Municipal solid waste management technological barriers: A hierarchical structure approach in Taiwan

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Abstract

The ecosystem of digital technologies in Industry 4.0 is growing continuously, new data and information sources integration rising has carried notable value in waste management transitions with various technological barriers remains. The municipal solid waste management technological attributes are illustrated by qualitative information, and it is hard to form the consistent interdependence hierarchical structure under interrelationships. This study applies the fuzzy Delphi method to obtain the valid attributes. Fuzzy decision-making trial and evaluation laboratory is to envisage the interrelationships among the attributes. The analytic network process is to test the consistency among the hierarchical structures. The results provide an insight of municipal solid waste management technological barriers in Taiwan. The cyber-physical limitations, artificial intelligence application challenges, and human interface problems as cause aspects. In practices, (1) inadequate public data, (2) robotic process automation limitations, and (3) lack of predictive and emergency assistance, hinders the municipal solid waste management technological improvement.

Keywords*:* Municipal solid waste management; technological barriers; Industry 4.0; sustainable municipal; fuzzy decision-making trial and evaluation laboratory; Analytical network process

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1. Introduction

Industry 4.0 (I4.0) plays an important role in carrying sustainable urban commodities by integrating in the municipal solid waste management (MSWM) framework (Kanojia & Visvanathan, 2021; Khan et al., 2022). As the ecosystem of digital technologies and instruments are growing continuously, and a rising petition to integrate and accomplish new data and information sources has carried noteworthy deviations in value and waste management transitions (Chen et al., 2018). Fatimah et al., (2020) proposed that reaching sustainability in MSWM is more possible, efficient, reliable, optimum, and transparent via the internet-of-things (IoT) and information communication implementation in the I4.0 revolution era. Cohen & Gil (2021) argued that data-driven, smart and intelligent, or digitalization techniques regards are escalating how municipal waste and resources are managed. However, the MSWM has been deal with various technological barriers remains to urban planners and practical engineers that requires serious attention by municipalities in achieving sustainable and smart performance (Abuga & Raghava, 2021; Onoda, 2020). This study aims to explore those MSWM technological barriers under I4.0 practices by which satisfactory achievement of a new smart and sustainable municipal management.

In Taiwan, MSWM is an elemental component of cities' sustainability concerning processing commotions, adaptableness, and the multiplicity of waste from generating source to treatment, and disposal stage (Fatimah et al., 2020). Taiwan has been implementing many MSWM practices due to a high-density population that massively upsurges the amount of solid waste. The municipalities and its local waste management administration have worked together to form a concomitant and effectual waste management network that perseveres the cities' sustainable standards. Certainly, it has achieved noteworthy successes, as the Taiwan was able to manage and capture 99.98% of waste, and the retrieval ratios touched to 53.5% in 2020 (Taiwan Environmental Protection Administration, 2020). However, as the increasing of waste disposal cost, the Taiwan's MSWM has reached it constrains regarding to the efficiency of waste diminishment and resource reutilization practices (Sung et al., 2020). Despite the well-practices in waste management, the waste is increasing, the MSWM infrastructure is continuously in heavy compression, and treatment and disposal charges have raised over the past years. The current technologies are getting to be expired and reaching their frontiers, and many of them confront either crave for maintenance or an end-of-life (Bui and Tseng, 2022). To detect MSWM opportunities and engage in sustainability, proper shifting in technological planning is important, and the accomplishment of I4.0 is a potential mid- and long-term direction; and the barriers on progressing and utilizing knowledge of I4.0 into the MSWM craves for being emphasized, since waste management data are inadequate or incoherent, the progress incline unstable. Further, public information management and security also presents exclusive social, ethical, lawful, confidentiality, and safety confronts that need to be tackled before factual deviations are attained (Chauhan et al., 2021). Therefore, in-depth investigation is essential to ensure the

MSWM move towards I4.0 properly, and create a risk-free environment of resource dissolve and society collapse, where MSWM are kept from being vulnerable.

I4.0 deploys the fundamental information technologies development via the cyber-physical systems, big data, Internet of Things (IoT), artificial intelligence, along with how human interacts to such technologies (Foresti et al., 2020; Roblek et al., 2020; Huang & Koroteev, 2021; Bui and Tseng, 2022). The waste management has used these technologies to capture, transmission, utilized such information to communication, testing and experiments, to enhance the operations capabilities and achieve efficient performance (Hannan et al., 2015; Esmaeilian et al., 2018; Cohen & Gil, 2021). Unforeseen coincidences are evaded, and reliability and safety are increased. For example, Fukuyama (2018) argued that the big data helps to forecast the outcomes of waste transportation laying down, or precisely evaluate the policies or pilot experiments on MSWM. Sharma et al. (2020) suggested the IoT is a driver of smart cities' transformation to form an advance waste management structure, conveyance, and to achieve better human life. Chauhan et al. (2021) and Kanojia & Visvanathan (2021) claimed that the cyber-physical systems imply integration and connection between physical and virtual to accomplish the predefined purposes. Mooney (2018) and Huang & Koroteev (2021) declared artificial intelligence allow authorities to run complex waste management system intelligently by determining the most optimal solutions. Further, Foresti et al. (2020) advocated human–machine interface activities support preparation in the MSWM preceding continuance, hence, reducing instructing costs, improving productivity, and create a human-machine interaction for smart supervisor design. However, so far, Taiwan's MSWM has not given any crucial employment and efficiently manipulate I4.0 technologies. Such technologies bear impending jeopardies, such as data privacy problems, cyber-attacks, liability concerns, enlarged maintenance and expenses, and augmented communal discrimination (Bui and Tseng, 2022). Although I4.0 is partially supporting MSWM, the processing protocols and standards to provide comprehensive structuring as well as a holistic digitalization processes still unclear due to not all the challenges and barriers on I4.0 practices are fully addressed (Cohen& Gil, 2021). Therefore, indicate the judicious barriers for the enhancement of MSWM performance and practical improvement in the I4.0 context is necessary.

An effective MSWM needs to integrate the entire waste management system and fit in complete operationalize related procedures (Marshall and Farahbakhsh, 2013; Batista et al., 2021; Khan et al., 2022). Fukuyama (2018) argued that cities should access big data to construct cyberspace architecture. Chen et al. (2021) highlighted the artificial intelligence, IoT need to be integrated to build and manage intelligent data systems to guarantee security and safety of smart waste management infrastructure. Mavrodieva & Shaw (2020) envisaged cyber-physical spaces for a more precise data since then improve the problem-solving ability and value foundation. however, this requires an excessive time and human wealth to transform the complex data into easy-to-use information to humans (Foresti et al., 2020). The human-machine interface should be concerned and customized to ensure effective arrangement, reduce the failures jeopardy; thus, reduce the aberrations and foster the waste elimination (Foresti et al., 2020; Batista et al., 2021). Yet, there is still various uncertain technological challenges with unobservable inter-relationship among the MSWM, causing multicollinearity hitches related to Taiwan's MSWM implementation due to the rapid apprehensions of wellness and sustainability objectives (Asefi et al., 2020; Nguyen et al., 2020). As an emergent matter for addressing the growing MSWM challenges, understanding the inter-relationship among I4.0 integrated barriers in MSWM will make better conceptual alignment in improving the practical performance. In sum, the objectives are as follow.

- To acquire a valid MSWM barrier set under I4.0 practices;
- To detect the causal inter-relationships inside the MSWM hierarchical structure under uncertainties;
- To indicate the judicious barrier obstructing Taiwan's MSWM under I4.0 practices.

Given the many interrelated attributes in decision-making difficulties, the use of multi-criteria decision-making tools is an ordinary appropriate. Since there is a vagueness and uncertainty in evaluators' linguistic references, A hybrid method, combining the fuzzy Delphi method (FDM), a fuzzy decision-making trial and evaluation laboratory (DEMATEL) and the analytic network process (ANP), is applied to acquire valid hierarchical structure and detect the causal inter-relationships among the measured barriers. The FDM are employed to refine the valid structural barriers stemmed from the literature (Tsai et al., 2021). The fuzzy DEMATEL is utilized to identify the causal inter-relationships within MSWM attributes (aspect and barriers) by forming the evaluators' perceptions (Tseng et al., 2018a). The ANP is to confirm the consistency among the hierarchical structures by assessing inter-dependencies among the attributes (Bui et al., 2020a).

This study helps MSWM decision-makers, municipals stakeholders, policy-makers, and government to empathize the noteworthy of I4.0 practices in MSWM implementation. Both theory and practice fields are contributed: (1) a valid MSWM technological barriers set under I4.0 practices is acquired to encompass the understanding of MSWM in the literature; (2) the barriers' causal inter-relationships are identified, and the dependent consistency among the barriers are shown to improve the MSWM structural network; and (3) critical barriers for the managerial enhancement in the I4.0 practices are identified supporting the practical MSWM implementation in Taiwan.

The residue of this study is excessed in 5 sections. The next section discusses the MSWM and I4.0 related literature, the applied method, and the MSWM technological barriers under I4.0 practices for measurement. The Taiwan MSWM case background and applied methods are described in the third section. The fourth and the fifth sections disclose the results and deliver theoretical and managerial implications. The last section covers this study's conclusion, contributions, limitations and suggestions for future works.

2. Literature review

This section discusses the MSWM and I4.0 associated literature, the proposed method, and the MSWM technological barriers under I4.0 practices for measurement.

2.1. Municipal solid waste management

Municipal solid waste (MSW) includes number of waste types, such as food, plastics, paper, textiles, glass, and metals; and the volume of deviates waste generation and characteristics is various from viewpoints, politic and legislation stratagems, the different economic views to (Burnley, 2007). The waste sources in mainly from industrialization, population growth, household incomes raise changing consumption precedents and preferences (Abuga & Raghava, 2021). The waste reflects the culture that creates it and has an undesirable and harmful effect on the social health and environment (Rana, 2017; Khan et al., 2022). MSWM is a complex system exaggerated by many aspects that vigorously influence each other and impossible to be described by taking a solitary and inert standpoint (Di Nola et al., 2018; Sharma et al., 2018; Bui et al., 2020a). Nguyen et al. (2020) argued that the MSW, its creation proportion and configuration, bearing not only on the appropriate management strategies, but also on the obtainability of operational technologies. Franchina et al. (2021) highlighted that cities authorities and the local waste management organizations should work together to form a strong and effective MSWM system to carry on sustainable standards. Therefore, understanding the composition of MSWM system is important for advancing the practical accomplishment on management decision.

The MSW generated amount has rapidly increased, and the waste substance is more complicated, as plastic and electronic waste spread, causes thrilling pressures for MSWM organizations and place a burden on municipals to appropriately handle those waste on both environmental and social level (Khan et al., 2022). How to effectively manage solid waste has become a fundamental challenge for the cities. Fatimah et al. (2020) proposed that the smartness of MSWM offers better decision-making guidelines and politic provisions, optimum technologies, proper treatment tools, to progress resources and waste management. This requires a complete scheme of new technologies to be settled and installed to helps achieving sustainable development goals (Cohen & Gil, 2021). However, the technological inadequacy has limited the operating determination as the economic constrains require to create more output with less input (Yeh, 2020). For example, Sharma et al. (2020) disclosed that the absence of directions, policy norms and regulations in internet standardization and connectivity are hindering the waste management practices in the city. Khan et al. (2022) criticized for barriers on developing scientific base, problems in implementation, and failure in cogitating local factors in choosing MSWM technologies appropriately and desirably. Thus, a MSWM resolution should be adaptable, replicable, and ascendable; while cities require pioneering, cross-industry function to enable MSWM practices.

Atzori et al. (2010) stated that city planning for information and data model possible to constantly control cities facilities such as transportation, energy distribution, and waste management is obligatory. Chauhan et al. (2021) claims a digital apparatus is needed to pick up the feedback, suggestions, and complaints on the public issues to better provide MSWM guidelines. Franchina et al. (2021) argued that to understand how the MSWM is integrate, a comprehend record of waste collection and treatment network in connection of product lifecycle inside the city is important. Thus, the involvement of I4.0 practice in MSWM is substantial to make a smart waste management system for the residents as well as for environmental well-beings.

2.2. Industry 4.0

I4.0 is a multiplex technological architype including tentative revolutions and integration between physical and digital worlds via cyber-physical structures (Tseng et al., 2021). The concept is known as smart, intelligent, digitalization, and data-driven regarding to operation management. Ghobakhloo (2020) proposed digitization of I4.0 enables the organizations to cutdown the waste and cost convolution, attain sustainable energy consumption throughout operational procedures, reduce faults, increase the transportation speed. The core of I4.0 advancements is information quality in addition to databases standards, which needs to be captured through appropriately technological applications (Chauhan et al., 2021; Cohen & Gil, 2021). Tabaa et al. (2020) and Tseng et al (2021) proposed the I4.0 revolutions aim to occupation new digital technologies that considers digital transformation is the crucial component of all activities. This execution cultivates smart structures and automated procedures with logical and systematic abilities by self-directed incorporating information technologies to acquire a unified, complex and intelligent practical network, which entails knowledge from various fields with deep interconnectedness among each other (Ayala et al., 2017; Onu and Mbohwa, 2021).

I4.0 plays substantial role in fostering the MSWM to achieve future urban sustainability. Digitization procedures, for instance, big-data, IoT, and data dispensation, are essential to achieve the sustainable development goals by improving waste and resource management (Tseng et al., 2018b). Cohen & Gil (2021) emphasized the IoT and innovative computational tools are magnifying how municipal waste and resources are managed. Pereira et al. (2017) and Chauhan et al. (2021) underlined the need of comprehensive tactic of smart technology's application as positioning platform and mobile appliances as the coin of I4.0 in building a waste management system in city region. The I4.0 have given way to improve resource utilization, solving material criticality and resource insufficiency problems, or release local authorities from financial burden (Huang et al. 2018). As the digital instruments and techniques continues to raise, there are needs to systematic integrate and manage them efficiently. However, how to precisely implement the concept endures challenges.

Although I4.0 allows organizations to interchange information, self-reliantly manage and accomplish activities themselves; there are still gaps for the practical model use due to various transition implementing barriers (Huang & Koroteev, 2021; Kanojia & Visvanathan, 2021). Foresti et al. (2020) argued there is need to have suitable technologies to align the multi-sectorial incorporation and constant enhancement that the I4.0 is based. Roblek et al. (2020) disputed technology and fiscal progress are intimately connected to the transition of city innovation. Thus, MSWM organizations need to consider the system readiness of I4.0 implementation before making a decisive decision. Seeking to design a smart and sustainable MSWM structure with a multi-dimensional maneuver in its technical accomplishment is important (Fatimah et al., 2020). This study investigates the critical MSWM barriers since then provide the fundamental disseminates and opportunities to progress a smart and sustainable MSWM under industry 4.0 practices.

2.3. Proposed method

The literature has emphasized the role of advance I4.0 technologies using various kind of method. Fatimah et al (2020) seek to sustainable circular economy from smart waste management network based on I4.0 using maturity score assessment analysis. Chauhan et al. (2021) used a DEMATEL method to analyze the interplay of healthcare waste disposal and circular economy enabled by I4.0 in smart city. Kanojia & Visvanathan (2021) assessed urban solid waste management interventions and circular economy using I4.0 readiness measurement tool in urban local body robustness. Yet, only few studies consider the complexity and assess the uncertainty of MSWM barriers due to forming proper operative networks problems (Bui et al., 2020b). Sharma et al. (2020) used hybrid of total interpretative structural modeling, fuzzy Matriced'Impacts Croises Multiplication Appliquean Classement, and DEMATEL method to present IoT blockades in smart city waste management. Bui et al. (2020b) identify the major barriers of sustainable solid waste management by applied the FDM approach. Although previous studies have stressed on barriers matters, there are a quantity of matters and uncertainties from both scientific content and measurement process still remain (Mavrodieva & Shaw, 2020). Esmaeilian et al. (2018) stated that concede the potential effects of uncertainties because of decision-making on technological obtainability as complex social-behavioral schemes is important. Batista et al. (2021) indicated that a holistic and interdisciplinary approach is necessary to absolute understand the scenarios issues the give the uncertainties and complexity.

A designed for multiple-attribute modeling under uncertainties to validate the MSWM hierarchical structure and to abridge the multifaceted inter-dependencies among the attributes (aspect and barriers) under interrelationship has not yet been fully addressed (Esmaeilian et al., 2018). This study used a hybrid method that combines the FDM, a fuzzy DEMATEL-ANP to acquire clarify hierarchical structure and detect the causal inter-relationship within the measured barriers. There is a vagueness and uncertainty in evaluators' linguistic references. This study uses FDM to refine the valid barriers stemmed from the literature (Tsai et al., 2021). Next, the inter-relationships among the attributes and the inter-dependent consistency among them are evaluated by involving the virtues inter-relationship of fuzzy DEMATEL and the ANP compensations in handling complex inter-dependencies, so that the link between theoretical philosophy (aspects) and practical incidents (barriers) is clarified. Particularly, the fuzzy DEMATEL is utilized to identify the causal inter-relationships within MSWM attributes by forming the evaluators' perceptions (Tseng et al., 2018a,b). The ANP is to explain the complex inter-dependencies and to confirm the consistency that among attributes in the hierarchical structure (Bui et al., 2020a). Bui et al. (2020a) used this hybrid method to examine the order the attributes grouping considering both inter-relationship and inter-dependence of MSWM capabilities for the operative compensations of sustainable cities. Tsai et al. (2021) assessed the fuzzy DEMATEL-ANP decision matrices using linguistics to show the consistency of a hierarchical sustainable solid waste management model. Given the many inter-related attributes in decision-making problems, the use of this hybrid tool is appropriate.

2.4. Proposed measure for MSWM Technological Barriers under I4.0 Practices

MSWM is an imperative service in the cities, especially with reverence to sustainable development and sustainability (Bui et al., 2020a). With the I4.0 technological transformation, a high level of digitalization is required (Foresti et al., 2020; Khan et al., 2022). Yet, the technological problems in virtual practices, is intensified by numerous opposes faces. The proposed hierarchical structure with 44 barriers composed in 5 aspects including big-data confrontations; cyber-physical limitations; internet-of-thing challenges; artificial intelligence application challenges; human interface problems and is shown in Appendix A.

The massive volumes of data results in big-data confrontations, which has been thrived in recent years (Roblek et al., 2020). Big-data management offers an ascendable construction for inclusive data diligences to tolerate for low dormancy and offline actions in real-time (Chen et al., 2021). To enhance MSWM, urban authorities and municipalities get benefits from cloud computing and big-data procurement along with the smart waste monitoring based on the data-driven decisions to optimize waste management task (Bui et al., 2020a). However, the unceasingly fluctuating in data itself and the diverse in the data wealth can be inaccurate to numerous issues that beyond person's manipulation like a serious failure or crash (Mavrodieva & Shaw, 2020). Data reliability indicates data the defensive in addition to the system, it is constantly restructured and endures every time accessed by the users (Sharma et al., 2020; Farooq et al., 2015). Thus, the public needs to know who manages their data, operates it, and how it is collected and redistributed. Authenticity, confidentiality, privacy, and security from the cyber thread are the challenging factor in management process (Chen et al., 2021). Further, this valuable knowledge will be wasted unless local governments has enough analytical tools and adequate data. The interoperable architecture deficiency, and mismatched technical paradigms are essential barriers for MSWM (Cohen & Gil, 2021). Although the data analytics and IoT are being settled and operated, the data model's multiplicity and absence of data harmonization and compatibility between data arrangements hamper their extensive convention and decreases information conversation throughout city planning.

The technological progressions regard to the cyber-physical systems have been instigated around the world (Chauhan et al., 2021). The aspect envisions a unite of the real world and the cyberspace to proficiently accumulate more detailed in personal data for solving problem and creating value (Mavrodieva & Shaw, 2020). The correlation between physical and cyber space necessitates hardware and software to elaborate and digitalize the ontologies, and enhance the humans-machines interaction. However, the issue is how the municipalities apply the cyberspace infrastructure and how they tackle the technical challenges to construct cyberspace architecture in MSWM (Fukuyama, 2018; Foresti et al., 2020). The cyber–physical space must be efficiently modernized to warrant quality, effectiveness, and sustainability across a user-friendly network, notifications, and data necessity to be constantly obtainable, intimate, and comprehensive to avoid the robotic process automation limitations, and problems in minimization and closed-looping the waste recycling procedure (Foresti et al., 2020). Still, cyberspace can only contribute to municipal structure if there are benefits for public/governmental institutions, private businesses, and citizens. Therefore, guaranteeing cyber-security and safety is urgent; yet, lack of emergency and predictive assistance, assorted concerns and relationships, and unable to do complex computation of the cyber infrastructure and performance has downgraded the identification and operative resource/instrument, hence weakening the power of MSWM organizations in controlling them.

The outline and parallel development of the Internet, or digital economy, has empowered the transformation from the third industrial revolution to the next, named as I4.0 (Roblek et al., 2020). IoT becomes increasingly widespread in wireless communications discipline as it signifies an emerging communication architype where numerous devices exchange data in the same context or act as singular thespians (Keogh et al., 2020). The IoT emphases on the interconnection among devices from an information dispensation viewpoint composed for an extensive network (Tabaa et al., 2020). A smart techniques compile has been anticipated for MSWM to exploit the IoT providing intelligent direction for the revealing of waste gathering, treatment, vigilant and announcement to pertinent institutions, operational costs minimization and data collection (Pardini et al., 2020; Franchina et al., 2021). Yet, the challenges exit making IoT is hard to be implemented in smart MSWM, when it requires piecing communications between the devices and humans together through a synchronized intelligent protocol (Kunst et al., 2018; Delgado et al., 2020). This may consist of a lack of IT infrastructure; inadequate technical knowledge and familiarity among workers or policymakers; internet connectivity, security and privacy problems; absence of guidelines, regulation and policy standardization; or lack of transparency and mobility; and high operational cost and payback; these influences IoT implementation in MSWM practices (Sharma et al., 2020). Therefore, how to acquaint with the existing comprehension about the relationship between the IoT and sustainable MSWM progress need to be criticized (Roblek et al., 2020). This require the IoT obligation to acclimate to the failures and be capable to self-configuration.

AI is a simulation of human intelligence in machines that replicate involuntary to human's mind and formulate their actions, for example, problem solving, learning, and decision-making (Bui and Tseng, 2022). It participates intelligently in processing and analyzing data to warrant better machine-to-machine communication (Tabaa et al., 2020). The AI technology innovation tolerates to initiative improve the capability and efficiency of smart MSWM in the city (Mooney, 2018). It is probable to connect with IoT technologies to develop remote management and automatic procedure of waste treatment systems (Onoda, 2020). The massive amount of data which need inordinate of human resources and time consumption is now analyzed much faster by AI and changed into easy-to-use information that people can use in public services and industry (Mavrodieva & Shaw, 2020). However, current initiatives cannot be continually used as a feat model, the AI information utilization face not only normal operational condition, such as machine break down in an operational procedure, but also insufficient to scope with the human level, and deep-learning fault, which require a restoration intervention with updated data, as well as advance AI algorithm elaboration to ensure a constant system recuperation (Foresti et al., 2020; Chen et al., 2021). Despite its capacity for better performance, the AI in its current stage is not sufficient to replace human control, complementing the waste management facility and computers execution that are not able to handle such complex missions in MSWM (Tabaa et al., 2020).

The human–machine interaction is a management type the autonomous robot objects dedicated to collaborate with human operator in the form of an automated procedure involved in cobotic relations (Tabaa et al., 2020). The aspect improves operative schedule, ensure nonconformity reduction with the notions of waste removal (Foresti et al., 2020). The digitalization results in a technological lifecycle reduction, entailing and adaptable human-machine communication systems for people who are not acquainted and slow catching up with the technological advancement. Due to restrictions such as small physical spaces, lack of the operations management integration; misconnection between cost saving sustainable methods operational and innovative transfers; absence of organizational resources; lack of human intercession, etc.; it is important to make efficient use availability (Keogh et al., 2021). Additionally, there is technical knowledge deficiency among planners, strategic and tactical planning, and inefficient performance measurement standard, evolving in the human issue interacting with informative network (Batista et al., 2021). Therefore, the presence of obstacles for MSWM in human-machine interaction context needs to be addressed.

The proposed hierarchical structure with 44 barriers composed in 5 aspects including big-data confrontations; cyber-physical limitations; internet-of-thing challenges; artificial intelligence application challenges; human interface problems and is shown in Appendix A.

3. Method

This section specifically addresses the background of Taiwan case and method of FDM, fuzzy DEMATEL, and ANP, as well as proposed analytic steps.

3.1. Case background

Taiwan represents a suitable case study to recognize the MSWM implementation benefits, principally among emerging countries. For the past decades, Taiwan's MSWM regarding the waste reduction has been appraised. In 2020, Taiwan has collected 97.42% of the waste, with 55.5% of waste amount was recovered and only 2.58% of it was landfilled (Taiwan Environmental Protection Administration, 2020). This is not only because of the solid waste reduction and resource recovery programs succeeds but also the experiences of rapid industrialization. Although Taiwan's limited waste management competences have been overextended to bulk, especially in industrial fields such as trends in circular economy or industrial symbiosis; yet, the MSWM has been under pressure due to the constrains of current waste handling capability (Bui and Tseng, 2022).

Taiwan, with its desire to transformation from a "garbage island" to a zero-waste, has many advantages as it has sophisticated engineering level and, breakthroughs many technological revolutions. The smart machineries program targets to pull Taiwan's strengths in information technology and machine-making to gain greater priority to burgeon I4.0. The Taiwanese government projected guidelines embrace increasing instruction of resource management, new technological diligences, advanced eco-designs, and environmental ascendency. Integrating Taiwan's developing I4.0 technology into MSWM is seen as an effective way to expand MSWM progress and enhancing the city management performance.

However, the main challenge in achieving a sustainable and smart MSWM in Taiwan is how to develop a holistic system capable to capture all the information from its public, flows of materials/goods, the consumption rotation, and the logistics within the city. Most municipals are lacking of the know-how to implicate smart system. Taiwan's system is complicated, the forecasts of MSWM under the consistent between socio-economic-environment and policy fluctuations necessitate more in-depth examination of latest information. The appropriate prediction of how to handle such MSWM barriers is crucial to long-term strategies. This study aims to explore MSWM barriers which by overcome them may bring new added value and advanced tactical I4.0 mechanisms.

3.2. Data collection

This study assesses experts' linguistic preferences on the critical MSWM barriers under I4.0 practices using the FDM, the fuzzy DEMATEL and ANP method. First, the theoretic contemplation and proposed MSWM aspects and barriers are criticized from the literature of previous studies, authors discussion under experts' consultant. Online interviews are engaged to convey the knowledge and expert systems reliability. Then, questionnaires are provided to collecting the expert linguistic preferences. A board with 30 experts is approached, involving 16 academician and researchers, and 10 practicians from the field, and 6 government officers from related agents, who have experience in working and studying in the MSWM context. The detail of experts is shown in Appendix B

3.3. Fuzzy Delphi method

The FDM is employed to tackle the experts' linguistic preferences (Kaufmann & Gupta, 1988). The linguistic terms are translated into triangular fuzzy numbers (TFNs) (see Table 1). The importance of attribute x is evaluate by the expert y as $h = \left(a_{xy}; b_{xy}; c_{xy}\right)$; $x = 1,2,3, \dots, n$; and $y = 1,2,3, \dots, m$. Accordingly, h_x represent the weight of attribute x and $h_x = (a_x; b_x; c_x)$, where $a_x = min\left(a_{xy}\right)$, $b_x = \left(\prod_1^m b_{xy}\right)^{1/m}$, and $c_x = max\left(c_{xy}\right)$.

The defuzzification is implied with a k cut as follows:

$$u_x = c_x - k(c_x - b_x),\ l_x = a_x - k(b_x - by_x),\ x = 1,2,3, \dots, n \quad (1)$$

The k value is varied between 0 and 1 depend on the expert preference is negative or positive. This study denotes $k = 0.5$ with fairly preference from experts. The convex combination value O_x is compute is then calculated using below equation:

$$O_x = \int(u_x, l_x) = k[u_x + (1 - k)l_x] \quad (2)$$

Formerly, the threshold $\mu = \sum_{x=1}^{n}(O_x/n)$ is formed to determine the valid attributes.

The attribute x is valid when $O_x \geq \mu$. In contrast, it is excluded from the structure.

Table 1. FDM linguistic terms' transformation table

Linguistic terms (performance/importance)	Corresponding TFNs
Extreme	(0.75, 1.0, 1.0)
Demonstrated	(0.5, 0.75, 1.0)
Strong	(0.25, 0.5, 0.75)
Moderate	(0, 0.25, 0.5)
Equal	(0, 0, 0.25)

3.4. Fuzzy Decision-Making Trial and Evaluation Laboratory

The fuzzy DEMATEL method is applied to abridge the complex inter-relationship by translating the linguistic preference of experts into fuzzy values. From the attribute set $X = \{x_1, x_2, x_3, \cdots, x_n\}$, the relationships between each two attributes are illuminated using a pairwise comparison. The linguistic preferences refer from VL (very low influence) to VHI (very high influence) are utilized to assemble the fuzzy direct relation matrix, as shown in Table 2. There are y members in the committee, the i^{th}attribute influences the j^{th} attribute provided by expert y^{th} is refered as the fuzzy weight $\tilde{x}_{ij}^{y}$.

Table 2. Fuzzy DEMATEL linguistic terms' transformation table

Scale	Linguistic variable	Corresponding TFNs
1	No influence	(0.0, 0.1, 0.3)
2	Very low influence	(0.1, 0.3, 0.5)
3	Low influence	(0.3, 0.5, 0.7)
4	High influence	(0.5, 0.7, 0.9)
5	Very high influence	(0.7, 0.9, 1.0)

Then, the fuzzy membership function $\tilde{g}^{y}_{ij} = (\tilde{g}^{y}_{1ij}, \tilde{g}^{y}_{2ij}, \tilde{g}^{y}_{3ij})$ is occupied to aggregate the weighted values. The corresponding fuzzy numbers are converted using below equation:

$$\mathrm{E} = \left(\mathrm{x}\tilde{g}^{y}_{1ij}, \mathrm{x}\tilde{g}^{y}_{2ij}, \mathrm{x}\tilde{g}^{y}_{3ij}\right) = \left[\frac{(g^{y}_{1ij} - \min g^{y}_{1ij})}{\Delta}, \frac{(g^{y}_{2ij} - \min g^{y}_{2ij})}{\Delta}, \frac{(r^{y}_{3ij} - \min g^{y}_{3ij})}{\Delta}\right] \quad (3)$$

where $\Delta = \max g^{y}_{3ij} - \min g^{y}_{1ij}$

The left (lv) and right (rv) values are transformed into normalized values and the total normalized crisp values is are then computed using below equations:

$$\left(\mathrm{lv}^{n}_{ij}, \mathrm{rv}^{n}_{ij}\right) = \left[\frac{(\mathrm{xg}^{y}_{2ij}}{\left(1 + \mathrm{xg}^{y}_{2ij} - \mathrm{xg}^{y}_{1ij}\right)}, \frac{\mathrm{xg}^{y}_{3ij}}{\left(1 + \mathrm{xg}^{y}_{3ij} - \mathrm{xg}^{y}_{2ij}\right)}\right] \quad (4)$$

$$\mathrm{cv}^{k}_{ij} = \frac{[\mathrm{lv}^{y}_{ij}\left(1 - \mathrm{lv}^{y}_{ij}\right) + (\mathrm{rv}^{y}_{ij})^2]}{(1 - \mathrm{lv}^{y}_{ij} + \mathrm{rv}^{y}_{ij})} \quad (5)$$

$$s^{y}_{ij} = ming^{y}_{ij} + cv^{y}_{ij}\Delta^{max}_{min} \quad (6)$$

The individual preference from each expert is calculated by obtaining the synthetic value using below equation:

$$\tilde{g}^{y}_{ij} = \frac{(s^{1}_{ij} + s^{2}_{ij} + s^{3}_{ij} + \cdots + s^{n}_{ij})}{y} \quad (7)$$

An $(n \times n)$ initial direct relation matrix (ID) is acquired as $ID = [\tilde{g}^{y}_{ij}]_{n \times n}$.

Then normalized direct relation matrix (ND) is obtained using below equation:

$$\mathrm{ND} = \alpha \otimes \mathrm{ID}, \quad \alpha = \frac{1}{\max\limits_{1 \le i \le k} \sum_{j=1}^{y} \tilde{g}^{y}_{ij}} \quad (8)$$

The total interrelationship matrix (TR) is computed using below equation:

$$TR = ND(I - ND)^{-1} \quad (9)$$

where TR denotes$[tr_{ij}]_{n \times n}$ $i, j = 1, 2, \cdots n$

Finally, the driving value (α) and the dependent value (β) are formed using below equations:

$$\alpha = [\textstyle\sum_{i}^{n} tr_{ij}]_{n \times n} = [tr_i]_{n \times 1} \quad (10)$$

$$\beta = [\textstyle\sum_{j}^{n} tr_{ij}]_{n \times n} = [tr_j]_{1 \times n} \quad (11)$$

Using $(\alpha + \beta)$ and $(\alpha - \beta)$ as horizontal and vertical axes, a causal inter-relationship diagram is illustrated. Particularly, $(\alpha + \beta)$ specifies the attributes' importance level; the higher value of $(\alpha + \beta)$ given to an attribute, the more important it is. Then, $(\alpha - \beta)$ is to clarify whether the attributes belong to cause or effect groups. If $(\alpha - \beta) > 0$, the attribute fits in the cause group; or else, it is assigned to the affect group.

3.5. Analytic network process

The ANP incorporates the attributes' inter-relationships into a hierarchical super-matrix to aggregate their convergent weights aiming to illustrating the inter-dependence between the aspects and barriers (Saaty, 2001, Bui et al., 2020a). Unlimited super-matrix U is composed from the DEMATEL to acquire the limited weighted super-matrix U^* using the below equation:

$$U^* = \lim_{n\to\infty} U^n \quad (12)$$

3.6. Proposed analysis steps

The proposed analysis steps are as follows (shown in Figure 1):

(1) MSWM barrier set under I4.0 is advocated

(2) The expert preferences on barriers are collected via questionnaire. The FDM is used to refine the barriers and valid the MSWM hierarchical structure. The linguistic preference are interpreted into TFNs and then transformed into precise values using equations (1)-(2).

(3) The fuzzy DEMATEL is adopted to identify the causal inter-relationships within the hierarchical structure and determine the essential barriers obstructing Taiwan's MSWM under I4.0 practices. The crisp values are computed and arranged to initial direct relations using Equation (3)-(7). Then, equations (8)-(11) are used to generate the total interrelation matrix was computed and map the cause-and-effect diagram of the aspects and barriers.

(4) An unlimited super-matrix U is assembled and the limited weighted super-matrix U^* is aggregated through the ANP using Equation (12). The inter-dependency and consistency between the aspects and barriers in the hierarchical structure are verified.

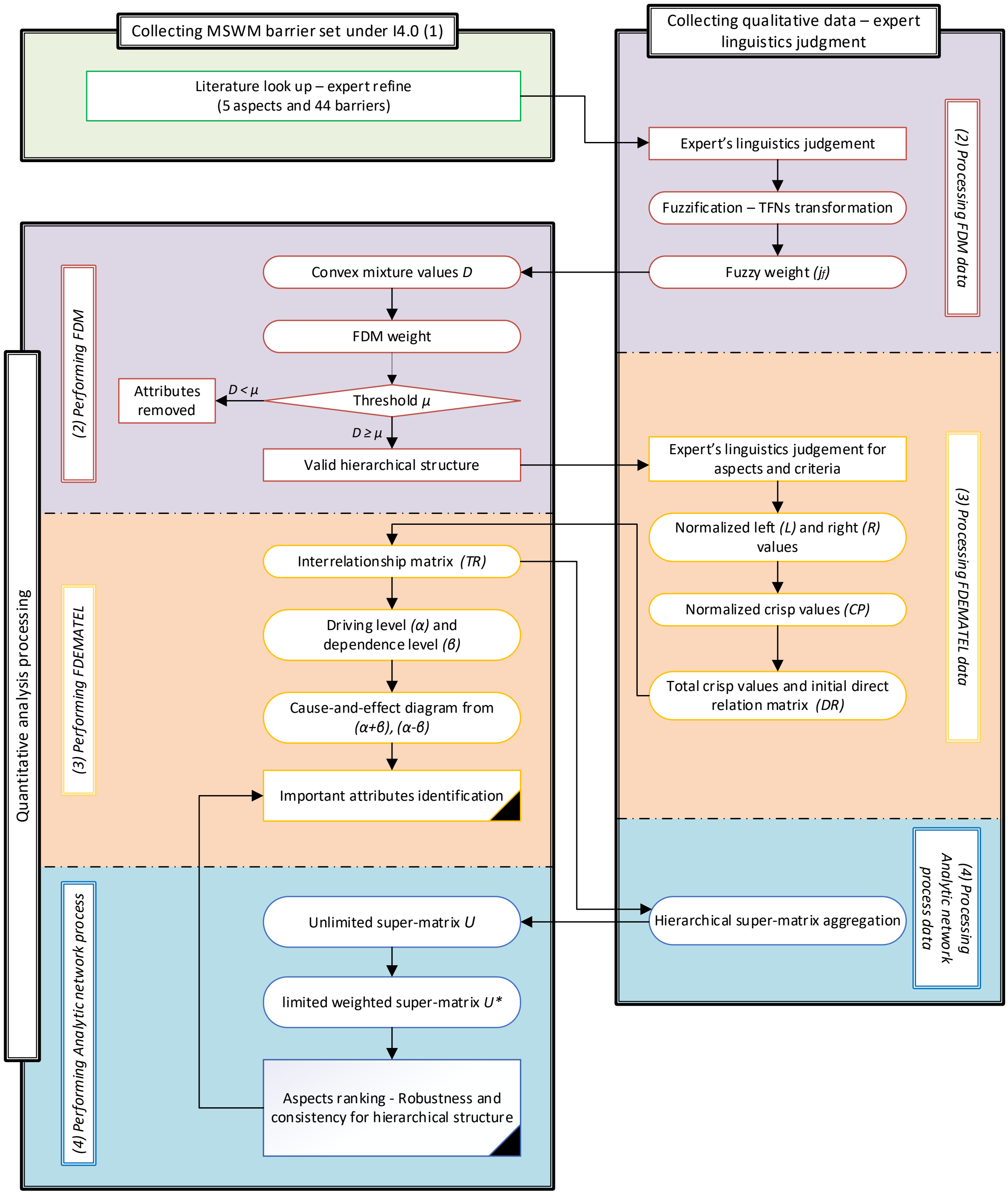

Figure 1. Proposed analysis steps

4. Result

The results of the FDM, fuzzy DEMATEL and ANP method are revealed in this section. A valid MSWM barrier structure under I4.0 practices is formed. The causal inter-relationships within the aspects and the critical barriers from practices are determined.

4.1. Fuzzy Delphi method

There are 5 aspects and 44 barriers are proposed as the initial attributes in this study. During the analysis procedure, the experts' linguistic preferences are converted into corresponding TFNs, as shown in Table 1. Each barrier's FDM weight is computed, the threshold is generated to validate the attributes. The invalid barriers are screen out with the threshold $\mu = 0.311$, as shown in Table 3. The result shows that there are 20 barriers are accepted 25 barriers are detached from the structure. The five aspects still remain and the valid hierarchical structure is shown in Table 4.

Table 3. FDM barriers result

Barriers	l_x	u_x	O_x	Decision
Inhibited by data differences, gaps, contrasts	0.000	0.500	0.250	Unaccepted
Fragmentary data connection	0.000	0.500	0.250	Unaccepted
Absence of data wealth,	0.004	0.871	0.437	Accepted
Lack of international standard in method uses of data	0.000	0.500	0.250	Unaccepted
Limited to information gathering	0.060	0.815	0.422	Accepted
Potential threats on data privacy, cyber threats	(0.388)	0.888	0.347	Accepted
Data curation, storage, and usage	0.000	0.500	0.250	Unaccepted
Inadequate public data	(0.324)	0.824	0.331	Accepted
Inadequate information policies	(0.329)	0.829	0.332	Accepted
Data creators and data custodians' trustworthiness	0.000	0.500	0.250	Unaccepted
Multi-tenancy, security, and data leakage rising.	(0.352)	0.852	0.338	Accepted
Lack of common information system	0.000	0.500	0.250	Unaccepted
Lack of Data availability	0.000	0.500	0.250	Unaccepted
Arbitrariness in the machine usage	0.000	0.500	0.250	Unaccepted
Robotic process automation limitations	(0.009)	0.884	0.440	Accepted
Small physical size	0.000	0.500	0.250	Unaccepted
Incapable of complex computing tasks of the infrastructure and computers performance	0.084	0.791	0.416	Accepted
Inefficiency criticality and risk	0.000	0.500	0.250	Unaccepted
Lack of predictive and emergency assistance	(0.404)	0.904	0.351	Accepted
Low frequencies and work activity for feedback analysis	0.000	0.500	0.250	Unaccepted
Downgrading in identification and operative resource/instrument	(0.333)	0.833	0.333	Accepted
The disruptive innovation crowdfunding and blockchain	0.000	0.500	0.250	Unaccepted
High-tech manufacturing industry for waste recovery.	0.000	0.500	0.250	Unaccepted
Waste minimization and closed loop (remanufacturing, recycling) perspective.	(0.370)	0.870	0.342	Accepted
Technical and managerial capabilities challenges	0.000	0.500	0.250	Unaccepted
Miscellaneous concerns and relationships.	(0.000)	0.875	0.438	Accepted
Side channels that lead towards vulnerabilities.	0.000	0.500	0.250	Unaccepted
Issues of accountability,	0.000	0.500	0.250	Unaccepted
Weak Addressability	0.000	0.500	0.250	Unaccepted
Weak Integrated information processing	(0.007)	0.882	0.439	Accepted
Weak User Interfaces	0.000	0.500	0.250	Unaccepted
Interactions problems	0.000	0.500	0.250	Unaccepted
Internet of Content and Knowledge unexploitation	0.000	0.500	0.250	Unaccepted
Lack of integration among IT networks	(0.383)	0.883	0.346	Accepted
Inadequate internet connectivity	0.000	0.500	0.250	Unaccepted
System failure issues/integrity	(0.359)	0.859	0.340	Accepted
Algorithms lack the ability to learn.	0.000	0.500	0.250	Unaccepted
Insufficient AI to reach the human level,	(0.019)	0.894	0.442	Accepted
Deep-learning breaking down	(0.425)	0.925	0.356	Accepted
Lack of knowledge and uncertainty	0.000	0.500	0.250	Unaccepted
Lack of the integration in operations management	(0.458)	0.958	0.364	Accepted
Transfers of frugal operational innovative methods and low-cost sustainable methods misconnection.	0.003	0.872	0.437	Accepted

Limited skilled workforce	0.000	0.500	0.250	Unaccepted
Lack of technical knowledge among planners	(0.060)	0.935	0.453	Accepted
	Threshold (μ)		0.311	

Table 4. Valid hierarchical structure

Aspects		Barriers	
A1	Big-data confrontations	B1	Absence of data wealth,
		B2	Limited to information gathering
		B3	Potential threats on data privacy, cyber threats
		B4	Inadequate public data
		B5	Inadequate information policies
		B6	Multi-tenancy, security, and data leakage rising.
A2	Cyber-physical limitations	B7	Robotic process automation limitations
		B8	Incapable of complex computing tasks of the infrastructure and computers performance
		B9	Lack of predictive and emergency assistance
		B10	Downgrading in identification and operative resource/instrument
		B11	Waste minimization and closed loop (remanufacturing, recycling) perspective.
		B12	Miscellaneous concerns and relationships.
A3	Internet-of-thing challenges	B13	Weak Integrated information processing
		B14	Lack of integration among IT networks
		B15	System failure issues/integrity
A4	Artificial intelligence application challenges	B16	Insufficient AI to reach the human level,
		B17	Deep-learning breaking down
A5	Human interface problems	B18	Lack of the integration in operations management
		B19	Transfers of frugal operational innovative methods and low-cost sustainable methods misconnection.
		B20	Lack of technical knowledge among planners

4.2. Fuzzy Decision-Making Trial and Evaluation Laboratory

The experts provide their preferences on the aspects' inter-relationships using linguistic scales. The fuzzy direct relation matrix and the defuzzification sequels are formed, shown in Appendix C. The average crisp values from all experts were integrated in an initial direction matrix, shown in Appendix D. The total interrelationship matrix was created showing the causal inter-relationship within the aspects, shown in Appendix 7. Afterward, the cause-and-effect diagram for aspects using $(\alpha + \beta)$ and $(\alpha - \beta)$ as the axes are shown Figure 2. The cyber-physical limitations (A2), artificial intelligence application challenges (A4), and human interface problems (A5) are the cause aspects, whereas the big-data confrontations (A1) and internet-of-thing challenges (A3) belong to effect group. The result shows that artificial intelligence application challenges (A4) is the most critical aspect in MSWM under I4.0 practices. The aspect interacts with the all-other aspects in the structure, it particularly has strong influence to (A1) and (A3), and medium influence to (A5). Followingly, the (A2) also have strong effect to (A1) and medium interaction with the aspect (A3). Along with the (A5), there are 3 cause aspects in MSWM under I4.0 practices.

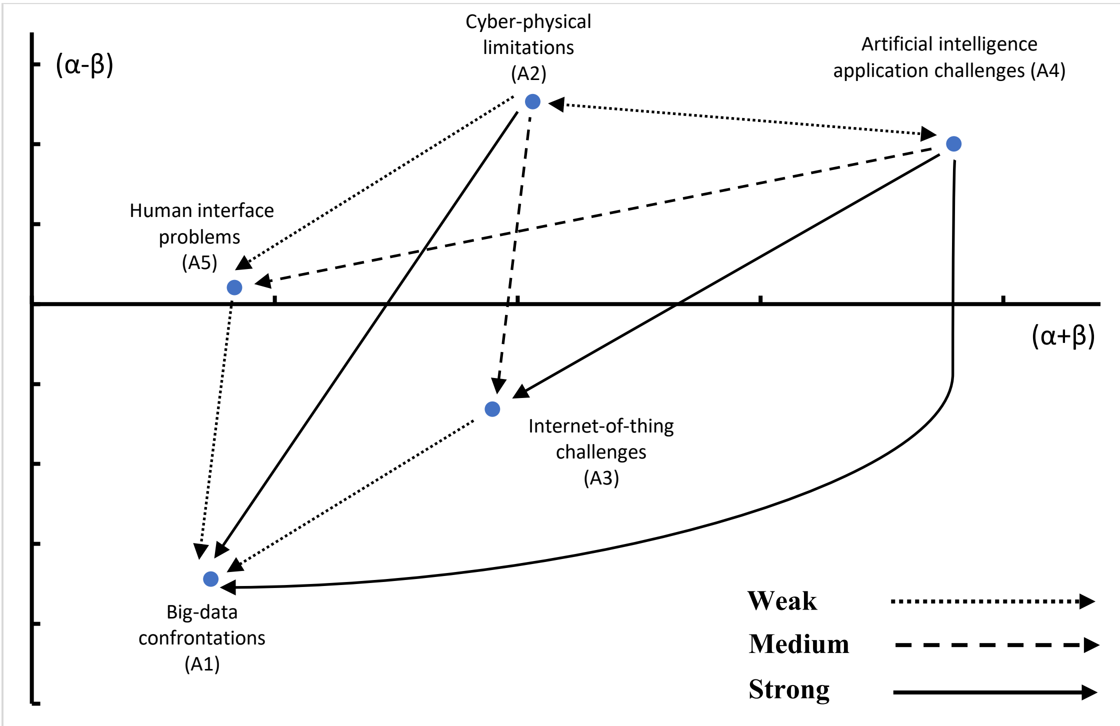

Figure 2. Cause-and-effect diagram for aspects

By recapping the above procedure, the barriers' initial direction matrix and total interrelationship matrix were generated respectively, shown in Appendix F and G. the cause-and-effect inter-relationships among the barriers is computed, shown in Appendix H. The cause-and-effect diagram for barriers is mapped, shown in Figure 3. The result shows that B1-B3, B6, B10, B12, B14, B17, B18 are affected barriers; and the cause barriers is B4, B5, B7-B9, B11, B13, B15, B16, B19, and B20. The top critical barriers obstructing practices are determined including inadequate public data (B4), robotic process automation limitations (B7), lack of predictive and emergency assistance (B9), insufficient AI to reach the human level (B16), lack of technical knowledge among planners (B20)

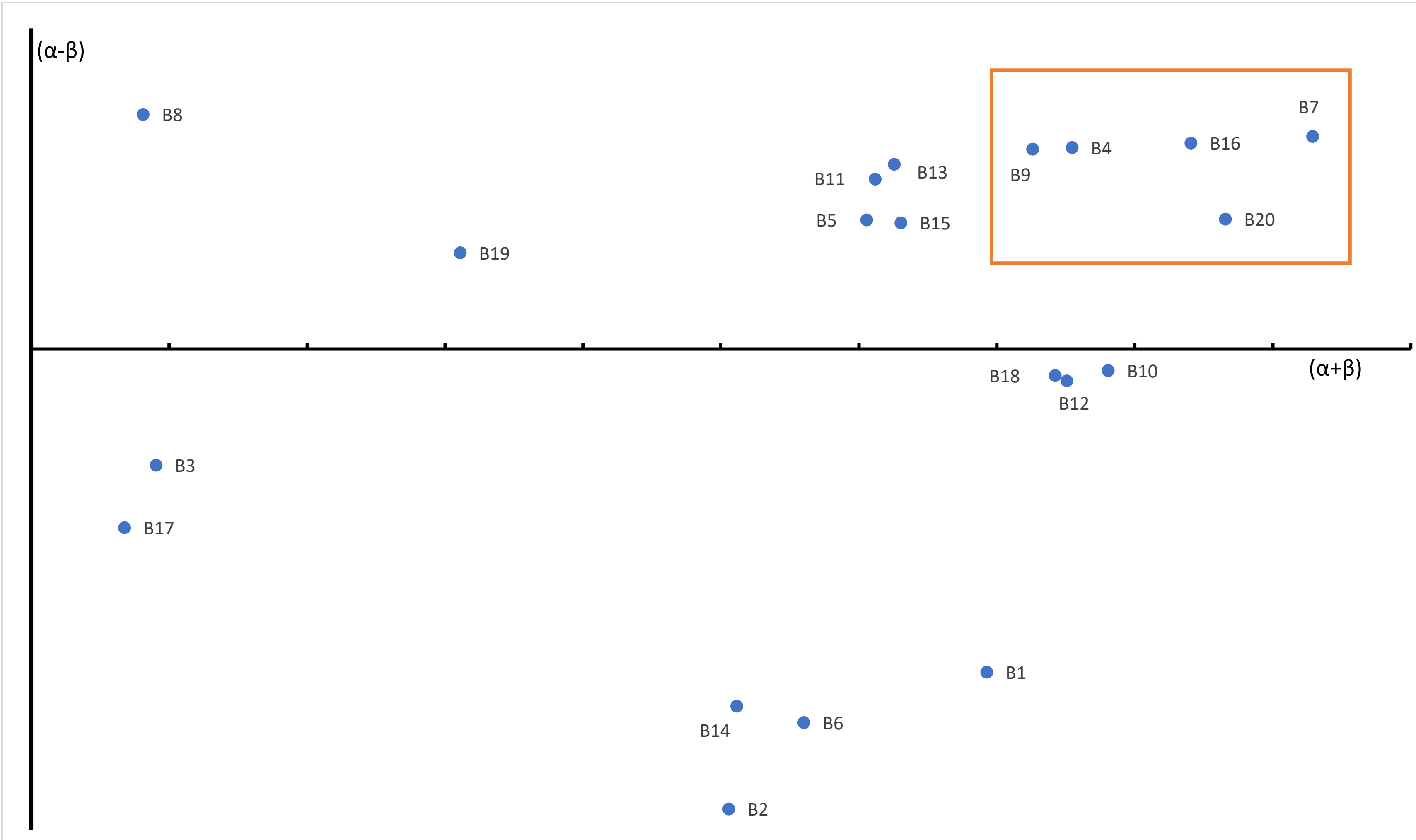

Figure 3. Cause-and-effect diagram for barriers

4.3. Analytic network process

The aspects and barriers' total inter-relationship value were incorporated into the unlimited super-matrix, shown in Appendix I, as the ack inter-dependence between aspects and barriers in the hierarchical structure. The convergent limited super-matrix was aggregated to show the aspect and barriers weight ranking, shown in Appendix J. The results illustrate that the ranking from top to the bottom for each cause or effected area consisting with the important value $(\gamma + \delta)$ of each aspect from the fuzzy DEMATEL result. The cause area, the three causing aspects are placed as artificial intelligence application challenges (A4) $>$ cyber-physical limitations (A2) $>$ human interface problems (A5) as rank number one to three in the ANP results. Followingly, the effected aspects are ranked in the fourth and fifth places as internet-of-thing challenges (A3) $>$ big-data confrontations (A1). Further, the top 5 critical barriers identified in the fuzzy DEMATEL analysis are also rank as number one to five according to the ANP result. This procedure dispatched the consistency of between aspects and criteria during the analysis process and confirmed the validity and reliability of the hierarchical structure.

5. Implications

The section delivers theoretical and managerial implications.

5.1. Theoretical implication

This study identified the cyber-physical limitations, artificial intelligence application challenges, and human interface problems as cause aspects that have fundamental obstruction in implementing I4.0 practices in MSWM.

I4.0 carries a merger of physical and digital ecospheres through cyber-physical networks done by implying connection and integration among physical and virtual elements (Chauhan et al., 2021; Kanojia & Visvanathan, 2021; Khan et al., 2022). The cyber-physical networks integrally facilitate the data from different devices into one system, reduces the cost and time for MSW dispensation, detailing, and commentary. The waste can be inevitably referred to specific handlers based on the waste feature and reduce the transportation time. The use of IoT sensors on waste sorting and measurement, the automatic monitoring waste needles and actuators, and monitoring environment standard can enable cyber-physical level in the waste management system (Onoda, 2020). Yet, the municipalities, which want to operate the cyberspace applications must confront the technical challenges in MSWM (Fukuyama, 2018; Foresti et al., 2020). Inclusive scrutiny for potential cyber-physical networks implementation, since then improve the problem-solving ability and value foundation for the purposed waste management system must be noticed (Mavrodieva & Shaw, 2020). Envisaged cyber-physical spaces for a more precise data, cyber security regarding physical safety and social well-being, and a minor magnitude to finances and human resource is needed. Therefore, moral and ethical issue sequel as political needs for appropriate legal tool to forestall of future impacts of cyber-physical systems developments, such as linked with intelligent robotics schemes or IoT is urgent. There should be a boundary drawn between public, municipal authorities and private sector as the limit applicability for policy- and decision-making. On the other, building an affordable cyber-physical systems service, the conceivable digital division between those using and those not using cyber-physical networks, become crucial to fostering information sharing and preventing data concentration and make cyber-physical networks in MSWM become realistic.

The technological application in the MSWM is preceding to high mechanize and complexity; requiring intelligent systems, which are able to obtain engineering tactics (Foresti et al., 2020). AI is efficient on solving mismatch difficulties, studying from fault event, and tackling incomplete and uncertain data. The AI tolerate municipalities to intelligently operate composite MSWM system by determining the most optimal solutions, thus, brings benefits to the entire ecosystem and cut down burden for city system (Mavrodieva & Shaw, 2020; Huang & Koroteev, 2021). For example, AI driven by machine learning and IoT sensor device can accurate mainframe data of training vision or help to organize different types of waste. Using AI with the robotic implementation for smart recycling can do the reprocessing exclusion and reduces a risk of diseases and high injury for humans (Chen et al., 2021). Yet, it is difficult to employ that a lot technical expertise without disrupting operations. AI for MSWM cannot be instigated fractally but needs to develop with an entire information technological ecosystem with strong interaction architectures to communicate easily in order to build reliable information system for better management and decision making (Tabaa et al., 2020). At the same time, the platform for real-time supervisory and assessment to optimize artificial logic and interactive operational processes should be updated to help the city develops intelligent waste collection, sorting, and treatment (Fatimah, 2020). Nevertheless, the artificial intelligence is potentially hacked resulting in technical faults and safety problems, the technology providers and developers crave to guarantee that the AI is cyber secure, and there is need for constant maintenance and progress to warrant this. Though the AI use might involve some contemplations such as cybersecurity, technological maturity, and investment costs, yet, if properly implemented this technology can bring actual positive outcomes.

The I4.0 technology can deliver better management efficient to MSWM system than humans and can effectively replace humans in time-consuming activities. Employees in waste management field involvement a higher infection and injury rate, together with occupational hazards, than other industry (Khan et al., 2022). The AI, IoT, physical devices interconnect over the digital platform offer comfort to human beings thanks to their intelligence, as well as reducing human errors and interventions (Abuga & Raghava, 2021). However, while increasing technological automation as smart MSWM techniques, the recognition of human factors and the human interaction level is correspondingly crucial. Integrated MSWM necessitates the presence of human providers, generators, data and information, thus, forming communication linkages between the machine and humans intelligently can certify efficient procedure, decrease the collapses threat; thus, cut the irregularities and promote the waste removal (Hannan et al., 2015; Esmaeilian et al., 2018; Foresti et al., 2020). Human–machine interface activities promotion helps the MSWM preceding run smoothly, therefore, reduce costs, improving productivity (Batista et al., 2021). To promote the human–machine interface, a smart human resource management system needs to be developed and connected with positions that are affected from the MSWM treatment, along with new job design, or redesign to adapted with the technology innovation. It is essential to ensure human resource teaching and training to reduce the dynamic and uncertain risk from technological transition problems. Job redesign should be involving changing work duties and responsibilities, and harmonize with the structural design within organization. Both law system and tool for resolving social conflicts between the human and machine should be form to guarantee the employee benefits, human right, while also foster the technology establishment. Additionally, the importance of human's experience and skills in collaborative with the MSWM advance infrastructure should be emphasized along with artificial learning abilities to support human work by offering accuracy, safety, force, comfort and flexibility, without affecting his/her decision-making (Tabaa et al., 2020).

5.2. Managerial implication

The top critical technological barriers to effective MSWM in Taiwan include inadequate public data, robotic process automation limitations, lack of predictive and emergency assistance, insufficient AI to reach the human level, lack of technical knowledge among planners

Public data in Taiwan is obtained from the social media, web, mobile applications, various types of databases and records such as surveys, geospatial information, and scrutinized conventional books and documents. Further, through AI implementation and data-driven IoT, it is easy to collect data from the location, type of waste and the amount of it (Chauhan et al., 2021). Yet, the importance of public data lies not in the volume of data collected, but in the strategy of using it to yield valuable information (Cohen & Gil, 2021). Public data, as well as cross-referenced from other databases can help to identify people's habits, local or national health records, dispersal of waste schedules; thus, detecting illegal behavior and warn of potential disruptions in waste management in real-time, developing waste collection and treatment programs based on public routines, quickly calculating and synthesizing a portfolio of risks before it can adversely affect MSWM operations; then help to optimize the MSWM activities (Chen et al., 2021). However, the inadequate and discrepancy between the amount of generated data and the data handling capacity to deliver sustainable municipal planning and MSWM still remains. Most of the current waste management infrastructures does not record the necessary data for the predictive operation interpretation. On the other, even if the Taiwanese MSWM institution has these data available, they also lack of enough software application and tools option to interpret the data. Thus, new mechanism should be giving to MSWM data-producing to attain effective maneuvers and make the easier changeover to data interpretation and organization readers such as sensor-based technologies and data detention development, data communication and transmission, analyzing abilities, and tracking routing experiments. In addition, shaping the data strategy, determining the necessary data sources, accessing, managing and storing data, infrastructure for data management, improving flexibility, speed and handling power are necessary to solve this problem. Putting people at the center to make data-driven decisions when governance systems operate on given credentials rather than instinct or experience (Foresti et al., 2020). As a result, reliable analysis and decisions will be made, which helps to reduce costs, shorten time, support new MSWM research and development activities and support administrators in decision making.

Robotic process automation uses cybernetic robots to undertake monotonous procedures that grasp the same action each time without aberration or decision-making (Tabaa et al., 2020). They perform physical actions, cooperating with heritage structures and other equipment accurately as a human, but more accurately, faster, and tirelessly. Robots have the ability to selflearn and upgrade to perform better in a fully automated digital process. It is a type of garbage sorting robot that uses AI and machine learning technology, allowing to identify more types of waste and get into more phase of waste management processes. As a result, staffs can involve more valuable work, as robotic process automation handle the repetitive, and occasionally ordinary duties inside the organization (Foresti et al., 2020). However, the technology is not an intellectual computing configuration, it is only best suited for specific judgement-based vs rules-based processes. In Taiwan, given full automation is impossible without being supervised and taking the important skills and experience from human operators. Thus, the collaborative robotic process automation should be capable to learn the task from the operator as the worker would show the robot how to do the job and deal with unexpected event. One limitation is robotic security, which is not necessarily related to task completion but to mitigate any security risks, it is still need more concerns from the IT staff and the technological providers.

Integration of predictive models and emergency assistance is necessary to entail the sustainability complexity problems in the short and long-term. Predictive analysis can assist study historical information to identify and avoid emergency disruption and potential faults. This is complete through utilizing the digital cyberspace architecture and the big-data to empower the feasibility zero-failure scrutiny (Fukuyama, 2018). While there are prevailing and possibilities illustrations, the solid and typical incorporated digital emergence on Taiwan MSWM effectiveness is not yet reach the actuality. The MSWM system must autonomously improve and recognizing the response that reacts for novelty prediction to arise. Indeed, predictive action can base on data analytics enabled by the I4.0 technology (Tseng et al., 2018b). There should be connection between the virtual world and reality, allowing to scrutinize data monitor waste management systems. The combination of information and communication technology and physical devices linked to the IoT system and up-to-date big data technologies can generate predictive paradigms and emergency assistance through statistical techniques and machine learning, thus optimize waste management services and operations effectiveness. With computer simulation help, problem can be forecast and solved, helping evade interruption, create new plans and opportunities, thus, eradicating the unnecessary costs and alleviating risks. The liberal of more and more strong AI with profounder predictive power and comprehensive understandability background will make it more invisible and accuracy. Yet, this also claim the critical role of trust in cyber automation from human, which may lead to negligence and possibly calamitous corollaries. The people without technological knowledge will react with a sense of rejection due to familiarity on personal experience but the machine.

The role of AI turn into astoundingly sophisticated. This technology brings many advantages, and doubtful and uncertain issues into the human society, and it will draw an even greater influence in the couple of decades. The MSWM has found effective approaches and resolutions for the operation and management problems with the application of machine learning and AI. which, in the case of waste management. For example, the AI application in intelligent waste bins. The AI and robotics in smart waste classification, the waste items are scanned with cameras and sensor, then examined by machine learning and deep-learning algorithms (Khan et al., 2022). However, in Taiwan, current technology is not strong enough to solve difficult tasks such as language, mutual consciousness, and complex logical thinking as human mind does. The cyber intelligence is based on algorithms to process power and data (Bui and Tseng, 2022). Therefore, it is good to supply machines with necessary algorithms to improve their processing and effectively integrate with the current hardware by merging human cognitive capabilities with machines, and considering the human intelligence to fixed and grow machine intelligence. The collaboration of the Taiwanese government, information and communication technologies providers, and other related participants is critical in helping to handle such MSWM problem with more political, technical, and financial supports. Yet, there will be massive job losses, socio-economic inequity, and the enormous income gap between general and professional labor in the future. Although AI will absolutely hasten higher reach in thinking and solving problems, this also grants challenges for people not about machines being too intelligent, but about them is being given too much authority. There are several apprehensions impending from technologists, scientists, politicians, and society to be aware of future commotions or robot invasion, not just thoughtlessly adore the benefits from AI; and whether or not, there are still serious questions for solving once the I4.0 revolution is fully established.

Planning is the initial stage for designing and developing MSWM. There will be good policy, reasonably sufficient budget, and taxes incentives if there are good waste management planning strategy. However, the plan from poor planners may lead to chaotic waste management schemes with deficient substructure, weak registration and employee's capability, insufficient data structures (Atzori et al., 2010; Batista et al., 2021). Despite the Taiwanese authorities pushing sustained exertions and numerous ingenuities to implement I4.0 practices, the progress is still uncertain. Understanding the role of technical knowledge among planners is important to drive the technology adoption in the existing MSWM. Technical knowledge influences the actions of top management and their opinion in the I4.0 implementation for more sustainable MSWM (Mavrodieva & Shaw, 2020). However, the insufficient knowledge is challenge waste management vision and regulatory guidelines. To solve the problem, the government can provide financial provision on smart waste management resolutions, research and development, which in order progress planner and top management to be more active and enrich their technical knowledge foundation in MSWM agenda. Further, providing free data online also empowered them to accountable for their performance towards the MSWM. As the Taiwan desires to comprehend the efficacy in executing MSWM strategies, they need to carry out an evidence-based execution of management direction to well inform to digital mechanism, as well as record the response, recommendations, and complaints to better replicate on the public issues on waste management services.

6. Conclusion

Industry 4.0 plays an important role in conveying sustainable urban commodities through the MSWM network integration. Yet, there are still numerous uncertain technological barriers with unnoticeable inter-relationship among them, triggering multicollinearity problems to MSWM implementation in Taiwan. This study aims to explore those MSWM technological barriers under I4.0 practices, which by overcoming them would result in satisfactory achievement of a new smart and sustainable municipal development. Since there is an uncertainty and vagueness in evaluators' linguistic preferences, and it is difficult to systematize hierarchical structure with the causal inter-relationships, this study applied a hybrid method of FDM, fuzzy DEMATEL and ANP to acquire valid hierarchical structure and identify causal inter-relationships among the measured barriers. The FDM are employed to validate the structural barriers stemmed from the literature. The fuzzy DEMATEL is to identify the causal inter-relationships among MSWM attributes by forming the evaluators' preferences. Finally, the ANP is to confirm the consistency among the hierarchical structures by assessing inter-dependencies between the aspects and barriers.

An initial attribute set of 5 aspects and 44 barriers are proposed in this study. The result shows that there are 20 barriers are accepted and 5 aspects still remains as a valid hierarchical structure. The cyber-physical limitations, artificial intelligence application challenges, and human interface problems are the cause aspects, with the artificial intelligence application challenges is the most critical aspect in MSWM under I4.0 practices. The top critical barriers obstructing MSWM practices in Taiwan are determined including inadequate public data, robotic process automation limitations, lack of predictive and emergency assistance, insufficient AI to reach the human level, lack of technical knowledge among planners.

This study helps MSWM municipals stakeholders, government, policy- and decision-makers, makers to empathize the noteworthy of I4.0 practices in MSWM implementation. Both theory and managerial fields are contributed through encompassing the understanding of MSWM in the literature by acquiring a valid MSWM technological barriers set under I4.0 practices. The barriers' causal inter-relationships are identified to improve the MSWM structural network. For managerial contribution, critical barriers for the practical MSWM improvement are identified supporting by the I4.0 practical implementation. In the trend of industrial- and digitalization, improving MSWM under I4.0 is getting more and more essential, the practical directions are provided to improve waste management activities in Taiwan, which need more courtesy than ever to stand and develop further in the revolution to a new smart and sustainable municipal performance.

Still, there are limitations need to be mentioned. This study identifies the MSWM technological barriers in the literature and verified by experts; still, there is incomplete detection on MSWM, which is hard to comprehensively addressed. Future study may expand their work and add more barriers the hierarchical framework for inclusive evaluation. Assessing the economic aspect might be a mindful direction since the cost seems to be a crucial challenge to imply the technology in MSWM. On the other, sample size is limited in 30 experts in this study, their preferences might idiosyncratic due to the high acquainting to the practice and theoretical context. Involving more experts in the evaluation process could make the result more accurately. Lastly, this study focusses on the MSWM under I4.0 in Taiwan, this may possibly affect the generalizability of the results and contribution. Next studies may extant this study as references for other waste management like industrial waste, healthcare waste, wastewater. Assessing in other region or countries backgrounds, and a comparison implementation among different localities is inspiring to bring better understandings for existing literature.

Author Contributions

Bui, TD- Conceptualize, original version and finalized the final version; Tseng, JW- Conceptualize, original version and finalized the final version; Tseng, ML- Conceptualize, original version and finalized the final version; Ali, MH- Conceptualize, original version and finalized the final version; Lim, MK- original version and finalized the final version

Availability of data and materials

No authorized

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Competing Interests

Not applicable

Ethical Approval

Not applicable

Funding

This study is partially supported from MOST 111-2221-E-468 -001 -, and 110-2221-468-010 Ministry of Science and Technology, Taiwan

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Appendix A. Initial proposed measures

Aspects	Barriers	References
Big-data management security	Inhibited by data differences, gaps, contrasts Fragmentary data connection Absence of data wealth, Lack of international standard in method use of data Limited to information gathering Potential threats on data privacy, cyber threats Data curation, storage, and usage Inadequate public data Inadequate information policies Data creators and data custodians' trustworthiness Multi-tenancy, security, and data leakage rising. Lack of common information system Lack of Data availability	Roblek et al., 2020; Chen et al., 2021; Bui et al., 2020a; Mavrodieva & Shaw, 2020; Sharma et al., 2020; Farooq et al., 2015; Cohen & Gil, 2021
Cyber-physical constraints	Arbitrariness in the machine usage Robotic process automation limitations Small physical size, Incapable of complex computing tasks of the infrastructure and computers performance Inefficiency criticality and risk Lack of predictive and emergency assistance Low frequencies and work activity for feedback analysis Downgrading in identification and operative resource/instrument The disruptive innovation crowdfunding and blockchain High-tech manufacturing industry for waste recovery. Waste minimization and closed loop (remanufacturing, recycling) perspective. Technical and managerial capabilities challenges	Chauhan et al., 2021; Mavrodieva & Shaw, 2020; Foresti et al., 2020; Fukuyama, 2018;

	Miscellaneous concerns and relationships. Side channels that lead towards vulnerabilities.	
Internet-of-thing challenges	Issues of accountability, Weak Addressability Weak Integrated information processing Weak User Interfaces Interactions problems Internet of Content and Knowledge unexploitation Lack of integration among IT networks Inadequate internet connectivity System failure issues/integrity	Keogh et al., 2020; Tabaa et al., 2020; Pardini et al., 2020; Franchina et al., 2021; Delgado et al., 2020; Kunst et al., 2018; Sharma et al., 2020; Roblek et al., 2020
Artificial intelligence application challenges	Algorithms lack the ability to learn. Insufficient AI to reach the human level, Deep-learning breaking down	Bui and Tseng, 2022; Mooney, 2018; Onoda, 2020; Mavrodieva & Shaw, 2020; Chen et al., 2021; Foresti et al., 2020; Tabaa et al., 2020
Human - machine interface problems	Lack of knowledge and uncertainty Lack of the integration in operations management Transfers of frugal operational innovative methods and low-cost sustainable methods misconnection. Limited skilled workforce Lack of technical knowledge among planners	Bui and Tseng, 2022; Tabaa et al., 2020; Mooney, 2018; Onoda, 2020; Batista et al., 2021; Mavrodieva & Shaw, 2020; Chen et al., 2021; Foresti et al., 2020; Subramanian et al., 2017; Keogh et al., 2021

Appendix B. Experts' demographic

Expert	Position	Education levels	Years of experience	Organization type (academia/practice)	Expertise
1	Chair professor	PhD	20	Academia	Waste management
2	Chair professor	PhD	12	Academia	Sustainable development
3	Professor	PhD	19	Academia	Circular economy
4	Professor	PhD	14	Academia	Solid waste reuse and recycle
5	Professor	PhD	15	Academia	Solid waste reuse and recycle
6	Professor	PhD	10	Academia	Waste management
7	Associate professor	PhD	9	Academia	Waste management
8	Associate professor	PhD	9	Academia	Sustainable development
9	Assistance professor	PhD	5	Academia	Sustainable development
10	Assistance professor	PhD	8	Academia	Urban planning
11	Assistance professor	PhD	7	Academia	Urban planning
12	Lecturer	PhD	4	Academia	Circular economy
13	Lecturer	PhD	4	Academia	Circular economy
14	Lecturer	PhD	5	Academia	Reverse logistic
15	Lecturer	PhD	10	Academia	Reverse logistic
16	Lecturer	PhD	10	Academia	Urban planning
17	Project manager	PhD	14	Practices	Urban planning
18	Project manager	Master	15	Practices	Sustainable development
19	Project manager	PhD	10	Practices	Solid waste reuse and recycle
20	Operation manager	Master	9	Practices	Solid waste reuse and recycle
21	Operation manager	Master	15	Practices	Waste management
22	Operation manager	PhD	10	Practices	Circular economy
23	Operation manager	PhD	7	Practices	Reverse logistic
24	Operation manager	Master	4	Practices	Logistic & transportation
25	Chair Director	PhD	14	Government agency	Waste management
26	Director	Master	11	Government agency	Solid waste reuse and recycle
27	Director	PhD	10	Government agency	Urban planning
28	Researcher	Master	8	Government agency	Urban planning
29	Researcher	Master	6	Government agency	Circular economy
30	Researcher	Master	6	Government agency	Waste management

Appendix C. Fuzzy direct relation matrix and the defuzzification results – Expert 1 example

			A1				A2				A3				A4				A5	
A1		[1.000	1.000	1.000]		[0.700	0.900	1.000]		[0.300	0.500	0.700]		[0.700	0.900	1.000]		[0.100	0.300	0.500]
A2		[0.700	0.900	1.000]		[1.000	1.000	1.000]		[0.700	0.900	1.000]		[0.300	0.500	0.700]		[0.500	0.700	0.900]
A3		[0.500	0.700	0.900]		[0.700	0.900	1.000]		[1.000	1.000	1.000]		[0.700	0.900	1.000]		[0.700	0.900	1.000]
A4		[0.700	0.900	1.000]		[0.300	0.500	0.700]		[0.700	0.900	1.000]		[1.000	1.000	1.000]		[0.700	0.900	1.000]
A5		[0.000	0.100	0.300]		[0.500	0.700	0.900]		[0.300	0.500	0.700]		[0.300	0.500	0.700]		[1.000	1.000	1.000]
		$\tilde{g}^{y}_{1ij}$	$\tilde{g}^{y}_{2ij}$	$\tilde{g}^{y}_{3ij}$		$\tilde{g}^{y}_{1ij}$	$\tilde{g}^{y}_{2ij}$	$\tilde{g}^{y}_{3ij}$		$\tilde{g}^{y}_{1ij}$	$\tilde{g}^{y}_{2ij}$	$\tilde{g}^{y}_{3ij}$		$\tilde{g}^{y}_{1ij}$	$\tilde{g}^{y}_{2ij}$	$\tilde{g}^{y}_{3ij}$		$\tilde{g}^{y}_{1ij}$	$\tilde{g}^{y}_{2ij}$	$\tilde{g}^{y}_{3ij}$
A1	1.000	[1.000	0.900	0.700]	0.700	[0.571	0.571	0.429]	0.700	[0.000	0.000	0.000]	0.700	[0.571	0.571	0.429]	0.900	[0.000	0.000	0.000]
A2		[0.700	0.800	0.700]		[1.000	0.714	0.429]		[0.571	0.571	0.429]		[0.000	0.000	0.000]		[0.444	0.444	0.444]
A3		[0.500	0.600	0.600]		[0.571	0.571	0.429]		[1.000	0.714	0.429]		[0.571	0.571	0.429]		[0.667	0.667	0.556]
A4		[0.700	0.800	0.700]		[0.000	0.000	0.000]		[0.571	0.571	0.429]		[1.000	0.714	0.429]		[0.667	0.667	0.556]
A5		[0.000	0.000	0.000]		[0.286	0.286	0.286]		[0.000	0.000	0.000]		[0.000	0.000	0.000]		[1.000	0.778	0.556]
		lv^{n}_{ij}	rv^{n}_{ij}			lv^{n}_{ij}	rv^{n}_{ij}			lv^{n}_{ij}	rv^{n}_{ij}			lv^{n}_{ij}	rv^{n}_{ij}			lv^{n}_{ij}	rv^{n}_{ij}	
A1		1.000	0.875			0.571	0.500			0.000	0.000			0.571	0.500			0.000	0.000	
A2		0.727	0.778			1.000	0.600			0.571	0.500			0.000	0.000			0.444	0.444	
A3		0.545	0.600			0.571	0.500			1.000	0.600			0.571	0.500			0.667	0.625	
A4		0.727	0.778			0.000	0.000			0.571	0.500			1.000	0.600			0.667	0.625	
A5		0.000	0.000			0.286	0.286			0.000	0.000			0.000	0.000			1.000	0.714	
		cv^{k}_{ij}				cv^{k}_{ij}				cv^{k}_{ij}				cv^{k}_{ij}				cv^{k}_{ij}		
A1		0.875				0.533				0.000				0.533				0.000		
A2		0.765				0.600				0.533				0.000				0.444		
A3		0.576				0.533				0.600				0.533				0.639		
A4		0.765				0.000				0.533				0.600				0.639		
A5		0.000				0.286				0.000				0.000				0.714		
		s^{y}_{ij}				s^{y}_{ij}				s^{y}_{ij}				s^{y}_{ij}				s^{y}_{ij}		
A1		0.875				0.673				0.300				0.673				0.100		
A2		0.765				0.720				0.673				0.300				0.500		
A3		0.576				0.673				0.720				0.673				0.676		
A4		0.765				0.300				0.673				0.720				0.676		
A5		0.000				0.500				0.300				0.300				0.743		

Appendix D. Aspects' initial direction matrix

	A1	A2	A3	A4	A5
A1	0.808	0.420	0.470	0.490	0.240
A2	0.612	0.753	0.629	0.565	0.493
A3	0.477	0.476	0.744	0.460	0.546
A4	0.690	0.422	0.599	0.792	0.674
A5	0.420	0.547	0.492	0.500	0.765

Appendix E. Total interrelationship matrix and cause-and-effect inter-relationships among aspects

	A1	A2	A3	A4	A5	α	β	$(\alpha+\beta)$	$(\alpha-\beta)$
A1	1.499	1.183	1.341	1.296	1.157	6.475	8.194	14.669	(1.720)
A2	1.773	1.595	1.732	1.641	1.558	8.300	7.032	15.331	1.268
A3	1.532	1.340	1.585	1.428	1.411	7.296	7.952	15.248	(0.656)
A4	1.855	1.529	1.773	1.770	1.673	8.601	7.597	16.198	1.004
A5	1.535	1.385	1.521	1.463	1.507	7.411	7.306	14.717	0.104

Appendix F. Barriers' initial direction matrix

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
B1	0.813	0.536	0.385	0.392	0.466	0.479	0.451	0.390	0.437	0.501	0.425	0.483	0.362	0.443	0.430	0.453	0.293	0.459	0.429	0.385
B2	0.478	0.807	0.293	0.390	0.500	0.422	0.458	0.474	0.399	0.381	0.333	0.407	0.348	0.412	0.393	0.397	0.384	0.425	0.320	0.504
B3	0.300	0.334	0.818	0.305	0.405	0.373	0.435	0.261	0.455	0.359	0.437	0.428	0.376	0.437	0.394	0.419	0.280	0.370	0.322	0.418
B4	0.573	0.483	0.370	0.798	0.472	0.411	0.528	0.323	0.448	0.456	0.437	0.444	0.419	0.479	0.411	0.416	0.477	0.560	0.474	0.556
B5	0.536	0.552	0.345	0.490	0.789	0.466	0.546	0.394	0.398	0.443	0.485	0.365	0.416	0.418	0.442	0.462	0.400	0.438	0.443	0.353
B6	0.524	0.384	0.346	0.418	0.409	0.773	0.465	0.368	0.397	0.480	0.397	0.443	0.408	0.423	0.355	0.391	0.376	0.464	0.360	0.507
B7	0.500	0.457	0.429	0.469	0.469	0.494	0.796	0.389	0.508	0.565	0.466	0.493	0.408	0.498	0.501	0.509	0.471	0.497	0.478	0.514
B8	0.473	0.496	0.391	0.372	0.440	0.361	0.404	0.813	0.406	0.372	0.352	0.412	0.308	0.347	0.379	0.410	0.318	0.434	0.290	0.417
B9	0.489	0.456	0.459	0.539	0.460	0.528	0.481	0.426	0.828	0.417	0.436	0.501	0.448	0.404	0.463	0.462	0.377	0.437	0.393	0.474
B10	0.426	0.527	0.507	0.500	0.428	0.497	0.482	0.444	0.494	0.803	0.462	0.411	0.441	0.454	0.423	0.456	0.253	0.502	0.469	0.448
B11	0.478	0.435	0.447	0.418	0.423	0.473	0.494	0.348	0.469	0.447	0.783	0.438	0.441	0.428	0.378	0.469	0.413	0.479	0.487	0.479
B12	0.428	0.393	0.393	0.422	0.420	0.493	0.498	0.419	0.487	0.545	0.454	0.793	0.446	0.462	0.429	0.494	0.361	0.510	0.391	0.499
B13	0.394	0.430	0.405	0.483	0.371	0.441	0.445	0.330	0.475	0.514	0.415	0.509	1.000	0.410	0.477	0.400	0.330	0.517	0.425	0.468
B14	0.304	0.370	0.412	0.425	0.396	0.436	0.436	0.380	0.442	0.407	0.409	0.484	0.487	0.803	0.404	0.458	0.420	0.369	0.334	0.442
B15	0.460	0.481	0.371	0.450	0.390	0.398	0.502	0.302	0.435	0.425	0.422	0.469	0.436	0.421	0.797	0.545	0.514	0.475	0.428	0.500
B16	0.547	0.514	0.384	0.534	0.484	0.492	0.515	0.350	0.438	0.527	0.430	0.516	0.470	0.468	0.545	0.804	0.304	0.492	0.418	0.461
B17	0.429	0.432	0.275	0.449	0.402	0.353	0.355	0.361	0.273	0.326	0.392	0.360	0.328	0.448	0.462	0.347	0.797	0.373	0.304	0.395
B18	0.416	0.394	0.379	0.431	0.423	0.510	0.465	0.445	0.494	0.520	0.449	0.433	0.475	0.487	0.438	0.481	0.463	0.784	0.424	0.440
B19	0.412	0.314	0.262	0.464	0.370	0.348	0.403	0.278	0.358	0.412	0.476	0.482	0.428	0.404	0.490	0.506	0.464	0.379	0.800	0.477
B20	0.523	0.435	0.441	0.481	0.471	0.502	0.417	0.332	0.520	0.523	0.511	0.533	0.522	0.513	0.436	0.526	0.432	0.412	0.399	0.784

Appendix G. Barriers' total interrelationship matrix

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
B1	0.593	0.549	0.471	0.533	0.528	0.545	0.559	0.456	0.535	0.558	0.522	0.553	0.516	0.535	0.527	0.550	0.461	0.549	0.492	0.548
B2	0.530	0.550	0.436	0.505	0.505	0.511	0.531	0.442	0.503	0.516	0.485	0.516	0.488	0.504	0.495	0.515	0.446	0.517	0.454	0.532
B3	0.475	0.466	0.463	0.463	0.462	0.473	0.494	0.390	0.477	0.480	0.464	0.485	0.459	0.474	0.463	0.484	0.406	0.477	0.425	0.489
B4	0.599	0.573	0.495	0.606	0.558	0.568	0.599	0.473	0.566	0.584	0.553	0.579	0.552	0.569	0.554	0.576	0.507	0.590	0.524	0.598
B5	0.575	0.560	0.475	0.554	0.571	0.553	0.580	0.464	0.540	0.561	0.538	0.550	0.531	0.542	0.537	0.560	0.481	0.557	0.502	0.555
B6	0.545	0.515	0.451	0.519	0.504	0.558	0.542	0.438	0.513	0.538	0.502	0.531	0.504	0.516	0.501	0.525	0.454	0.532	0.468	0.543
B7	0.613	0.591	0.520	0.593	0.577	0.598	0.648	0.498	0.593	0.617	0.576	0.606	0.571	0.592	0.584	0.608	0.525	0.605	0.543	0.615
B8	0.509	0.498	0.430	0.484	0.479	0.485	0.505	0.461	0.485	0.496	0.469	0.497	0.464	0.478	0.475	0.497	0.422	0.499	0.434	0.503
B9	0.587	0.567	0.502	0.576	0.553	0.577	0.590	0.482	0.603	0.576	0.549	0.582	0.551	0.557	0.556	0.578	0.493	0.574	0.512	0.586
B10	0.577	0.571	0.505	0.568	0.546	0.571	0.587	0.481	0.565	0.613	0.549	0.569	0.548	0.559	0.549	0.574	0.477	0.577	0.517	0.579
B11	0.570	0.550	0.488	0.548	0.535	0.557	0.576	0.461	0.551	0.564	0.571	0.560	0.537	0.546	0.533	0.564	0.484	0.563	0.509	0.571
B12	0.573	0.553	0.489	0.556	0.541	0.567	0.585	0.475	0.560	0.583	0.544	0.605	0.545	0.557	0.546	0.574	0.485	0.574	0.505	0.581
B13	0.563	0.552	0.486	0.558	0.531	0.556	0.574	0.461	0.554	0.574	0.535	0.570	0.599	0.546	0.546	0.559	0.477	0.570	0.504	0.572
B14	0.516	0.508	0.454	0.515	0.498	0.518	0.534	0.435	0.513	0.525	0.498	0.530	0.508	0.550	0.502	0.527	0.455	0.516	0.461	0.531
B15	0.569	0.555	0.480	0.552	0.531	0.549	0.577	0.456	0.547	0.562	0.534	0.564	0.536	0.545	0.577	0.572	0.496	0.563	0.503	0.574
B16	0.607	0.587	0.506	0.589	0.569	0.587	0.608	0.485	0.576	0.602	0.562	0.598	0.567	0.578	0.578	0.628	0.497	0.594	0.527	0.598
B17	0.484	0.471	0.400	0.473	0.456	0.465	0.480	0.396	0.451	0.470	0.454	0.471	0.448	0.470	0.465	0.470	0.456	0.472	0.418	0.481
B18	0.571	0.552	0.486	0.556	0.541	0.567	0.580	0.477	0.560	0.579	0.543	0.566	0.547	0.558	0.546	0.572	0.496	0.602	0.508	0.574
B19	0.524	0.499	0.434	0.515	0.492	0.505	0.527	0.421	0.501	0.522	0.502	0.526	0.498	0.505	0.508	0.529	0.457	0.514	0.507	0.531
B20	0.604	0.578	0.512	0.583	0.567	0.588	0.597	0.483	0.584	0.601	0.570	0.599	0.573	0.582	0.566	0.598	0.510	0.585	0.525	0.631

Appendix H. Cause-and-effect inter-relationships among the barriers

	γ	δ	$(\gamma + \delta)$	$(\gamma - \delta)$
B1	10.579	11.184	21.764	(0.605)
B2	9.984	10.845	20.828	(0.861)
B3	9.268	9.485	18.752	(0.217)
B4	11.225	10.848	22.073	0.377
B5	10.785	10.543	21.328	0.242
B6	10.201	10.900	21.100	(0.699)
B7	11.671	11.274	22.945	0.398
B8	9.572	9.133	18.706	0.439
B9	11.151	10.778	21.929	0.374
B10	11.082	11.122	22.204	(0.040)
B11	10.838	10.520	21.359	0.318
B12	10.997	11.057	22.054	(0.060)
B13	10.887	10.541	21.428	0.345
B14	10.095	10.763	20.857	(0.668)
B15	10.844	10.608	21.452	0.236
B16	11.444	11.059	22.503	0.385
B17	9.152	9.487	18.639	(0.335)
B18	10.981	11.031	22.011	(0.050)
B19	10.017	9.837	19.855	0.180
B20	11.435	11.192	22.628	0.243

Appendix I. Unlimited super-matrix

	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
A1	1.4988	1.1825	1.3410	1.2956	1.1565	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A2	1.7732	1.5952	1.7320	1.6408	1.5583	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A3	1.5324	1.3399	1.5846	1.4277	1.4112	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A4	1.8552	1.5294	1.7734	1.7696	1.6733	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A5	1.5345	1.3848	1.5211	1.4634	1.5071	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B1	0.0000	0.0000	0.0000	0.0000	0.0000	0.5930	0.5489	0.4707	0.5334	0.5277	0.5455	0.5593	0.4556	0.5353	0.5579	0.5220	0.5527	0.5161	0.5351	0.5265	0.5498	0.4606	0.5490	0.4917	0.5484
B2	0.0000	0.0000	0.0000	0.0000	0.0000	0.5298	0.5496	0.4365	0.5055	0.5045	0.5113	0.5311	0.4415	0.5034	0.5164	0.4852	0.5161	0.4876	0.5042	0.4954	0.5153	0.4465	0.5170	0.4545	0.5324
B3	0.0000	0.0000	0.0000	0.0000	0.0000	0.4755	0.4656	0.4634	0.4630	0.4615	0.4726	0.4941	0.3897	0.4768	0.4799	0.4643	0.4847	0.4588	0.4739	0.4630	0.4839	0.4060	0.4771	0.4247	0.4889
B4	0.0000	0.0000	0.0000	0.0000	0.0000	0.5994	0.5732	0.4952	0.6062	0.5575	0.5684	0.5987	0.4735	0.5663	0.5840	0.5527	0.5792	0.5517	0.5691	0.5541	0.5764	0.5073	0.5903	0.5239	0.5976
B5	0.0000	0.0000	0.0000	0.0000	0.0000	0.5745	0.5605	0.4745	0.5535	0.5708	0.5535	0.5795	0.4639	0.5403	0.5613	0.5377	0.5497	0.5311	0.5419	0.5373	0.5603	0.4809	0.5566	0.5020	0.5548
B6	0.0000	0.0000	0.0000	0.0000	0.0000	0.5449	0.5149	0.4514	0.5187	0.5044	0.5584	0.5423	0.4383	0.5135	0.5378	0.5022	0.5305	0.5042	0.5156	0.5013	0.5249	0.4543	0.5317	0.4683	0.5432
B7	0.0000	0.0000	0.0000	0.0000	0.0000	0.6128	0.5912	0.5201	0.5928	0.5773	0.5981	0.6481	0.4980	0.5934	0.6168	0.5759	0.6057	0.5706	0.5916	0.5841	0.6076	0.5246	0.6047	0.5431	0.6147
B8	0.0000	0.0000	0.0000	0.0000	0.0000	0.5093	0.4980	0.4305	0.4842	0.4794	0.4854	0.5054	0.4608	0.4852	0.4956	0.4685	0.4972	0.4644	0.4780	0.4751	0.4971	0.4224	0.4986	0.4337	0.5032
B9	0.0000	0.0000	0.0000	0.0000	0.0000	0.5870	0.5669	0.5022	0.5759	0.5529	0.5774	0.5903	0.4816	0.6028	0.5762	0.5491	0.5819	0.5515	0.5573	0.5561	0.5778	0.4932	0.5740	0.5119	0.5856
B10	0.0000	0.0000	0.0000	0.0000	0.0000	0.5765	0.5710	0.5046	0.5683	0.5463	0.5708	0.5870	0.4809	0.5648	0.6132	0.5488	0.5690	0.5476	0.5594	0.5485	0.5738	0.4769	0.5775	0.5171	0.5795
B11	0.0000	0.0000	0.0000	0.0000	0.0000	0.5704	0.5498	0.4881	0.5484	0.5346	0.5568	0.5763	0.4609	0.5507	0.5645	0.5714	0.5603	0.5367	0.5456	0.5329	0.5637	0.4844	0.5634	0.5089	0.5709
B12	0.0000	0.0000	0.0000	0.0000	0.0000	0.5727	0.5529	0.4890	0.5564	0.5415	0.5666	0.5846	0.4750	0.5602	0.5828	0.5442	0.6050	0.5445	0.5565	0.5455	0.5740	0.4850	0.5745	0.5053	0.5807
B13	0.0000	0.0000	0.0000	0.0000	0.0000	0.5635	0.5515	0.4857	0.5578	0.5310	0.5558	0.5735	0.4608	0.5540	0.5743	0.5350	0.5705	0.5989	0.5457	0.5458	0.5586	0.4773	0.5703	0.5044	0.5723
B14	0.0000	0.0000	0.0000	0.0000	0.0000	0.5158	0.5081	0.4541	0.5145	0.4979	0.5179	0.5341	0.4352	0.5133	0.5245	0.4985	0.5299	0.5082	0.5504	0.5018	0.5270	0.4548	0.5163	0.4607	0.5313
B15	0.0000	0.0000	0.0000	0.0000	0.0000	0.5689	0.5553	0.4798	0.5523	0.5314	0.5490	0.5774	0.4561	0.5471	0.5624	0.5338	0.5640	0.5364	0.5452	0.5774	0.5722	0.4958	0.5633	0.5028	0.5736
B16	0.0000	0.0000	0.0000	0.0000	0.0000	0.6072	0.5870	0.5060	0.5892	0.5688	0.5874	0.6083	0.4850	0.5756	0.6023	0.5618	0.5976	0.5673	0.5779	0.5785	0.6277	0.4973	0.5939	0.5273	0.5983
B17	0.0000	0.0000	0.0000	0.0000	0.0000	0.4843	0.4714	0.4004	0.4731	0.4561	0.4646	0.4797	0.3963	0.4511	0.4704	0.4539	0.4714	0.4478	0.4697	0.4650	0.4703	0.4565	0.4721	0.4176	0.4807
B18	0.0000	0.0000	0.0000	0.0000	0.0000	0.5706	0.5522	0.4865	0.5565	0.5410	0.5674	0.5801	0.4771	0.5599	0.5790	0.5428	0.5664	0.5467	0.5584	0.5457	0.5716	0.4955	0.6019	0.5080	0.5735
B19	0.0000	0.0000	0.0000	0.0000	0.0000	0.5241	0.4987	0.4345	0.5155	0.4916	0.5048	0.5268	0.4208	0.5005	0.5216	0.5024	0.5262	0.4984	0.5052	0.5079	0.5289	0.4569	0.5139	0.5071	0.5315
B20	0.0000	0.0000	0.0000	0.0000	0.0000	0.6039	0.5779	0.5118	0.5831	0.5668	0.5881	0.5971	0.4826	0.5838	0.6012	0.5701	0.5989	0.5726	0.5823	0.5662	0.5981	0.5104	0.5846	0.5246	0.6313

Appendix J. Convergent limited super-matrix

	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	Weight	Rank
A1	0.1694	0.1694	0.1694	0.1694	0.1694	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1694	5
A2	0.2182	0.2182	0.2182	0.2182	0.2182	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2182	2
A3	0.1915	0.1915	0.1915	0.1915	0.1915	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1915	4
A4	0.2258	0.2258	0.2258	0.2258	0.2258	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2258	1
A5	0.1951	0.1951	0.1951	0.1951	0.1951	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1951	3
B1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	0.0000	13
B2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470	0.0000	17
B3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0437	0.0000	19
B4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0000	4
B5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0000	12
B6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0481	0.0000	14
B7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0550	0.0000	1
B8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0451	0.0000	18
B9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0526	0.0000	5
B10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0522	0.0000	6
B11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0000	11
B12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0518	0.0000	7
B13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0513	0.0000	9
B14	0.0000	0.0000	0.0000	0.0000	0.0000	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0476	0.0000	15
B15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0511	0.0000	10
B16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0000	2
B17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0000	20
B18	0.0000	0.0000	0.0000	0.0000	0.0000	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0000	8
B19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0472	0.0000	16
B20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0539	0.0000	3