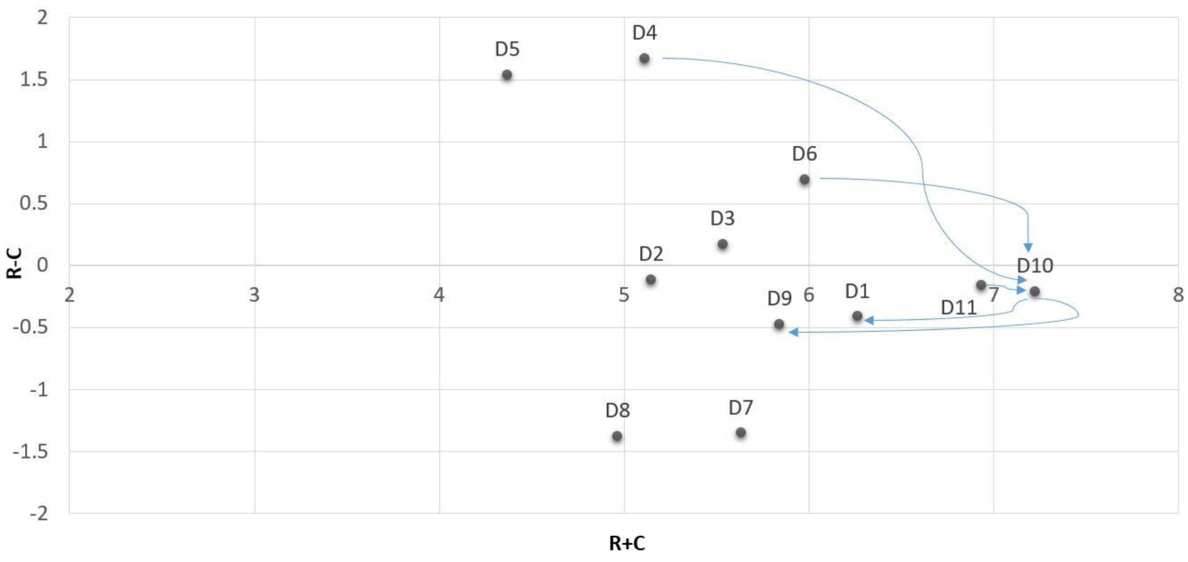
D1 (Profit increase), D5 (Improved speed of operations in waste management) and D2 (Cost saving) are the most prominent drivers, although all are effect drivers. This reflects a set of business priorities typical of firms in the Pearl River Delta of China. Due to rapidly rising operating costs, many businesses in the region rely on speed to be competitive and profitable (Zhang & Huang, 2012; Zhang et al., 2012; Huang et al., 2013), although cost control is still important.

4.5 *Results from the Public Sector Technology User's Perspective*

Table 4 and Figure 4 present the results from the perspective of the technology user in the public sector. By adding 1.5 standard deviations to the mean of the total relation matrix, the threshold value is calculated as 0.392 for determining a significant relationship.

Table 4. Total relation matrix from the public sector technology user’s perspective

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
D1	0.243	0.259	0.263	0.154	0.135	0.221	0.381	0.260	0.295	0.365	0.350
D2	0.348	0.174	0.243	0.179	0.094	0.160	0.251	0.224	0.226	0.332	0.287
D3	0.333	0.216	0.193	0.151	0.107	0.193	0.345	0.294	0.289	0.357	0.376
D4	0.347	0.320	0.292	0.147	0.190	0.250	0.387	0.332	0.329	**0.407**	0.390
D5	0.270	0.222	0.225	0.157	0.107	0.301	0.349	0.304	0.301	0.366	0.352
D6	0.378	0.290	0.293	0.212	0.121	0.214	0.353	0.329	0.358	**0.401**	0.386
D7	0.178	0.144	0.146	0.097	0.146	0.252	0.182	0.242	0.240	0.261	0.252
D8	0.150	0.120	0.123	0.083	0.094	0.228	0.220	0.148	0.211	0.192	0.224
D9	0.288	0.239	0.245	0.119	0.122	0.245	0.296	0.309	0.210	0.310	0.300
D10	**0.422**	0.357	0.330	0.175	0.148	0.289	0.366	0.367	**0.402**	0.317	0.334
D11	0.378	0.290	0.324	0.245	0.149	0.284	0.360	0.361	0.294	**0.406**	0.295



Significant relationships: D4-D10, D6-D10, D10-D1, D10-D9, D11-D10

Figure 4. DEMATEL prominence-causal relationship diagram from the public sector technology user’s perspective

Figure 4 show three important causal drivers: D4 (Operational challenges in waste management that require smart solutions), D5 (Improved speed of operations in waste management), and D6 (Alignment with organisational vision/marketing image). The results are consistent with the understanding acquired from the government agency in an earlier interview: it would consider a smart waste management technology if such technology could benefit its operations, for example, by overcoming challenges and improving speed. The alignment with policy directions from the higher level is also important. However, cost/profit considerations are not at the top of its priority list, which is understandable, given that it is not profit-oriented. The two most prominent drivers are D10 (Top management's environmental values) and D11 (Increasing price-performance ratio of industry 4.0 technologies). This suggests that an immediate implementation is largely dependent on the leadership team's attitude and whether a relevant technology is justifiable from a price-performance viewpoint. Apparently, economic factors are important, and they influence the attitude of the management on sustainability initiatives (Mangla et al., 2018; Farooque et al., 2019b).

D10 (Top management's environmental values) shows significant dependence on D4 (Operational challenges in waste management that require smart solutions), D6 (Alignment with organisational vision/marketing image), and D11 (Increasing price-performance ratio of industry 4.0 technologies). Initially, we were surprised by these results because we thought that one's environmental values were relatively independent of other factors. After taking the results back to the respondent, we realised that our belief was not valid for the current situation in China. Environmental values have just started evolving there and are not yet deeply rooted in people's minds. Consequently, D10 (Top management's environmental values) is often contingent on the practical benefits of implementing smart waste management technologies, and on the organisational vision and government policy directions.

For the same reason, D7 (Market demand) and D8 (Regulatory pressure) are the most obvious effect drivers from the perspective of the government agency. The market for smart waste management technologies is still at a nascent stage. Its growth is highly dependent on the operational benefits that the evolving industry 4.0 technologies can deliver for the supply chain operations of waste management. The Chinese government has a rather pragmatic approach to exerting regulatory pressure. It is more likely to push for the use of the latest technologies for improving waste management when (a) the industry is concerned about environmental protection and (b) the technologies have reached a good price-performance ratio.

4.6 Summary of Findings

The DEMATEL analysis results presented above offer insights from three different representative stakeholders: a technology provider, a private sector user and a public sector user. Comparing and contrasting the results from a holistic perspective, we summarise the key findings as follows.

1. The most fundamental causal drivers of smart waste management lie in what it can do for the supply chain operations of waste management in terms of overcoming operational challenges, recovering value, speeding up operations, saving cost and improving profit.
2. There is a virtuous cycle between market demand and the improving price-performance ratio of industry 4.0 technologies. Market demand stimulates research and development investment in industry 4.0 technologies to improve their price-performance ratio. Conversely, better price-performance ratio stimulates greater market demand for smart waste management solutions.
3. Regulatory pressure has a great impact on the uptake of smart waste management solutions. However, the actions of the relevant government agencies in China are

dependent on the effectiveness and price-performance ratio of industry 4.0 technologies and on the attitude within the industry about environmental protection.

4. The CSR expectations of the public can influence organisational behaviors. However, the effect is mainly felt by publicly-listed large enterprises in China due to their visibility. Privately-owned small- and medium-sized enterprises are yet to be influenced much at present.
5. Top management's environmental values drive the adoption of the latest industry 4.0 technologies for more sustainable waste management. However, environmental values are not yet deep-rooted in the Chinese business culture, and are often contingent on organisational vision and government policy directions.

All the key findings summarised above are original and contribute to the development of literature on sustainable waste management. The generic aspects of key findings 3-5 were also reported by earlier studies (Zhu et al., 2014; Mangla et al., 2018; Farooque et al., 2019b), confirming the validity of this research. However, our study findings provide additional insights that are unique and contextual to Chinese industries, so they might serve as a useful guide for managers and policy makers.

5. Discussion

We can advance several general propositions based on the findings presented above. First, the most fundamental driver of smart waste management is the effectiveness of industry 4.0 technologies for improving the supply chain operations of waste management. Second, the market demand for smart waste management solutions and their price-performance ratio are both improving over time and enforce each other in a virtuous cycle. Third, regulatory pressure has a deep impact, but the Chinese government is rather pragmatic about exerting it for the implementation of industry 4.0 technologies in waste management. The fourth is that the business leaders in China have some commitment to environmental values, but it is fairly superficial; pressure from the government, the public, and higher-level management are necessary if business leaders are to take action to invest in the latest industry 4.0 technologies for improving the sustainable operations of waste management. Based on these general propositions, we derive policy and managerial implications in the following two subsections.

5.1 Policy Implications

To expedite a transition to CE as part of its national development strategy, the Chinese government should make it a priority to support the research, development and commercialisation of industry 4.0 technologies for improving the supply chain operations of waste management. Improvements in smart waste management technologies have a direct and significant impact on their adoption, engendering the virtuous cycle between the market demand and the price-performance ratio. The government can provide financial support in the form of research and development funds, subsidies and tax benefits available to providers of the technology for smart waste management solutions. Given how the drivers interact, such support is likely to snowball the uptake of smart waste management solutions, which will, in turn, advance the government's CE agenda. The government should also consider supporting, promoting and benchmarking of enterprises that take the lead in the use of smart waste management technologies. The government can involve industry associations to organise site visits and tours to help the industries to learn from the leading enterprises about smart waste management. In this way, more enterprises and managers will become aware of the potential benefits of smart waste management technologies, and their implementation in their own businesses.

Although CE has been legislated in China as part of its national development strategy, only modest progress has been made in implementing it over the past ten years (Mathews &

Tan, 2016). There is a need for the Chinese government to exert regulatory pressure to bring CE from legislative paper further into the realm of concrete actions. The National Development and Reform Commission (NDRC) has been responsible for the promotion of CE in China. It needs to strengthen its enforcement mechanism to implement CE at the micro (supply chain operations) level. It should be noted that the NDRC has only published CE indicators for the macro (regional economy) and meso (industrial park) levels, but not for the micro level (Geng et al., 2012). Developing industry-specific micro-level indicators will be useful for measuring the progress toward more sustainable supply chain operations of waste management. Thus, it will galvanise the adoption of the latest industry 4.0 technologies for making waste management more effective. Although it will be a challenging task to develop a diverse range of specific, micro-level indicators for a large variety of industries, the NDRC should gear up its efforts to do so. Publication of such indicators will make it feasible to better measure the performance of supply chain operations of waste management for a transition to a circular economy.

The Chinese government needs to embark on a journey to transform its culture into one that seriously values environmental sustainability. The Chinese government started its economic reform in 1978. In the first three decades, there was a negligence of environmental protection as economic growth was given an absolute priority. In the most recent decade, the resulting environmental degradation issues drove the Chinese government to turn away from the traditional measure of GDP to that of green GDP in order to make development sustainable. However, environmental values are still far from being deeply embedded in the Chinese culture and in the decision-making of the government and of enterprises. The Chinese government should continue to fine-tune its green GDP measurements and monitoring system, so as to transform its governance culture and to guide the business culture to commit more to environmental sustainability. There is also a need to exert greater regulatory pressure on businesses and citizens to protect the environment, and a need to hold people accountable for irresponsible behaviour toward the environment. The Chinese government should also improve its environmental education in schools to instill environmentally-friendly values in the younger generations and deepen the public's commitment to environmental protection.

5.2 Managerial Implications

Smart waste management presents a good business opportunity for technology providers, as the market has a promising future; however, it is still at a nascent stage. The first movers are likely to gain an advantage by establishing their brands and customer base. However, they must continuously invest in research and development to improve the effectiveness and cost-efficiency of the technologies. This is not just to stimulate market growth, but also to defend market share, as competitors are likely to race for innovation in the rapidly-evolving industry 4.0 landscape. Among the wide variety of industry 4.0 technologies available, there is a need to focus on those which are relatively mature and low-risk, having a favourable price-performance ratio when commercialised into smart waste management systems. To this end, technology providers should conduct a thorough investigation and comparison of relevant industry 4.0 technologies before deciding which one to invest in for the supply chain operations of waste management.

Potential users of smart waste management technologies should be aware of and consider products on the market for improving the supply chain operations of their waste management activities. On one hand, they can evaluate whether some of the existing products suit their operational needs, enabling them to manage waste more sustainably and at the same time be better off financially. On the other hand, they may partner with industry 4.0 technology providers to develop smart waste management solutions that are not available in the market and to overcome their own operational challenges in this area. The resulting solutions may make the user a sustainability leader in the industry, enhancing their brand image and marketing position. Each potential user should analyse the unique trade-offs that they face and the options available, to decide on technology providers' expertise and solutions, or to invest in resources to jointly develop solutions with technology providers.

Non-government organisations (NGOs) may play an important role in driving the implementation of more sustainable and smarter waste management solutions. Given that the business leaders in China are very pragmatic about environmental sustainability, a push from NGOs is likely to win the commitment of some business leaders who otherwise would not be supportive. At present, the public and the media mainly pay attention to the publicly-listed large enterprises. However, NGOs may be able to exert pressure on some small- and medium-sized enterprises as well. An example of a potentially helpful NGO is the Institute of Public and Environmental Affairs (IPE), a non-profit environmental research organisation based in Beijing, China. Since 2006, the IPE has been collecting, collating and analysing government and corporate information to build a database on the environment. By publishing the data free online, the IPE has empowered the public to hold the government and businesses accountable for their environmental performance. The researchers advocate establishment of more NGOs to promote environmental protection, to monitor the government's and businesses'environmental management, and to hold them accountable for their irresponsible actions toward the environment.

6. Conclusions

CE has been increasingly explored as an effective approach to supply chain sustainability. The development of industry 4.0 technologies provides business firms with an opportunity to upgrade their supply chain operations in line with CE, especially the waste management operations. Our study focuses on the drivers of industry 4.0-enabled smart waste management in supply chain, providing an initial insight from the perspective of waste management on the interplay between CE and industry 4.0.

We used a mixed-methods approach in this study, including semi-structured interviews and the fuzzy DEMATEL technique. We found 11 key drivers of the implementation of smart waste management in supply chain operations. We analysed the causal effects of these 11 key drivers based on data from different supply chain actors. We found that the fundamental causal driver is the effectiveness of industry 4.0 technologies for improving operational performance in supply chain waste management (D4 and D5). Interestingly, we found a virtuous cycle between market demand (D7) and increasing price-performance ratio of industry 4.0 technologies (D11), indicating interrelationships between the drivers. Other important causal drivers include regulatory pressure (D8) and top management's environmental values (D10).

Our study makes three contributions. First, we complement the existing literature on smart waste management by exploring the drivers at the supply chain level, thereby adding insights on the integration of industry 4.0 in the context of CE. Waste management is an original area in CE and, most likely, the initial step in any CE implementation (Govindan & Hasanagic, 2018; Su et al., 2013). The previous studies on smart waste management mostly focused on the meso- and macro- levels, which is likely to be in line with the widely-used top-down approach to CE adoption (Geng & Doberstein, 2008; Geng et al., 2012). In contrast, our study explored a bottom-up approach to industry 4.0 technologies-driven CE implementation. Business firms are a major force for waste generation, innovation and use of industry 4.0 technologies (Fatorachian & Kazemi, 2018; Ghisellini et al., 2016). The "micro-level" drivers of smart waste management found in our study draw from the business firms' perspective to add an increment of understanding about the interplay between industry 4.0 and CE. Also, our focus on smart waste management in supply chain operations covers a more complete flow of waste generation. Because our findings are from the supply chain perspective, they are more likely to maximise the adoption and value of smart waste management. Second, we found causal effects among the drivers, showing a clear roadmap to adopting smart waste management. These causal effects illuminate the prioritisation of the fundamental driving forces and the adoption process. For example, technology providers and policy makers should primarily focus on presenting the explicit improvement in supply chain operational performance to be gained through smart waste management. Understanding these causal effects shows ways to improve effectiveness and efficiency in the adoption and propagation of industry 4.0-driven CE practices. Third, our study focuses on Chinese firms. China is a leading country in CE adoption (Masi et al., 2018). Our findings, therefore, provide timely guidance for Chinese firms as they consider and compare business risks and government policies and explore new business opportunities. In addition, our analyses is relevant to the CE context in China at the macro- and micro-level (e.g., constraints of government regulations and top management commitment) and, furthermore, to other emerging markets (e.g., India [Mangla et al., 2018a] and United Arab Emirates [Thornton et al., 2013]). Emerging economies are more likely to share sustainability practices with each other than with non-emerging economies (Yadav et al., 2019). The similar development patterns of CE imply the applicability of our findings in the broad range of emerging markets. In particular, China is a leading emerging country that has implemented CE at the national level for over ten years (Geng et al., 2012). Our study based on Chinese firms is more likely to provide practical and confirmatory results for other emerging economies which are waiting to follow CE adoption.

Although this study was based on careful and rigorous analysis, there are inevitable trade-offs and limitations. Also, some avenues of future research may be derived. The novelty of applying smart waste management in supply chains constrained the sample size in DEMATEL analyses and meant that the findings had to be of an exploratory nature. Future research can build on this study to include a broader scope in the supply chain operations of smart waste management (e.g., logistics service providers). This research focuses on waste management, while production, consumption and other areas are also important in the structure of CE practices in China (Su et al., 2013). It would be interesting to study how these drivers of smart waste management could contribute to implementations in other areas in CE practice (e.g., production and consumption). The interaction of drivers across different areas of industry 4.0-enabled CE would provide a holistic framework for building sustainable supply chains. Also, future research can explore the drivers of smart waste management in the context of developed countries (e.g., Germany) and provide comparative analyses with those reported in our research. The CE infrastructure of developed countries is substantially different from that of emerging economies (Yadav et al., 2019). Study of common and contrasting drivers in emerging and industrialised countries could inform a dynamic structure which is applicable for business firms operating across different market environments (e.g., multi-national firms).

Acknowledgements

The authors would like to acknowledge partial financial support from the National Natural Science Foundation of China (51875251), 2018 Guangzhou Innovation Leading Talent Program(China)(201909010006), Blue Fire Project (Huizhou) Industry-University-Research Joint Innovation Fund of the Ministry of Education (China) (CXZJHZ201722), and the Fundamental Research Funds for the Central Universities (11618401).

Annexure 1 – Interview Protocol

1. Is your organisation involved in the practice of smart waste management?
2. If yes, what type of equipment/systems are available? List out the Industry 4.0 technologies employed and describe them.

3. Can you please give some examples of how the technologies are used?

4. If applicable, what were the important factors that drove the implementation of smart waste management in your supply chain operations?

5. If applicable, what are the factors that push your organisation to continuously improve a smart waste management system?

Annexure 2 – Profile of research participants in the first stage

Participant Number	Industry sector	Designation	Years of experiences
n1	Manufacturing (smart waste equipment/systems)	Vice-general manager	15
n2	Manufacturing (smart waste equipment/systems)	Administrative specialist	4
n3	Logistics	General manager	18
n4	Government	Secretary of the community Party committee	31
n5	Healthcare	secretary	6
n6	Property development and construction	Administrative director	5
n7	Manufacturing	Chief human resource officer	12
n8	Manufacturing	Chairman of the Workers' Union	20
n9	Manufacturing	Engineer	10
n10	Manufacturing	Security and Environmental Management Director	11
n11	Manufacturing	General manager	15
n12	Manufacturing	Sales director	30
n13	Manufacturing	Executive	30
n14	Manufacturing	Secretary	5

Annexure 3 – Profile of research participants in the second stage

Participant Number	Industry sector	Designation	Years of experiences
p1	Manufacturing (smart waste equipment/systems)	Vice-general manager	15
p2	Property development and construction	Buyer	5
p3	Government	Government administrator	10

References

Aazam, M., St-Hilaire, M., Lung, C. H., & Lambadaris, I. (2016, October). Cloud-based smart waste management for smart cities. In *2016 IEEE 21st International Workshop on Computer Aided Modelling and Design of Communication Links and Networks (CAMAD)* (pp. 188-193). IEEE.

Anagnostopoulos, T., Zaslavsky, A., Kolomvatsos, K., Medvedev, A., Amirian, P., Morley, J., & Hadjieftymiades, S. (2017). Challenges and Opportunities of Waste Management in IoT-Enabled Smart Cities: A Survey. IEEE Transactions on Sustainable Computing, 2(3), 275–289. https://doi.org/10.1109/TSUSC.2017.2691049

Batista, L., Bourlakis, M., Smart, P., & Maull, R. (2018a). In search of a circular supply chain archetype – a content-analysis-based literature review. Production Planning & Control, 29(6), 438–451. https://doi.org/10.1080/09537287.2017.1343502

Batista, L., Bourlakis, M., Liu, Y., Smart, P., & Sohal, A. (2018b). Supply chain operations for a circular economy. Production Planning & Control, 29(6), 419–424. https://doi.org/10.1080/09537287.2018.1449267

Bell E., Bryman A., & Harley B. (2018). Business Research Methods. 5th Edition. UK: Oxford University Press.

Binder, C. R., Quirici, R., Domnitcheva, S., & Stäubli, B. (2008). Smart Labels for Waste and Resource Management. Journal of Industrial Ecology, 12(2), 207–228. https://doi.org/10.1111/j.1530-9290.2008.00016.x

Bodamer, D. (2017, June 26). The waste and recycling industry and the Internet of Things. Waste 360. Retrieved from https://www.waste360.com/fleets-technology/waste-and-recycling-industry-and-internet-things

Catania, V., & Ventura, D. (2014). An approch for monitoring and smart planning of urban solid waste management using smart-M3 platform. In Proceedings of 15th Conference of Open Innovations Association FRUCT (pp. 24–31). St. Petersburg, Russia: IEEE. https://doi.org/10.1109/FRUCT.2014.6872422

Chen, X., Pang, J., Zhang, Z., & Li, H. (2014). Sustainability assessment of solid waste management in China: a decoupling and decomposition analysis. *Sustainability*, *6*(12), 9268-9281.

Chi, X., Streicher-Porte, M., Wang, M. Y. L., & Reuter, M. A. (2011). Informal electronic waste recycling: A sector review with special focus on China. Waste Management, 31(4), 731–742. https://doi.org/10.1016/j.wasman.2010.11.006.

Chowdhury, B., & Chowdhury, M. U. (2007). RFID-based real-time smart waste management system. In 2007 Australasian Telecommunication Networks and Applications Conference (pp. 175–180). Christchurch, New Zealand: IEEE. https://doi.org/10.1109/ATNAC.2007.4665232

Deitz, G., Hansen, J., & Richey, R. G. (2009). Coerced integration: The effects of retailer supply chain technology mandates on supplier stock returns. International Journal of

Physical Distribution & Logistics Management, 39(10), 814–825. https://doi.org/10.1108/09600030911011423

de Sousa Jabbour, A. B. L., Chiappetta Jabbour, C. J., Godinho Filho, M., & Roubaud, D. (2018). Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. Annals of Operations Research, 270(1–2), 273–286. https://doi.org/10.1007/s10479-018-2772-8.

Duong, L. N. K., Wood, L. C., Wang, J. X., & Wang, W. Y. C. (2017). Transport on-demand in a service supply chain experiencing seasonal demand: Managing persistent backlogs. International Journal of Operations Research, 14(3), 121–138.

Eccles, R. G., Ioannou, I., & Serafeim, G. (2014). The Impact of Corporate Sustainability on Organisational Processes and Performance. Management Science, 60(11), 2835–2857.

Esmaeilian, B., Wang, B., Lewis, K., Duarte, F., Ratti, C., & Behdad, S. (2018). The future of waste management in smart and sustainable cities: A review and concept paper. *Waste management*, *81*, 177-195.

Farooque, M., Zhang, A., Thurer, M., Qu, T., Huisingh, D., 2019a. Circular supply chain management: A definition and structured literature review. *Journal of Cleaner Production*, 228, 882-900.

Farooque, M., Zhang, A. & Liu, Y. (2019b). Barriers to circular food supply chains in China. *Supply Chain Management: An International Journal*, 24(5), 677-696. https://doi.org/10.1108/SCM-10-2018-0345

Fatorachian, H., & Kazemi, H. (2018). A critical investigation of Industry 4.0 in manufacturing: theoretical operationalisation framework. Production Planning & Control, 29(8), 633–644. https://doi.org/10.1080/09537287.2018.1424960

Flammer, C. (2013). Corporate Social Responsibility and Shareholder Reaction: The Environmental Awareness of Investors. Academy of Management Journal, 56(3), 758–781.

Folianto, F., Low, Y. S., & Yeow, W. L. (2015, April). Smartbin: Smart waste management system. In *2015 IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)* (pp. 1-2). IEEE.

Fu, X., Zhu, Q. and Sarkis, J. 2012. Evaluating green supplier development programs at a telecommunications systems provider. International Journal of Production Economics, 140, 357-367.

Gaur, J., Mani, V., Banerjee, P., Amini, M., & Gupta, R. (2019). Towards building circular economy: a cross-cultural study of consumers' purchase intentions for reconstructed products. *Management Decision*, *57*(4), 886-903.

Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. C. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. Omega, 66, 344–357. https://doi.org/10.1016/j.omega.2015.05.015

Gentles, S. J., Charles, C., Ploeg, J., & McKibbon, K. (2015). Sampling in Qualitative Research: Insights from an Overview of the Methods Literature. The Qualitative Report, 20(11), 1772-1789.

Geng, Y., & Doberstein, B. (2008). Developing the circular economy in China: Challenges and opportunities for achieving "leapfrog development." International Journal of Sustainable Development & World Ecology, 15(3), 231–239. https://doi.org/10.3843/SusDev.15.3:6

Geng, Y., Zhu, Q., Doberstein, B., & Fujita, T. (2009). Implementing China's circular economy concept at the regional level: A review of progress in Dalian, China. *Waste Management*, *29*(2), 996-1002.

Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: an evaluation and critical analysis. Journal of Cleaner Production, 23(1), 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Giunipero, L. C., Hooker, R. E., & Denslow, D. (2012). Purchasing and supply management sustainability: Drivers and barriers. Journal of Purchasing and Supply Management, 18(4), 258–269. https://doi.org/10.1016/j.pursup.2012.06.003

Glouche, Y., & Couderc, P. (2013). A Smart Waste Management with Self-Describing objects. Presented at the Second International Conference on Smart Systems, Devices and Technologies (SMART'13), Rome, Italy.

Gölcük, İ. & Baykasoğlu, A. (2016). An analysis of DEMATEL approaches for criteria interaction handling within ANP. *Expert Systems with Applications*, 46, 346–366.

Govindan, K., Diabat, A. and Madan Shankar, K. (2015). Analyzing the drivers of green manufacturing with fuzzy approach. Journal of Cleaner Production, 96, 182-193.

Govindan, K. & Chaudhuri, A. (2016). Interrelationships of risks faced by third-party logistics service providers: A DEMATEL based approach. *Transportation Research Part E: Logistics and Transportation Review*, 90, 177–195.

Govindan, K., & Hasanagic, M. (2018). A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. International Journal of Production Research, 56(1–2), 278–311. https://doi.org/10.1080/00207543.2017.1402141.

Gu, B., Wang, H., Chen, Z., Jiang, S., Zhu, W., Liu, M., ... & Yang, J. (2015). Characterization, quantification and management of household solid waste: A case study in China. *Resources, Conservation and Recycling*, *98*, 67-75.

Gutierreza, J. M. Jensenb, M., Heniusa, M. and Riazc, T. (2015). Smart waste collection system based on location intelligence. Procedia Computer Science, 61, 120-127.

Hazen, B. T., Mollenkopf, D. A., & Wang, Y. (2017). Remanufacturing for the Circular Economy: An Examination of Consumer Switching Behavior. Business Strategy and the Environment, 26(4), 451–464. https://doi.org/10.1002/bse.1929

Hobson, K. (2016). Closing the loop or squaring the circle? Locating generative spaces for the circular economy. Progress in Human Geography, 40(1), 88–104. https://doi.org/10.1177/0309132514566342.

Hong, I., Park, S., Lee, B., Lee, J., Jeong, D., & Park, S. (2014). IoT-based smart garbage system for efficient food waste management. *The Scientific World Journal*, Volume 2014, 1-14

Hsu, C.-C., Choon Tan, K., Hanim Mohamad Zailani, S. and Jayaraman, V. 2013. Supply chain drivers that foster the development of green initiatives in an emerging economy. International Journal of Operations & Production Management, 33, 656-688.

Huang, G. Q., Zhang, A. & Liu, X. (2013). A supply chain configuration model for reassessing global manufacturing in China. Journal of Manufacturing Technology Management, 24(5), 669-687.

Jensen, J. P., & Remmen, A. (2017). Enabling Circular Economy Through Product Stewardship. Procedia Manufacturing, 8, 377–384. https://doi.org/10.1016/j.promfg.2017.02.048

Kang, H. S., Lee, J. Y., Choi, S., Kim, H., Park, J. H., Son, J. Y., … Noh, S. D. (2016). Smart manufacturing: Past research, present findings, and future directions. International Journal of Precision Engineering and Manufacturing-Green Technology, 3(1), 111–128. https://doi.org/10.1007/s40684-016-0015-5

Kansara, R., Bhojani, P., & Chauhan, J. (2019). Smart Waste Management for Segregating Different Types of Wastes. In *Data Management, Analytics and Innovation* (pp. 33-46). Springer, Singapore.

Kumar, S., Smith, S. R., Fowler, G., Velis, C., Kumar, S. J., Arya, S.,& Cheeseman, C. (2017). Challenges and opportunities associated with waste management in India. *Royal society open science*, *4*(3), 160764.

Li, W. and W. Lin (2016), 'Circular Economy Policies in China', in Anbumozhi, V. and J. Kim (eds.), Towards a Circular Economy: Corporate Management and Policy Pathways. ERIA Research Project Report 2014-44, Jakarta: ERIA, pp.95-111.

Lin, R.-J. (2013). Using fuzzy DEMATEL to evaluate the green supply chain management practices. Journal of Cleaner Production, 40, 32-39.

Liqiang, Huo (2019), 10 urban areas to pilot China's 'no-waste city' plan, Retrieved from http://english.gov.cn/policies/policy_watch/2019/01/28/content_281476498146346.htm

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters, 3, 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001.

Lu, J. W., Chang, N. B., Liao, L., & Liao, M. Y. (2015). Smart and green urban solid waste collection systems: advances, challenges, and perspectives. *IEEE Systems Journal*, *11*(4), 2804-2817.

Luthra, S., & Mangla, S. K. (2018a). Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. *Process Safety and Environmental Protection*, *117*, 168-179.

Luthra, S., Mangla, S. K., Shankar, R., Prakash Garg, C., & Jakhar, S. (2018b). Modelling critical success factors for sustainability initiatives in supply chains in Indian context using Grey-DEMATEL. *Production Planning & Control*, *29*(9), 705-728.

Malinauskaite, J., Jouhara, H., Czajczyńska, D., Stanchev, P., Katsou, E., Rostkowski, P., ... & Anguilano, L. (2017). Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. *Energy*, *141*, 2013-2044.

Mangan, J. and Lalwani, C. (2016). Global logistics and supply chain management. (3rd ed.). John Wiley& Sons, Ltd.

Mangla, S. K., Luthra, S., Mishra, N., Singh, A., Rana, N. P., Dora, M., & Dwivedi, Y. (2018a). Barriers to effective circular supply chain management in a developing country context. Production Planning & Control, 29(6), 551–569. https://doi.org/10.1080/09537287.2018.1449265

Mangla, S. K., Bhattacharya, A, & Luthra, S. (2018b). Call for papers: The management of operations achieving sustainability in supply chain operations in the interplay between Circular Economy and Industry 4.0. Production Planning & Control. Retrived from https://www.tandfonline.com/toc/tppc20/current

Masi, D., Kumar, V., Garza-Reyes, J. A., & Godsell, J. (2018). Towards a more circular economy: exploring the awareness, practices, and barriers from a focal firm perspective. Production Planning & Control, 29(6), 539–550. https://doi.org/10.1080/09537287.2018.1449246

Mathews, J. A. and Tan, H. 2016. Circular economy: Lessons from China. Nature, 531, 440-2.

Omar, M. F., Termizi, A. A. A., Zainal, D., Wahap, N. A., Ismail, N. M., & Ahmad, N. (2016). Implementation of spatial smart waste management system in malaysia. IOP Conference Series: Earth and Environmental Science, 37, 012059. https://doi.org/10.1088/1755-1315/37/1/012059.

Pan, S. Y., Du, M. A., Huang, I. T., Liu, I. H., Chang, E. E., & Chiang, P. C. (2015). Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. *Journal of Cleaner Production, 108*, 409-421.

Pardini, K., Rodrigues, J., Kozlov, S., Kumar, N., & Furtado, V. (2019). IoT-Based Solid Waste Management Solutions: A Survey. *Journal of Sensor and Actuator Networks*, *8*(1), 1-25.

Park, J., Sarkis, J., & Wu, Z. (2010). Creating integrated business and environmental value within the context of China's circular economy and ecological modernization. Journal of Cleaner Production, 18(15), 1494–1501. https://doi.org/10.1016/j.jclepro.2010.06.001.

Ranta, V., Aarikka-Stenroos, L., Ritala, P., & Mäkinen, S. J. (2018). Exploring institutional drivers and barriers of the circular economy: a cross-regional comparison of China, the US, and Europe. *Resources, Conservation and Recycling, 135*, 70-82.

Ramya, E., & Sasikumar, R. (2017, February). A survey of smart environment conservation and protection for waste management. In *2017 Third International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)* (pp. 242-245). IEEE.

Ramasami, K., & Velumani, B. (2016, December). Location prediction for solid waste management—A Genetic algorithmic approach. In *2016 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC)*(pp. 1-5). IEEE.

Sadef, Y., Nizami, A. S., Batool, S. A., Chaudary, M. N., Ouda, O. K. M., Asam, Z. Z., & Demirbas, A. (2016). Waste-to-energy and recycling value for developing integrated solid waste management plan in Lahore. *Energy Sources, Part B: Economics, Planning, and Policy*, *11*(7), 569-579.

Saha, H. N., Auddy, S., Pal, S., Kumar, S., Pandey, S., Singh, R., & Saha, S. (2017, August). Waste management using Internet of Things (IoT). In *2017 8th annual industrial automation and electromechanical engineering conference (IEMECON)* (pp. 359-363). IEEE.

Singh, J., & Ordoñez, I. (2016). Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. *Journal of Cleaner Production*, *134*, 342-353.

Shao, J., Taisch, M. & Ortega-Mier, M. (2016). A grey-Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis on the barriers between environmentally friendly products and consumers: practitioners' viewpoints on the European automobile industry. *Journal of Cleaner Production*, 112, 3185–3194.

Sroufe, R. (2003). Effects of Environmental Management Systems on Environmental Management Practices and Operations. Production and Operations Management, 12(3), 416–431. https://doi.org/10.1111/j.1937-5956.2003.tb00212.x

Su, B., Heshmati, A., Geng, Y., & Yu, X. (2013). A review of the circular economy in China: moving from rhetoric to implementation. Journal of Cleaner Production, 42, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020

Shyam, G. K., Manvi, S. S., & Bharti, P. (2017). Smart waste management using Internet-of-Things (IoT). In 2017 2nd International Conference on Computing and Communications Technologies (ICCCT) (pp. 199–203). https://doi.org/10.1109/ICCCT2.2017.7972276

Si, S.-L., You, X.-Y., Liu, H.-C., & Zhang, P. 2018. DEMATEL technique: A systematic review of the state-of-the-art literature on methodologies and applications. Mathematical Problems in Engineering, 2018, https://www.hindawi.com/journals/mpe/2018/3696457/

Tang, C. S. (2018). Socially responsible supply chains in emerging markets: Some research opportunities. Journal of Operations Management, 57, 1–10. https://doi.org/10.1016/j.jom.2018.01.002

The Ellen MacArthur Foundation. (2013). Towards the circular economy. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

Thakker, S., & Narayanamoorthi, R. (2015, March). Smart and wireless waste management. In *2015 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)* (pp. 1-4). IEEE.

Thornton, L. M., Autry, C. W., Gligor, D. M., & Brik, A. B. (2013). Does socially responsible supplier selection pay off for customer firms? A cross-cultural comparison. Journal of Supply Chain Management; Wheat Ridge, 49(3), 66–89.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British journal of management*, *14*(3), 207-222.

Veleva, V., Bodkin, G., & Todorova, S. (2017). The need for better measurement and employee engagement to advance a circular economy: Lessons from Biogen's "zero waste" journey. Journal of Cleaner Production, 154, 517–529. https://doi.org/10.1016/j.jclepro.2017.03.177

Venkatesh, V. G., Zhang, A., Luthra, S., Dubey, R., Subramanian, N. & Mangla, S. (2017). Barriers to coastal shipping development: An Indian perspective. Transportation Research Part D: Transport and Environment, 52, 362-378.

Walker, H., Di Sisto, L. and Mcbain, D. 2008. Drivers and barriers to environmental supply chain management practices: Lessons from the public and private sectors. Journal of Purchasing and Supply Management, 14, 69-85.

Wahab, M. H. A., Kadir, A. A., Tomari, M. R., & Jabbar, M. H. (2014, October). Smart recycle bin: a conceptual approach of smart waste management with integrated web based system. In *2014 International Conference on IT Convergence and Security (ICITCS)* (pp. 1-4). IEEE.

Wen, Z., Wang, Y., & De Clercq, D. (2016). What is the true value of food waste? A case study of technology integration in urban food waste treatment in Suzhou City, China. Journal of Cleaner Production, 118, 88–96. https://doi.org/10.1016/j.jclepro.2015.12.087

Wu, W.-W., & Lee, Y.-T. (2007). Developing global managers' competencies using the fuzzy DEMATEL method. Expert Systems with Applications, 32(2), 499–507. https://doi.org/10.1016/j.eswa.2005.12.005

Xu, R., 2017. Technologies enable rubbish source separation in a residential community for beautiful homes and environment, Mandarin Pages. Mandarin Pages, Auckland.

Yadav, G., & Desai, T. N. (2016). Lean Six Sigma: a categorized review of the literature. *International Journal of Lean Six Sigma*, *7*(1), 2-24.

Yadav, G., Mangla, S. K., Luthra, S., & Jakhar, S. (2018). Hybrid BWM-ELECTRE-based decision framework for effective offshore outsourcing adoption: a case study. *International Journal of Production Research*, *56*(18), 6259-6278.

Yadav, G., Mangla, S. K., Luthra, S., & Rai, D. P. (2019). Developing a sustainable smart city framework for developing economies: An Indian context. Sustainable Cities and Society, 47, 101462. https://doi.org/10.1016/j.scs.2019.101462

Yong, R. (2007). The circular economy in China. Journal of Material Cycles and Waste Management, 9(2), 121–129. https://doi.org/10.1007/s10163-007-0183-z

Zhang, A & Huang, G. Q. (2012). Impacts of business environment changes on global manufacturing outsourcing in China. Supply Chain Management: An International Journal, 17 (2), 138-151.

Zhang, A., Huang, G. Q. & Liu, X. (2012). Impacts of business environment changes on global manufacturing in the Chinese Greater Pearl River Delta: a supply chain perspective. Applied Economics, 44(34), 4505-4514.

Zhu, Q., Sarkis, J. and Lai, K.-H. 2014. Supply chain-based barriers for truck-engine remanufacturing in China. Transportation Research Part E: Logistics and Transportation Review, 68, 103-117.

Table 1. Recent developments in smart waste management

Author (s) & year	**Major contribution in smart management**
Anganostopoulous et al. (2017)	Dynamic waste management model using sensors, RFID, and actuators
Saha et al. (2017)	Integrated web-based solution called smartbox, which optimises waste collection
Lu et al. (2017)	New bin scheduling algorithm using multi-restricted and multi-compartmental routing problem
Ramya et al. (2017)	Smart bin solutions
Aazam et al. (2016)	Cloud-based smart waste management monitoring system for all stakeholders
Ramasami et al. (2016)	Location decision algorithm to select suitable land for the landfill construction
Thakker et al. (2015)	Container screening system using near-infrared spectroscopy (NIR) to alert about the problems of dumps that are not cleaned on time.
Folionto et al. (2015)	Intelligent monitoring system
Wahab et al. (2014)	Smart system of trash recycling

Table 2. Total relation matrix from the technology provider's perspective

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
D1	0.104	0.094	0.053	0.075	0.134	0.146	0.148	0.050	0.126	0.096	0.062
D2	0.218	0.050	0.038	0.077	0.056	0.089	0.134	0.032	0.049	0.050	0.043
D3	**0.278**	0.155	0.067	0.157	0.117	0.172	0.180	0.055	0.104	0.109	0.100
D4	**0.260**	0.167	0.173	0.100	0.161	0.176	0.189	0.058	0.081	0.110	0.146
D5	0.200	0.182	0.127	0.148	0.077	0.113	0.127	0.070	0.064	0.069	0.133
D6	0.228	0.122	0.106	0.176	0.109	0.122	0.254	0.135	0.161	0.176	0.098
D7	**0.298**	0.171	0.109	0.176	0.175	0.188	0.131	0.093	0.120	0.164	0.158
D8	**0.249**	0.120	0.127	0.200	0.197	0.171	0.206	0.083	0.209	**0.256**	0.216
D9	**0.244**	0.139	0.124	0.196	0.188	0.237	0.171	0.149	0.110	**0.252**	0.177
D10	0.204	0.137	0.158	0.193	0.181	**0.230**	0.167	0.145	0.200	0.118	0.172
D11	0.206	0.154	0.094	0.156	0.154	0.123	0.170	0.078	0.097	0.105	0.076

Table 3. Total relation matrix from the private sector technology user's perspective

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
D1	0.239	**0.327**	0.270	0.187	0.304	0.254	0.208	0.121	0.152	0.203	0.236
D2	0.296	0.188	0.234	0.195	0.240	0.253	0.148	0.108	0.126	0.138	0.143
D3	0.245	0.267	0.152	0.185	0.223	0.209	0.136	0.074	0.117	0.126	0.130
D4	0.276	0.269	0.277	0.138	0.280	0.230	0.193	0.110	0.133	0.143	0.148
D5	**0.377**	**0.369**	**0.340**	0.229	0.218	0.263	0.214	0.124	0.151	0.166	0.172
D6	0.279	0.203	0.181	0.144	0.224	0.137	0.174	0.140	0.120	0.132	0.137
D7	0.256	0.250	0.191	0.156	0.233	0.177	0.114	0.103	0.170	0.178	0.180
D8	**0.383**	**0.377**	**0.317**	0.237	0.289	0.230	0.151	0.097	0.155	0.209	0.215
D9	0.140	0.136	0.124	0.103	0.126	0.115	0.095	0.074	0.061	0.093	0.095
D10	**0.325**	0.312	0.287	0.270	**0.324**	0.300	0.224	0.132	0.234	0.145	0.216
D11	**0.349**	**0.340**	0.314	0.237	0.289	0.269	0.180	0.127	0.199	0.241	0.147

Table 4. Total relation matrix from the public sector technology user’s perspective

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
D1	0.243	0.259	0.263	0.154	0.135	0.221	0.381	0.260	0.295	0.365	0.350
D2	0.348	0.174	0.243	0.179	0.094	0.160	0.251	0.224	0.226	0.332	0.287
D3	0.333	0.216	0.193	0.151	0.107	0.193	0.345	0.294	0.289	0.357	0.376
D4	0.347	0.320	0.292	0.147	0.190	0.250	0.387	0.332	0.329	**0.407**	0.390
D5	0.270	0.222	0.225	0.157	0.107	0.301	0.349	0.304	0.301	0.366	0.352
D6	0.378	0.290	0.293	0.212	0.121	0.214	0.353	0.329	0.358	**0.401**	0.386
D7	0.178	0.144	0.146	0.097	0.146	0.252	0.182	0.242	0.240	0.261	0.252
D8	0.150	0.120	0.123	0.083	0.094	0.228	0.220	0.148	0.211	0.192	0.224
D9	0.288	0.239	0.245	0.119	0.122	0.245	0.296	0.309	0.210	0.310	0.300
D10	**0.422**	0.357	0.330	0.175	0.148	0.289	0.366	0.367	**0.402**	0.317	0.334
D11	0.378	0.290	0.324	0.245	0.149	0.284	0.360	0.361	0.294	**0.406**	0.295

Annexure 2 – Profile of research participants in the first stage

Participant Number	Industry sector	Designation	Years of experiences
n1	Manufacturing (smart waste equipment/systems)	Vice-general manager	15
n2	Manufacturing (smart waste equipment/systems)	Administrative specialist	4
n3	Logistics	General manager	18
n4	Government	Secretary of the community Party committee	31
n5	Healthcare	secretary	6
n6	Property development and construction	Administrative director	5
n7	Manufacturing	Chief human resource officer	12
n8	Manufacturing	Chairman of the Workers' Union	20
n9	Manufacturing	Engineer	10
n10	Manufacturing	Security and Environmental Management Director	11
n11	Manufacturing	General manager	15
n12	Manufacturing	Sales director	30
n13	Manufacturing	Executive	30
n14	Manufacturing	Secretary	5

Annexure 3 – Profile of research participants in the second stage

Participant Number	Industry sector	Designation	Years of experiences
p1	Manufacturing (smart waste equipment/systems)	Vice-general manager	15
p2	Property development and construction	Buyer	5
p3	Government	Government administrator	10

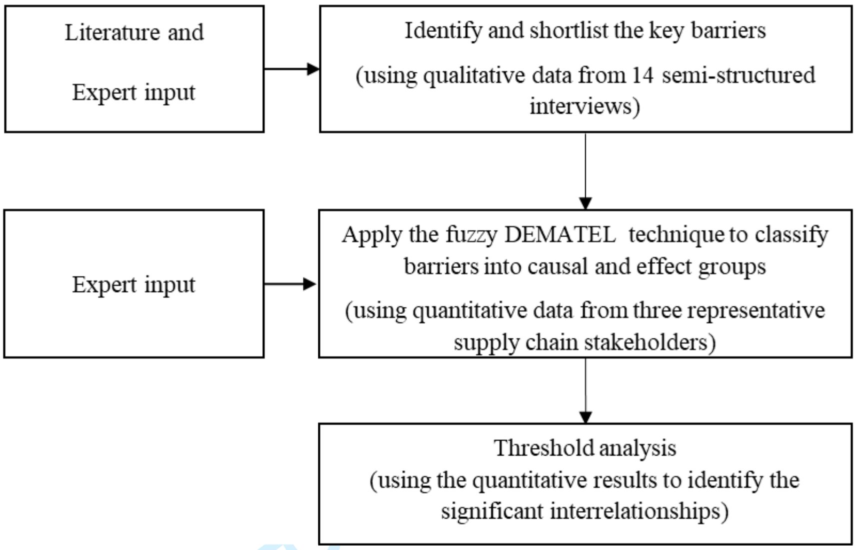
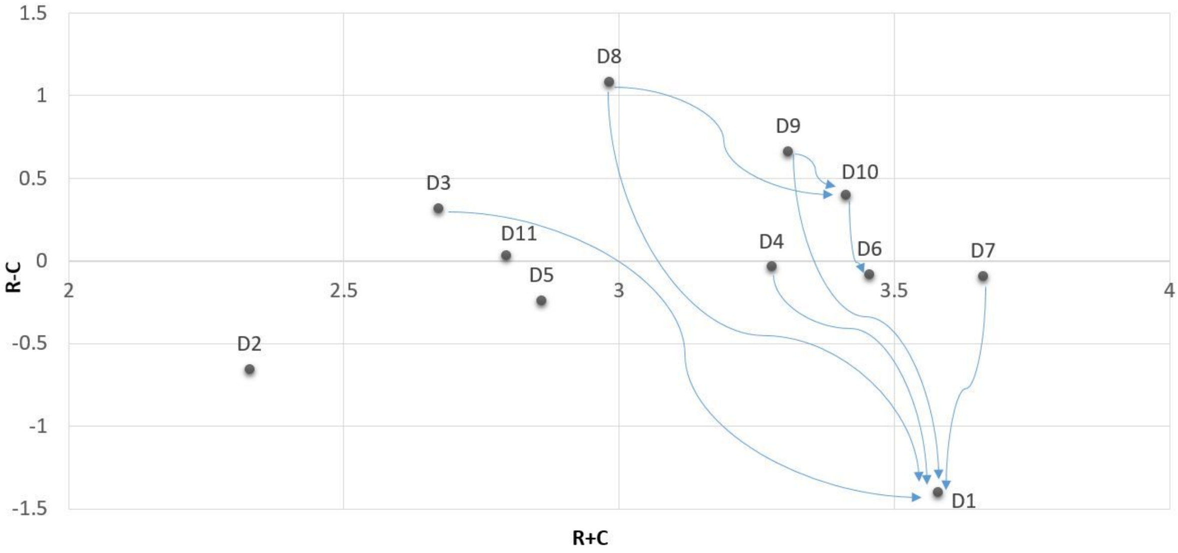
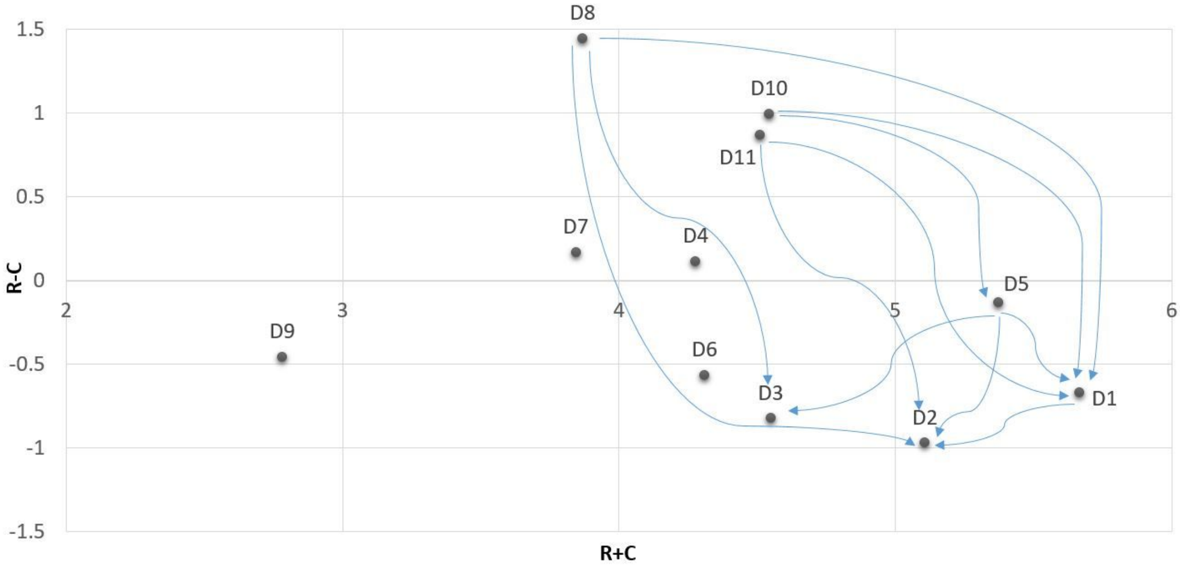


Figure 1. Research Framework



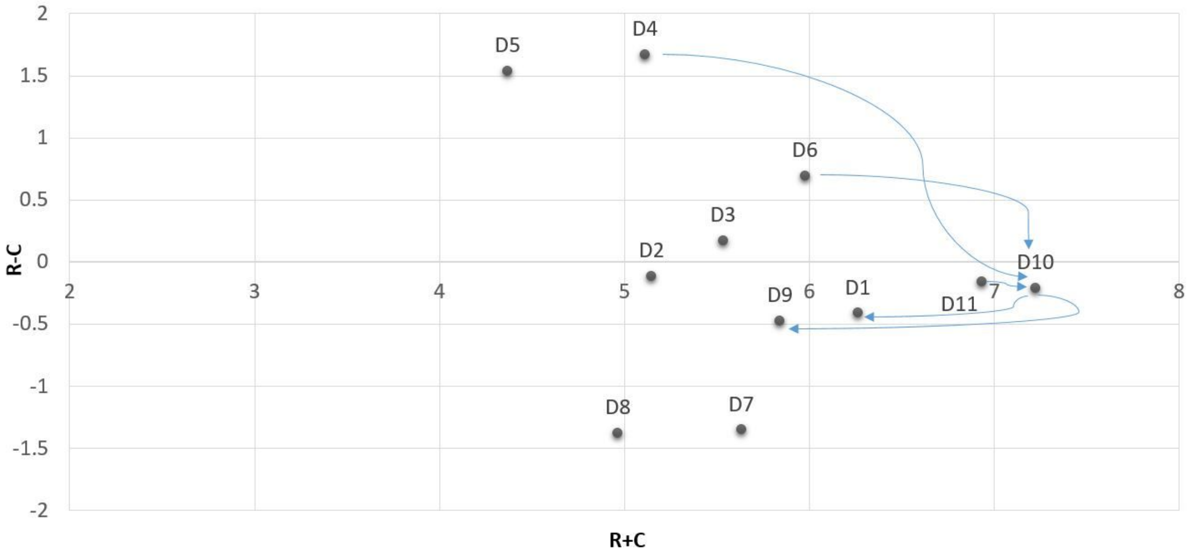
Significant relationships: D3-D1, D4-D1, D7-D1, D8-D1, D8-D10, D9-D1, D9-D10, D10-D6

Figure 2. DEMATEL prominence-causal relationship diagram from the technology provider's perspective



Significant relationships: D1-D2, D5-D1, D5-D2, D5-D3, D8-D1, D8-D2, D8-D3, D10-D1, D10-D5, D11-D1, D11-D2

Figure 3. DEMATEL prominence-causal relationship diagram from the private sector technology user’s perspective



Significant relationships: D4-D10, D6-D10, D10-D1, D10-D9, D11-D10

Figure 4. DEMATEL prominence-causal relationship diagram from the public sector technology user’s perspective