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Zero waste manufacturing: A framework and review of technology, research, and implementation barriers for enabling a circular economy transition in Singapore

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ABSTRACT

Zero waste manufacturing (ZWM) is a concept to support countries transition to a circular economy by developing manufacturing technologies and systems that eliminate waste across entire waste value chains to the fullest extent possible through reuse and recycling. Implementation of ZWM, particularly in dense urban settings such as Singapore, presents challenges for stakeholders, which stem from issues related to land scarcity, productivity, and labor shortage. A framework to address these challenges is proposed comprising six themes of design for zero waste, smart waste audit and reduction planning, smart waste collection, high-value mixed waste processing, collaborative platform for industrial symbiosis, and waste to resource conversion and recycling. A systematic literature review is used to examine industry technologies and research across the six themes to determine how the technologies can support ZWM. The research reveals that a variety of mature waste measurement, collection, and conversion technologies can be integrated through internet-of-things applications and a collaborative platform for industrial symbiosis to support Singapore and other countries in developing a ZWM ecosystem. This research examines the technical limitations of implementing ZWM technologies in dense urban settings using Singapore as a case study. Future areas of research are then proposed to overcome the implementation barriers so that ZWM can be enabled.

1. Introduction

Transitioning to a circular economy has drawn significant attention from countries across the world as a new pathway for mitigating the growing volumes of waste that is coupled with today's economic growth. The predominant linear "take, make, and dispose" economic development model has resulted in inefficient use of resources that threatens the stability of natural ecosystems and survival of humanity (Ghisellini et al., 2016). More recently, the unsustainable nature of the linear economic system has gained even greater attention due to China's decision in late 2017 to implement a ban against imports of 24 categories of waste from the rest the world. A year later, other countries in Asia such as India, Malaysia, Thailand, and Vietnam have followed the same initiative by implementing their own waste import bans and tightening restrictions. This has forced nations such as the United States, the United Kingdom, Australia, and Japan to urgently rethink their waste management practices. Global municipal solid waste (MSW) generation is estimated at 2.01 billion tonnes per year and by 2050 it is expected to increase to approximately 3.4 billion tonnes per year (World Bank, 2018). A majority of the global waste ends up in landfills, open dumps, oceans, or other parts of the environment due to suboptimal waste management systems and low recycling rates around the world. Only 7% of global plastic waste was recycled (National Geographic, 2017) while for electronic wastes, it was estimated that only 20% of the global total is documented to have been collected and recycled properly (Baldé et al., 2017). Strategies are therefore needed that prioritize reducing material consumption levels and break away from conventional waste management in a linear economy and transition to a circular economy where wastes are reduced and reused as resources across multiple supply chains at every opportunity (Young et al., 2010).

Singapore is working towards becoming a zero waste nation as the country is faced with the similar global challenge of figuring out the next destination to put its growing amounts of waste. As outlined in the Sustainable Singapore Blueprint by the Ministry of the Environment and Water Resources (MEWR), the country is prioritizing development

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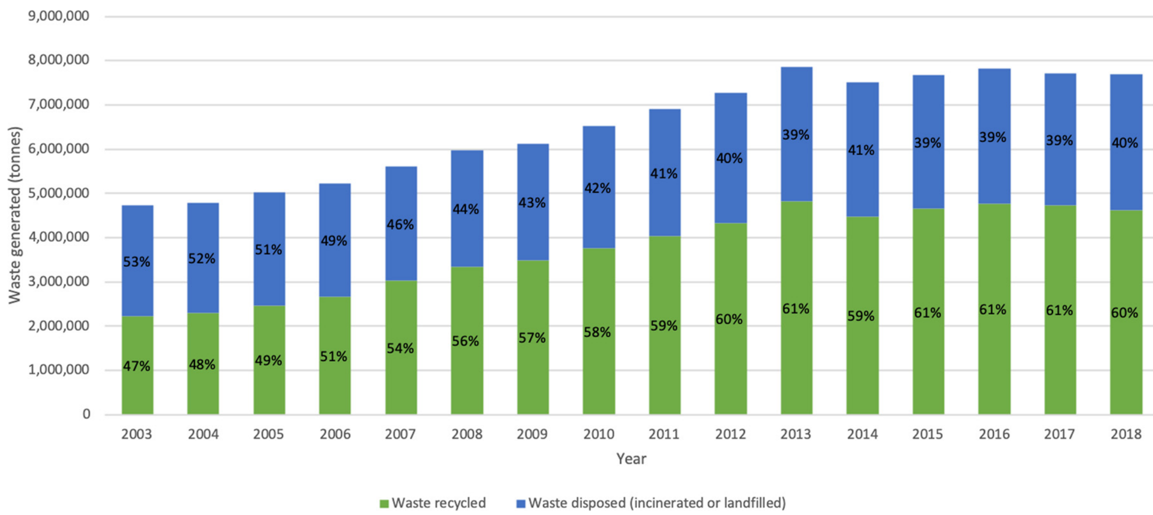

Fig. 1. Waste disposal and recycling in Singapore between 2003 and 2018 (National Environment Agency).

of efficient waste collection, management, recycling, and disposal systems (Ministry of the Environment and Water Resources, Government of Singapore, 2015). As an affluent and highly urbanized country with very little land available for use, Singapore is highly reliant on its four waste-to-energy plants to incinerate its non-recyclable wastes. The incineration bottom ash and non-incinerable wastes are stored at its first and only offshore landfill on Semakau island. Space on Semakau island will quickly disappear as the landfill is expected to max out by 2035, a decade sooner than the original 2045 projection. The population and affluence of the city-state is expected to climb which will correspondingly increase future waste generation. As shown in Fig. 1, in 2018, Singapore generated 7.7 million tonnes of waste with 60% of the volume recycled and 40% either incinerated or sent to a landfill.

The steady rise in recycling rates from 47% in 2003 to 60% in 2018 has helped Singapore mitigate waste challenges. However, the rate of waste generated has also increased similarly and the amount of waste sent to the incinerators and landfill has not shown much improvement.

In parallel to the waste challenges, Singapore has prioritized advancing its manufacturing sector which contributes to 20% of its gross domestic product (GDP) and 14% of total employment (Ministry of Trade and Industry, 2017). To advance the manufacturing sector, Singapore has adopted industry 4.0 technologies as a pathway that is expected to add USD27 billion in total manufacturing output, boost labor productivity by 30%, and create 22,000 new jobs by 2024 (Boston Consulting Group, 2017). Industry 4.0 is the fourth stage of the industrial revolution where computers, automation technologies, and manufacturing systems integrate together into cyber-physical systems that monitor the physical processes of a factory and make its own decisions (Zheng et al., 2018, Lopes de Sousa et al., 2018, Lee et al., 2015). The two-way communication of data between the components, machines and digital devices results in networked manufacturing systems that are intelligently cross-linked across all hierarchical levels of a value chain (Stock and Seliger, 2016). To catalyze the adoption of I4.0, the Government of Singapore has committed USD2.4 billion under the five-year Research, Innovation and Enterprise 2020 plan to support advancements of technological capabilities in the manufacturing and engineering sectors (National Research Foundation, 2016). Global experiences have shown however that although advancements in manufacturing result in rising living standards, it also brings about adverse environmental impacts due to unsustainable consumption and production patterns (Tseng et al., 2018).

Zero waste manufacturing (ZWM) offers a solution to Singapore and other countries' waste management and manufacturing objectives. The concept focuses on developing manufacturing systems that eliminate waste across entire value chains to the fullest extent possible by minimizing waste generation and maximizing the use of wastes as resources in other supply chains. In ZWM, waste is viewed as a manufacturing value chain where waste is generated, collected, and recycled. ZWM aims to improve waste reduction and recovery across multiple supply chains and stakeholders to maximize resource efficiency.

The holistic life cycle approach of ZWM can address the dual objectives of future advancements in manufacturing and waste reduction. However, an overarching challenge of achieving ZWM is that as global manufacturing moves through the fourth industrial revolution, the diversity and volume of waste will continue to evolve and stakeholders along the waste value chain may not be able to keep up at the same pace (World Economic Forum, 2016). To identify the technologies that stakeholders can implement to achieve ZWM, this study proposes a holistic framework comprising six technology themes that aim to mitigate waste generation across the life cycle stages of production and consumption systems. These six themes include:

(i) design for zero waste
(ii) smart waste audit and reduction planning
(iii) smart waste collection
(iv) high-value mixed waste processing
(v) collaborative platform for industrial symbiosis
(vi) waste to resource conversion and recycling.

As shown in Fig. 2, the six themes of the ZWM framework are connected together by addressing specific technical needs of stakeholders across the manufacturing waste value chain: producers who are also the waste generators, waste collectors, and waste to resource converters or recyclers.

The ways in which all six themes support the three major waste value chain stakeholders move towards ZWM is outlined in Table 1.

Integrated together, the collection of technologies under all six themes can minimize waste along the whole waste value chain. The ZWM framework offers both environmental and economic benefits for a country's manufacturing sector. Implementing technologies under the six themes allows manufacturing companies to reduce the volume of waste generated and prevent waste from entering the landfill. Waste reduction and recycling through ZWM reduces greenhouse gas emissions, energy consumption, and reliance on virgin materials which translates to economic cost savings.

Previous studies have reviewed how the zero waste concept and different technologies have been applied in different stages of production and waste management systems (Zaman, 2015; Singh et al., 2017). However, there is a need for studies to examine the technical challenges stakeholders of the waste value chain - waste generators, waste

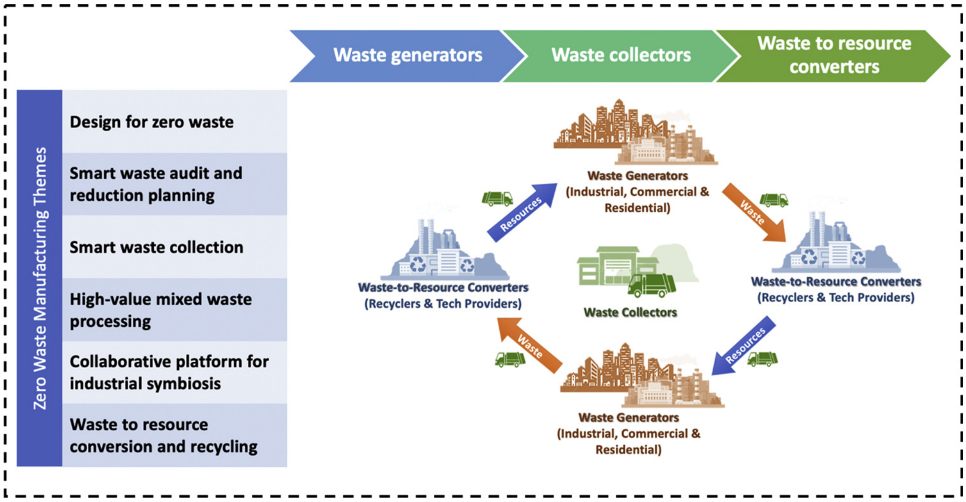

Fig. 2. Overview of zero waste manufacturing framework.

collectors, and waste to resource converters - may face in implementing existing technologies to meet their zero waste goals and transition to a circular economy. Certain ZWM technologies may face barriers during implementation in dense urban settings. There is a need to identify the technical challenges waste stakeholders operating in dense urban settings may face as per capita waste generation is greater for countries or regions with high urbanization rates (World Bank, 2018) and it is projected that more than two-thirds of the world's population will be residing in urban centers by 2050 (United Nations, 2018). The objective of this research is to therefore answer the questions, what are the latest industry technologies under each theme of ZWM and what are the challenges that hinder implementation of these technologies to achieve the goals of ZWM in Singapore and other highly urbanized regions around the world? This study first used a systematic review approach to identify and review the state-of-the-art technologies and research literature under the six themes of the ZWM framework. Based on the thematic review, the feasibility of implementing the technologies is examined using Singapore as a case study for a high income and highly

Table 1
Stakeholder benefits under each theme of ZWM.

Theme	Stakeholder	Support the theme provides to stakeholder
Design for zero waste	**Generators**	Products can be designed and manufactured that use less materials or can be reused which minimizes waste generation.
	Collectors	Products can be designed for disassembly allowing for easy collection, sorting and thereafter, reuse or waste recycling.
	Converters	Products can be designed to be broken down more easily into sub-components and materials so that they can be separated to facilitate efficient recycling.
Smart waste audit and reduction planning	**Generators**	Automated waste auditing and reporting processes can efficiently estimate the magnitude and composition of waste generated to provide the necessary data for managing and mitigating waste.
	Collectors	Data from smart waste audits can be used by waste collectors to know the magnitude and type of waste different entities are generating in real time and therefore know where and when to collect a specific type of waste that is desired.
	Converters	Different waste to resource converters can use smart waste audits for real-time information about the magnitude and type of waste being generated at different sites and then quickly identify who to engage with to use the specific waste.
Smart waste collection	**Generators**	Being connected to a smart waste collection system with sensors and smart waste bins allows waste generators to have their wastes collected more efficiently and avoids unmanageable waste overflow.
	Collectors	Data from smart waste collection systems help optimize waste collection routes that maximize the number of full bins collected which improves utilization of assets (trucks) and manpower and minimizes collection time and costs.
	Converters	Waste to resource converters connected to a smart waste collection system can have real-time information about when wastes will arrive at their facilities which can support in planning recycling operations and predict incoming materials.
High-value mixed waste processing	**Generators**	Automated sorting and segregation allow for recovery of valuable materials from waste generators that was disposed in a single mixed stream due to lack of capacity or infrastructure to do source separation.
	Collectors	Waste collectors can collect mixed waste streams and have it sorted to recover materials that can then be sent to other facilities for waste to resource conversion.
	Converters	Automated sorting and segregation of mixed wastes before recycling increases waste to resource conversion yields.
Collaborative platform for industrial symbiosis	**Generators**	Waste generators can be matched with companies that desire their wastes for reuse or recycling.
	Collectors	Collectors can become logistic service providers for companies connected on a collaborative platform for waste to resource matching and exchanges. Data from the collaborative platform can identify for collectors where their services may be needed.
	Converters	The collaborative platform can provide information to waste to resource converters about which companies have the waste that specific converters desire for reuse and recycling.
Waste to resource conversion and recycling	**Generators**	Waste generators will have technology options for recovering value from their waste materials instead of disposing it to a landfill or incinerator.
	Collectors	Collectors can provide the service of delivering wastes to the appropriate waste to resource converter.
	Converters	Converters will have the technology needed to convert waste to resources and then sell the recycled materials as a feedstock for another supply chain.

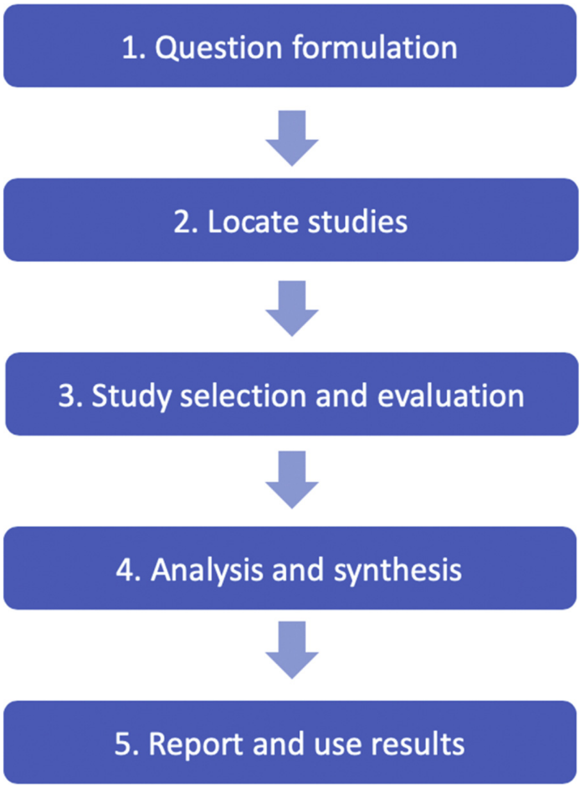

Fig. 3. Systematic literature review procedure.

urbanized city. Then, future areas of research in ZWM are proposed to address the implementation barriers identified. The intended audience of this research includes government decision makers, manufacturing companies and associations, waste collectors and converters, research institutions in Singapore and other countries and cities that seek to understand how current ZWM technologies can be applied to achieve advanced manufacturing and waste reduction goals. The findings of this research can be used to develop a roadmap that outlines the strategic research and development direction for building a ZWM ecosystem in Singapore and other urban settings. This review is designed to encourage researchers, businesses, and decision-makers implement strategies and activities for moving towards ZWM.

2. Materials and methods

This research applies the systematic literature review (SLR) methodology to conduct a review process that is replicable and transparent (Denyer and Tranfield, 2009). Once the research questions were established, the systematic procedure outlined in Fig. 3 was used to find and select relevant studies.

Apart from the academic literature, grey literature sources were included in this study as they provide updated sources of information regarding technologies applied in practice. These pieces of evidence suggest their real-world applicability to instances of manufacturing and waste-related issues.

2.1. Question formulation

The primary review question formulated was: What are the latest industry technologies in each theme of ZWM that can be implemented together to achieve both manufacturing and waste management goals in Singapore and similar cities? The secondary questions developed that support the primary question were:

1 How do the technologies under each theme contribute to achieving ZWM?
2 What future areas of research should be pursued to address the limitations of the technologies identified under the themes of the ZWM framework?

2.2. Locating studies

Two decisions were made in the selection of the search engines and the keywords. Scopus and ScienceDirect were used to identify scientific papers related to the six themes of ZWM. Scopus was selected because it is the largest citation and abstract database while ScienceDirect was selected because the database contains many of the journals with studies that are related to the topics being explored in this review. The general Google search engine was also used to find grey literature sources such as business reports, news articles, and company information about technologies and businesses related to the ZWM themes that have already been implemented in the global market. Search keywords were determined through a two-step process. First, the six ZWM themes were used in the search engines. Then, related concepts and synonyms that frequently appeared in the first search and were related to the research question were then used to narrow the search into a final search string. The keywords for the search strings used in the search engines are listed in Table 2.

For the theme of waste to resource conversion and recycling, the search criteria were narrowed down to focus primarily on technologies for recycling wastes in the food, paper, plastics, and electronics sectors because those waste categories present the greatest opportunities for recycling in Singapore. In 2018, Singapore recycled only 56% of paper and cardboard wastes, 17% of food waste, and 4% of plastic waste (National Environment Agency of Singapore, 2019b). For electronic wastes, the National Environment Agency (NEA) reported that Singapore generated around 60,000 tonnes in 2014. This made Singapore the second-highest generator of electronic wastes in the East and Southeast Asia region (Honda et al., 2016).

Table 2
Keywords used in search strings for ZWM themes.

Concept	Search string
Smart waste audit	“smart waste audit” OR “waste audit”
Smart waste collection	“smart waste collection” OR “smart waste” OR “smart waste bin”
High value mixed waste processing	“high value mixed waste processing” OR “mixed waste processing”
Product recycling	“product recycling” OR “product remanufacturing”
Food waste recycling	“food waste recycling” OR “food waste recovery” OR “food waste to energy”
Paper and cardboard recycling	“paper recycling technology” OR “waste paper recycling technology” OR “cardboard recycling technology” OR “waste cardboard recycling technology”
Plastic recycling	“plastic recycling technology” OR “waste plastic recycling technology”
Electronic waste recycling	“e-waste recycling technology” OR “ewaste recycling technology” OR “electronic waste recycling technology”
Design for zero waste	“design for zero waste” OR “design for disassembly” OR “modular product technology”
Collaborative platform for industrial symbiosis	“industrial symbiosis network” OR “industrial symbiosis tool” OR “industrial symbiosis platform”

Table 3
Inclusion and exclusion criteria for title and abstract screening.

Attribute	Inclusion	Exclusion
Field of study	Field of study must be related to waste management and recycling, manufacturing, and environmental sustainability.	Field of study is not related to waste management and recycling, manufacturing, and environmental sustainability (e.g. policy, finance, urban management and planning).
Context within field	Title/abstract contains cues on technology, systems, and processes to improve waste and resource management, reduction, and recycling in manufacturing industry practices.	Title/abstract contains cues of related topics (e.g. advanced manufacturing technologies, material recovery technologies, computational methods), but do not directly discuss applications to improving environmental sustainability in manufacturing practices.
Subject of discussion	Title/abstract has to include discussion or description of the technology, systems, or process applied in improving waste and resource management, reduction and recycling in manufacturing processes. The technology, system, or process should elaborate on the functions and should be implementable or has been implemented.	Title/abstract discusses principles and fundamental zero waste concepts; history of zero waste; zero waste cases analysis with no relation to technology, systems, or processes that support the objectives of ZWM.

2.3. Study selection and criteria

The main criteria for shortlisting the search results under each of the six themes for further analysis was technology which included hardware, software, and services. Only studies and other information published in 2008 and onwards were included to obtain contemporary research and state-of-the-art technologies applied in practice. Each type of information source was screened in a different manner to filter out false positive results from the automated search engines as follows:

1 Scientific studies: The title and the abstract were screened
2 Business reports: The executive summaries and introductions were screened
3 Company websites: Homepages were screened
4 News articles: The title and the first three paragraphs of the article were screened

Table 3 lists the criteria developed to determine topic relevance before further detailed selection.

The screening determined which studies, reports, or news articles were directly relevant to the scope of this research and would go through a full text review. As shown in Table 4, criteria were then developed to ensure the information was relevant for answering the research question.

The shortlist resulted in 52 research papers, business reports, websites, and news articles that went through a full text review.

The subsequent sections of this research describe the findings of the thematic analysis of six pre-defined themes of ZWM and their technologies. Section 4 discusses how the technologies in the themes can be integrated to achieve ZWM and examines the limitations the ZWM technologies may face during implementation in dense urban settings. Section 5 proposes future areas of research in ZWM that are needed to overcome the limitations of the technologies examined in this study.

3. State-of-the-art technologies in zero waste manufacturing

Each theme of ZWM addresses a group of technologies needed for waste generators, waste collectors, and waste to resource converters to move towards ZWM. Through the thematic review, technologies are identified that the ZWM stakeholders could adopt to overcome their unique waste management challenges. An excel spreadsheet that classifies the ZWM technologies and studies reviewed in this research is provided in the supporting information.

3.1. Design for zero waste

Design for zero waste focuses on designing products that use less materials and/or are easier to disassemble. This reduces the amount of waste generated, makes it easier to collect used parts, and makes it more feasible to recover parts or materials from the product at its end of life. In the manufacturing industry, design for disassembly (DfD) and additive manufacturing (AM) are able to achieve this goal. DfD is a design strategy that considers the future need to disassemble a product for repair, refurbishment, and recycling. Through DfD, valuable parts and materials that still have value can be easily recovered and used in the same or different products. AM technology constructs products by directly joining materials layer by layer following a digital design template. AM products can be developed to more precise design specifications and shapes from start to finish, which helps eliminate waste generated along the manufacturing process, compared to conventional manufacturing.

3.1.1. Design for disassembly

Ameliorating product design during the development phase can increase the recovery rate of products and their materials. DfD guidelines state that maximizing a product's ability to be disassembled can be achieved during the design stage by looking at how to reduce the number of product parts, lower product disassembly costs, shorten disassembly time, and solve all the existing problems in disassembly (Soh et al., 2014). For DfD products to be successful and well received by customers, it is recommended that they meet 14 different characteristics provided by Wang et al. (2014). To support decision-making in DfD, Low et al. (2014) proposed a tool based on modular product architecture.

Products with modular architectures are a notable example of DfD because they can be disassembled into a number of subassemblies, parts, and components. Each subassembly can be considered a module that can be independently created and then used again in other product

Table 4
Subject matter relevance criteria for full text review.

Type of paper	Content profile of paper	Paper must contain
Conceptual	Conceptual description of technology. Yet to present evidence of implementation.	Concept of the technology, demonstrable by the logic and design and applicable to ZWM themes.
Review and trends	Description of industry trends and issues about a type of technology applicable to ZWM.	Details about the development status, industry standards, challenges and gaps, of technology applicable to ZWM.
Empirical	Description of how the technology works, what it can achieve, with evidence of successful testing or implementation.	Details about the functions, processes, and outputs of the technology and the relationships between the steps, and what issues the technology solves.

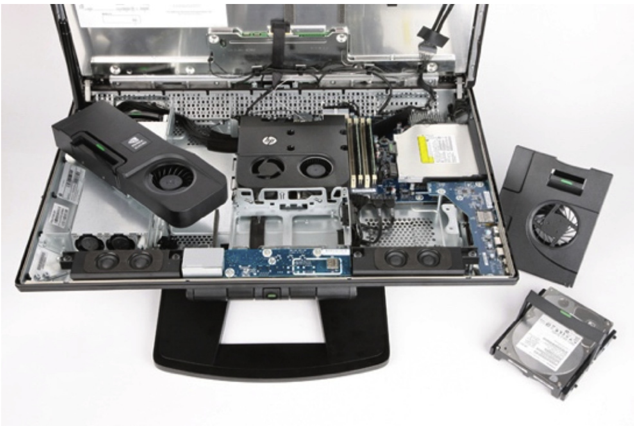

Fig. 4. Internal design of the HP Z1 computer.

systems (Ernst and Young, 2015; Sabaghi et al., 2016). Manufacturing products with modular architectures allows parts to be easily broken down into a number of standardized building blocks, which can be rearranged to create different configurations and variants (Rios et al., 2015). Parts of modular products are also easily replaceable. One example of a modular product is Hewlett Packard's HPZ1 computer as illustrated in Fig. 4.

The HPZ1 monitor contains all the machine's workings and all hardware components can be removed for repair without the need for tools (Ellen MacArthur Foundation, 2013).

Modular construction of buildings has been shown to achieve the benefits of DfD. Modular buildings make it easier to deconstruct them and recover the materials for other product supply chains, as opposed to completely demolishing them (Kamali et al., 2018; Kamali and Hewage, 2017). The company Yorkon manufactures modular components of buildings off-site and connects all the pieces of the final building at the determined location as shown in Fig. 5.

Modular construction does not necessarily restrict the finished design and can save money and time due to less disruption and wastes generated compared to onsite construction of a building from scratch (Kamali and Hewage, 2016).

3.1.2. Additive manufacturing

AM technology produces objects from a three-dimensional (3D) model by joining materials layer by layer, directly from raw materials such as metal and plastic in powder, liquid, sheet, or filament form without the need for molds, tools, or dies. AM builds products to more precise design specifications which reduces waste material generated during product fabrication compared to traditional manufacturing (Niaki et al., 2019). 3D printing is the most well-known type of AM that allows products to be engineered to a specific order from the customer and spare-parts can be produced to precise specifications (Kreiger et al., 2014). 3D printed products are more flexible in terms of customization capabilities. This enables manufacturing to happen outside of a factory and closer to the point where the product will be consumed (Kellens et al., 2017). Some multinational companies have invested in AM for enhancing their business. General Electric invested USD50 million in a factory that 3D prints 35,000 fuel nozzles each year because AM technology uses less material than conventional manufacturing processes which reduces production costs (Massachusetts Institute of Technology, 2013). Several shoe companies such as Adidas, Nike, Feetz, and United Nude, are now using 3D printing technology to give customers shoes that are custom made for them right at the store (CNN, 2017). 3D printed shoes use the exact amount of materials required and can help avoid generation of waste materials that typically occurs in conventional shoe production.

Fig. 5. Example of a modular building by Yorkon (Ellen MacArthur Foundation, 2013).

Design for zero waste contributes to building a ZWM ecosystem because it helps prevent waste generation right at the start of product life cycles. Making products that are easier to disassemble, remanufacture, and refurbish increases opportunities for products and their components to be reused in the same or different product life cycle. Conducting research to advance design for zero waste will support product reuse, upgrade, and maintenance resulting in reduced consumption of raw materials and energy.

3.2. Smart waste audit and reduction planning

Smart waste audits comprise hardware and software solutions that analyze waste volumes, automatically segregate waste, and assess opportunities for waste reduction and diversion though recycling or reuse. Current hardware research and development has been focused on waste bins that automatically segregate waste by analyzing the material content through cameras and sensors (Bin-e, 2017; CleanRobotics, 2016). On the software side, smart waste audits are carried out through online tools that use data analytics to review waste generation data, existing waste collection practices and costs, and current levels of onsite recycling (Ng et al., 2017). These digital tools then identify opportunities for increasing waste recycling and cost saving opportunities. Gershman, Brickner & Bratton, Inc. (GBB) developed an internet-based tool called Smart Engine that identifies cost-saving opportunities for different workplaces. The tool utilizes an extensive database of waste and recycling information from GBB's 20 years of experience in the industry and national databases. After the tool was developed and tested, many businesses conducted their waste audits through SmartEngine (Gershman, Brickner, and Bratton, Inc., 2017). SMARTWaste is another online smart waste auditing tool developed by BRE. This tool was designed to simplify reporting for environmental compliance in construction projects by managing environmental data in construction and allows users to input the data from their projects. Users have reported that SMARTWaste helped reduce onsite waste generation by 40% (BRE, 2017).

Smart waste audits and reduction planning technologies contribute to building a ZWM ecosystem because they enable waste audits to be carried out more efficiently. Advanced hardware and software solutions for collecting and analyzing waste generation data at different sites reduce the time and costs to complete waste audits and measure the potential for waste reduction and recycling.

3.3. Smart waste collection

Current trends in smart waste collection have resulted from new technology enablers that include geographic information systems (GIS), data access networks, sensors, and Internet-of-Things (IoT) (Shukla and Shukla, 2017). The global smart waste collection technology market is expected to grow from USD57.6 million in 2016 to more than USD223 million in 2025 (Navigant Research, 2016). Companies leading in commercialized technology solutions for smart waste collection are Bigbelly Solar; Cognito Tech Solutions; Compology; Ecube Labs; Enevo; IoTsens; SmartBin; SmartUp Cities; System Level Solutions; Urbiotica; and WAVIoT.

Modern smart waste collection systems include an integrated network of sensors, smart waste bins, trucks, maps, and a data management center all integrated together to maximize efficiency of waste collection (Srikantha, 2017). They are designed to solve the current complicated and costly process composed of inefficient routes serviced by a fleet of trucks on disconnected and arbitrary schedules (Ecube Labs, 2017a). As a result, collection costs can represent nearly two-thirds of waste management expenditures (Gershman, Brickner, and Bratton Inc., 2015). In smart waste collection systems, sensors are set up at waste bins connected to a remote network. The sensors measure bin fill levels and send the data to a central database that uses data analytics to monitor sensors and optimize collection routes by skipping empty or low traffic bins (Gutierrez et al., 2015). Algorithms are then used to conduct predictive analyses of data history to estimate fill levels in advance. The results are then used to plan out optimized collection routes for waste hauling trucks that minimize pick-up points and the number of vehicles dispatched. Collection routes are sent to truck drivers through a mobile phone application in real time and can be updated by GPS navigation. The parameterization of the multitude of factors such as distances between points, facility options, and processing costs is necessary to accurately model the complexities of multiplicities and spatial heterogeneities in municipal solid waste systems (Cheng et al., 2017a, b). Fig. 6 illustrates components of a smart waste collection system.

The fundamental component of smart bins are sensors that can be attached to any type of waste bin and continuously measure fill level, temperature, and bin tilt using ultrasonic wireless technology. Sensors are also capable of detecting all types of solid and liquid materials such as general waste, glass, waste oil, and lubricants. They can also perform geopositional tracking to ensure that owners always know the location of their containers (Omar et al., 2016). Wireless ultrasonic sensors also serve as a communication node that send waste bin information to a central data server through a cellular network. Future sensor technology will be able to measure humidity, motion, or weight of the bin to provide better data about the composition of waste at different sites. Other larger and more complex smart waste bins exist that provide services beyond fill level monitoring and wireless data transfer. One example is the Bigbelly smart bin, as shown in Fig. 7.

Fig. 7. Bigbelly smart waste bin.

The bin is powered by solar photovoltaic electricity, can compact waste within the receptacle to reduce volume and overflow, and is equipped with a Wi-Fi unit that can serve as a public internet hotspot (Bigbelly, 2017). The waste compacting feature helps reduce the collection trips needed to empty the bin. More advanced smart bins are being built with capabilities to automatically sort waste deposited into the bin, which would reduce labor, time, and costs in waste management (Bin-e, 2017). This waste sorting function is based on a combination of mechanical and electronical components, and software with elements of artificial intelligence.

Data systems in smart waste collection monitor and optimize daily selection of waste bins to be emptied and calculate the routes and schedules accordingly. Powered by information and communications technology infrastructure, data about bin fill level, locations of bins and trucks, road traffic congestion, time of day, and other factors are collected from all smart waste bins. Algorithms then process this data to calculate the most efficient collection routes to be taken (Ecube Labs, 2017a). The data system then transmits the optimized collection routes directly to the drivers' mobile phone or tablet computer. These online tools enable managers of smart waste collection systems to monitor all operations in real time from either a desktop computer or remotely on a mobile device. Smart waste collection online tools are designed to learn

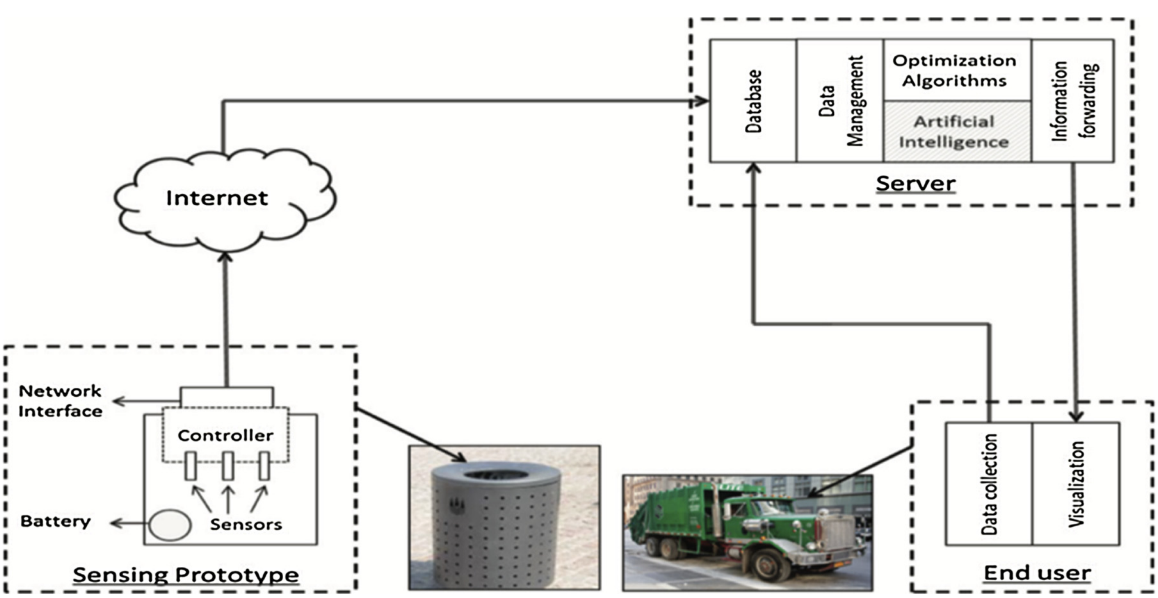

Fig. 6. Components of a smart waste collection system (Gutierrez et al., 2015).

from experience and can make decisions based not only on the daily waste level status but also on future waste forecasts, traffic congestion, balanced cost-efficiency functions, and other factors that humans are unable to foresee. The advanced data systems in smart waste collection enable optimized selection of trashcans to be collected which improves collection efficiency and reduces operation costs.

Many cities across the world have already implemented smart waste collection systems in urban management programs in tandem with IoT technology advancements (GreenBiz, 2017). Companies such as Ecube Labs and Bigbelly Solar have already successfully deployed their smart waste collection systems technologies at universities, city streets, train stations, and airports in Dublin, Los Angeles, Melbourne, Seoul, and Washington D.C (Bigbelly, 2017; Ecube Labs, 2017b). These projects have resulted in waste collection cost savings as high as 85%.

Smart waste collection technologies contribute to building a ZWM ecosystem because waste producers, collectors, and converters become digitally connected to enhance waste management operations. Waste management assets such as collection trucks are able to perform more efficiently because they can be dispatched along a route with bins at fill levels that are maxed out or near maximum capacity, as opposed to driving through a collection route with bins at low fill levels. Data from smart waste management systems and their components can be used to create strategies that identify the best route and time of day during the week that is best for collection. This reduces the amount of labor, trucks deployed, and fuel required to carry out waste collection operations. Efficient collection of recyclables through smart waste collection systems will also enable more conversion of waste to resources for other supply chains.

3.4. High-value mixed waste processing

Mixed waste processing (MWP) uses a combination of new and existing technologies at large facilities to sort out the recyclables from streams of mixed waste. The goal of high-value MWP is to achieve greater yields of recycled products that are valuable for end-users. One of the greatest challenges in achieving high-value MWP is developing technology that processes single streams of mixed waste and segregates products with very minimal contamination in a cost-effective manner. Overall, the MWP industry is moving towards large regional single-stream facilities, as opposed to small-scale operations (Gershman, Brickner, and Bratton Inc., 2015). Modern MWP facilities are mature and employ demonstrated technology for processing MSW and capturing recyclables.

Nearly all modern MWP facilities include a pre-sort to eliminate bulky or prohibitive materials, a method to open bags, and screens that remove fine materials (Gershman, Brickner, and Bratton Inc., 2016). Advancements in MWP are expected to be primarily focused on improvements in identification and segregation technologies such as optical sensors that can target and separate specific plastics. Optical units in modern material recovery facilities (MRFs) are mostly used to recover polyethylene terephthalate (PET) and high-density polyethylene (HDPE). However, optical units can also be used to recover other recyclable mixed plastics, frequently referred to as plastics grade #3 through #7. Table 5 provides details about state-of-the-art technologies used across all processes for MWP.

Combining MRFs and MWP systems have potential to significantly increase both volume and total revenue from recycling materials (Gershman, Brickner, and Bratton Inc., 2015). Routing MRF residue to the MWP facility could allow for greater potential of reprocessing and recovery of recyclables. The MWP facility could also serve as the consolidation point for all the non-recovered material output streams which would improve efficiency. This would allow the MRF to still recover high quality recyclables while the MWP facility would recover additional recyclables of adequate quality.

High-value MWP contributes to building a ZWM ecosystem by increasing recovery rates of valuable materials from mixed waste streams and reduces the magnitude of waste sent to the landfill. Increasing MWP allows for greater segregation of waste that can be reused as resources in other supply chains. Even after residents have separated out recycled commodities, the average MSW stream may contain up to half of the total volume of recyclables, and in many cases more than half. Conducting research to improve high-value MWP will help reduce future landfill costs. The costs of landfilling waste will only rise due to the rapidly declining availability of landfill space. Another benefit of improving high-value MWP is that the technology does not require consumer participation, education, or sorting behavior.

3.5. Collaborative platform for industrial symbiosis

Collaborative platforms for industrial symbiosis are an ongoing field of research focused on developing digital technologies that identify suitable waste to resource matches and facilitates those exchanges between different companies in a specific area or region (Fraccascia and Yazan, 2018). This promotes industrial symbiosis, an association between two or more industrial facilities or companies where wastes and by-products of one supply chain become resources for another. These platforms function similarly to social networking platforms such as LinkedIn, Uber, and Airbnb where people's demands are matched with supplies of resources and products. Currently, several internet-based platforms exist that facilitate industrial symbiosis. Industry organizations or facilitator companies usually offer these internet-based platform tools that allow businesses to discuss synergies through symbiosis in a safe and common environment (Chertow and Park, 2015). Platforms that are commercialized or under development usually include an interface where users input data about the waste and resources they have available or desire; a database for storing all the information about the different users and companies; and algorithms for matching different users based on their waste and resource needs (Low et al., 2018; Raabe et al., 2017; Song et al., 2015). Table 6 provides details that distinguish each of the different existing collaborative platforms designed to facilitate industrial symbiosis.

Expected future development of these platforms include software upgrades that use advanced data analytics and models to perform automated waste recycle and reuse matches. This would allow human labor to focus on verification and supervision instead of time-consuming research and analysis. Research is being done to upgrade these platforms to enable material informatics. This uses data mining and machine learning processes to analyze large ensembles of primary and waste material data to deliver the knowledge to end-users that require them for product development (Ramakrishna et al., 2018). Another area of research for this technology is development of analytical tools that calculate the environmental and economic benefits of the potential waste to resource exchanges and material processing systems using life cycle assessment (Jose and Ramakrishna, 2018). Future research is also being done to digitally connect all stakeholders involved in ZWM and have them interact on a cyber-physical environment as illustrated in Fig. 8.

A collaborative platform for industrial symbiosis contributes to building a ZWM ecosystem because these online platforms provide the necessary intelligence to connect all types of organizations to trade wastes and by-products between each other in an economically favorable manner. Manufacturing companies usually lack the knowledge about what kind of wastes can be converted into resources. Even if the companies have the technical capacity in this area, practical concerns arise such as the business viability and the willingness of companies to become partners to carry out waste to resource exchanges. Collaborative platforms for industrial symbiosis can catalyze ZWM by providing greater knowledge about which waste and by-products can be recaptured in other product supply chains which reduces waste generation and primary resource consumption.

Table 5
State-of-the-art technologies used at MWP facilities (Gershman, Brickner, and Bratton Inc., 2016).

Technology	Type of equipment used and process carried out
Conveyors	Rubber and metal belts are used to move materials to and from processing equipment, sort stations, and to final storage. Modern conveyors include belt cleaning mechanisms that remove fine and wet materials that tend to stay on the belt.
Bag openers	Mechanical parts that release materials from closed plastic trash bags without resizing or changing the contents. Most designs of bag openers allow large and unbreakable objects to pass through by exiting spring loads or other mechanisms without jamming the bag breaker.
Primary shredders	Hammermills, grinders, and high-speed shredders are used to reduce the size of the waste. The downside to hammermills is that they create a lot of dust and fines, and do not work as well on materials such as plastic film that does not shear or break easily.
Secondary shredders	Secondary shredders are used only when additional size reduction of mixed waste is needed such as in the production of materials for refused-derived fuel, densification, or other processes. Types of secondary shredders are high-speed, high inertia hammermills, medium-speed single rotor shredders, and low-speed shear shredders with multiple shafts and are almost always used in conjunction with primary size reduction.
Screens	Mechanically separate materials by size. Types of screens include vibratory screens, trommel screens, disc screens, and ballistic screens. Each screen agitates and spreads out materials to break up loosely bound items and separate smaller items from larger ones.
Ferrous magnets	Types of magnets currently used are belt magnets, head pulley magnets, and drum magnets. The belt magnet consists of a cleated rubber belt that travels between two non-magnetic pulleys over a central magnet that can either be a permanent magnet or an electromagnet. Head pulley magnets are permanent magnets set up as the head pulley of a conveyor. Drum magnets have non-magnetic steel covers that rotate about fixed internal permanent or electromagnets.
Non-ferrous magnets	Eddy current separator units are commonly used as a non-ferrous magnet to separate non-ferrous metals such as aluminum and copper from a stream of materials.
Air separation systems	Air drum separators remove heavy or light items from the material stream, or to occasionally split high-volume streams into similar composition fractions.
Optical sorting systems	Optical sorting systems use near-infrared light and sensors to recognize different plastics at processing plans. The technology uses light to illuminate the material stream and sensors that collect the reflected or transmitted light to analyze the light properties using spectrometry. The spectrometry reveals the wavelengths that are reflected by the objects.
Densification systems	Densification compacts resulting material streams from an MWP facility into a smaller, more transportable form that can be easily stored. These transportable forms include balers for recovered plastics and fiber or a residue compactor that presses the residue stream into a container. The two types of balers commonly used at MWP facilities are single-ram and double-ram.

3.6. Waste to resource conversion and recycling

3.6.1. Food waste to energy

Mature technologies for converting food waste to energy uses biological, thermal, and thermochemical reactions to yield products that can be used as raw energy. Anaerobic digestion and fermentation are the biological processes employed. Thermal and thermochemical processes use incineration, pyrolysis, gasification, hydrothermal oxidation (Pham et al., 2015). The efficiency of food waste to energy conversion technologies is strongly reliant on pretreatment and quality of waste. Table 7 lists the energy products and by-product of each food waste to energy technology.

Each class of food waste to energy conversion technology has its own benefits and challenges. Anaerobic digestion has been successfully commercialized to generate biogas from food waste. However, it is challenged by the duration of conversion since it can take 20-40 days for the microbial reaction to be completed (Pham et al., 2015). Fermentation has demonstrated itself to be a technically feasible process for producing ethanol from food waste. However, the overall economic viability of fermentation needs further research to determine ways to reduce the costs of converting food waste to ethanol. Waste incineration with heat recovery has been used to deal with food waste, but there are few studies that provide consistent information about the amount of energy recovered from incinerating food waste. Furthermore, food waste is not well-suited for incineration because of its high moisture content and contains non-combustible components. Food waste that is incinerated is usually in the general flow of MSW and is not treated in a separate group. Pyrolysis and gasification are complex thermal processes involving chemical and physical interactions that take place at temperatures above 600 degrees Celsius in an oxygen-free environment (Pham et al., 2015). The syngas gas produced can be burned directly or be used as fuel for gas engines and turbines or be used as feedstock for producing chemicals such as methanol. Similar to incineration, the specific properties of the solid waste can significantly affect the waste to energy gasification process. To date, there are not any gasification and pyrolysis processes that can solely deal with food waste. Hydrothermal carbonization has received more research attention because it can deal with waste streams with moisture content as high as 80–90%. Hydrothermal carbonization uses a wet process to convert food wastes to a high value energy-rich resource under autogenous pressure and low temperatures of 100 to 250 degrees Celsius. The energy-rich resource, often called hydrochar, is sterile, hygienic, and is easy to store and transport. It has been reported that the highly carbonized and energy-rich material has a composition equivalent to that of lignite coal (Berge et al., 2011). Hydrothermal carbonization technology therefore offers an efficient way of converting a wide variety of food wastes without the need for an energy-intensive drying process, which is a common requirement in other food waste to energy technologies.

Table 6
Collaborative platforms for industrial symbiosis that exist or are under development.

Name	Distinguishing Features
The Materials Marketplace *Pathway 21*	Platform has engaged 23 large U.S. companies and facilitated 68 potential waste to resource matches, and has received several awards since 2015 (Pathway 21, 2019).
SYNERGie 4.0 *International Synergies*	Software was developed using International Synergies' project experiences. Currently being used by industrial symbiosis practitioners in nine countries to allow users to characterize, search, and match their company's resources within a site and across multiple sites (International Synergies, 2019).
Waste-to-Resources Matching Platform *Singapore Institute of Manufacturing Technology*	Currently under development and is targeting food manufacturing, consumer products, chemicals, and pharmaceutical sectors in Singapore (Raabe et al., 2017; Low et al., 2018).
SymbioSyS *University of Cantabria*	Tool is based on ICT-web systems with a large database that stores both tacit knowledge of experiences and practices and explicit information about activities. Tool has been tested within an industrial park community consisting of 25 small and medium sized enterprises from different industrial sectors (Álvarez and Ruiz-Puente, 2017).

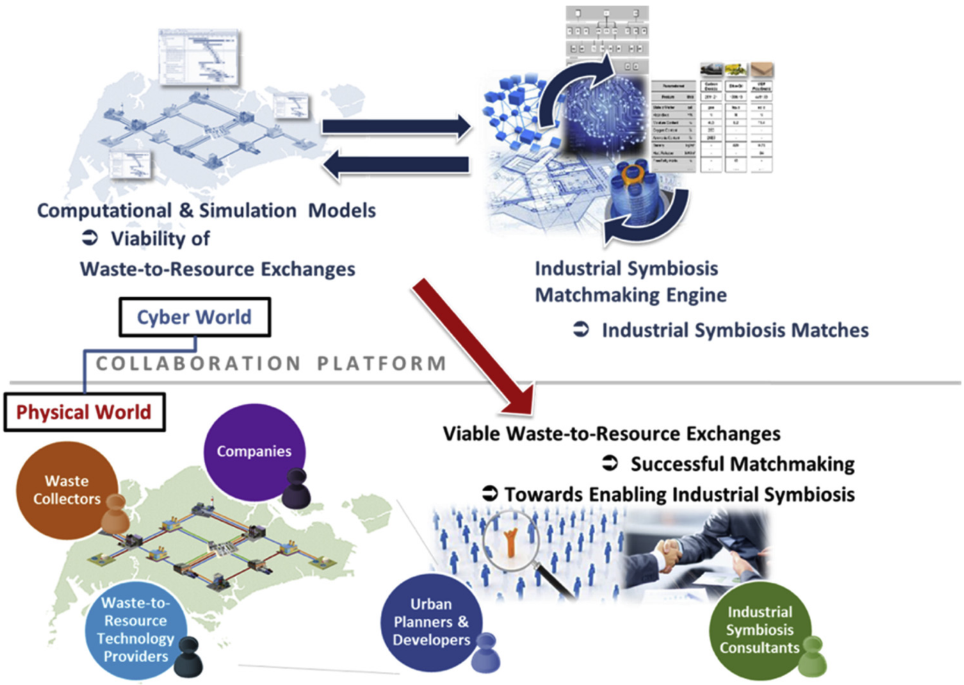

Fig. 8. Cyber-physical display of platform for waste-to-resource matching between companies.

3.6.2. Paper and cardboard

Commercialized paper and cardboard recycling technologies and processes are similar across the world. The main difference between regions, countries, and cities is the manner in which waste paper and cardboard is collected to the recycling facilities. The current practice starts with shredding collected recycled paper in pulpers and then mixing the fibres with water and chemicals, which are then heated into a slurry mix (Misman et al., 2008). Contaminants are then removed from the slurry mix and the mix is then put onto a conveyor belt to allow the fibres to bond together. Heated metal rollers then dry the paper which is then made into large rolls for new paper products. Due to different grades of paper, there is a limited amount of times that paper can be recycled. The length of paper fibers become shorter after every round of recycling which reduces its grade. Advancements in paper and cardboard recycling technology can be achieved through improvements in process efficiency at factories (ABB, 2018). This entails reductions in energy and chemical use at all stages of the recycling process through increasing the use of heat recovery, cogeneration, self-generated biomass fuel, efficient motors, and efficient steam use.

3.6.3. Plastics

Plastic recycling is currently done at large centralized facilities that take advantage of economies of scale in producing low-value products. There is strong demand for recycled plastic from manufacturing companies because recycled materials are a preferred choice for cost reduction and reducing waste. State-of-the-art plastic recycling processes can be categorized under four different classes as shown in Fig. 9.

Primary recycling is commonly known as re-extrusion and can only handle clean or semi-clean scrap plastic after the contaminated parts are sorted out. This makes MSW not suitable for primary recycling because of high contamination. Secondary recycling uses screw extrusion, injection moulding, and blow moulding to transform plastic materials through mechanical means into low value products. The processes involved in secondary recycling include cutting and shredding, separating contaminants, and separating flakes by floating. The final recycled plastic product is stored and then resold after pigments and other additives have been added. Plastic strands are then extruded further to make pellets based on the requirements and then the final products are manufactured. Tertiary recycling uses various methods such as pyrolysis, cracking, gasification, and chemolysis to recycle plastic materials by recovering monomers from plastic solid waste through depolymerization. Tertiary recycling can be separated into two types of techniques, chemical and thermal recycling. Quaternary recycling incinerates plastic waste that has already gone through primary, secondary, and tertiary recycling to recover energy. This method is only done when there is no other way to dispose plastic waste that is no longer valuable in other supply chains. Incineration of plastic waste emits harmful air pollutants such as carbon dioxide, nitrous oxides, sulfur dioxide, volatile organic compounds, particulate matter, particulate-bound heavy metals, polycyclic aromatic hydrocarbons, polychlorinated dibenzofurans, and dioxins.

Recycled plastic materials can be used in a variety of products to replace ceramic, wood, and metals because plastics are very functional, hygienic, light, and economical. Recycled plastics are typically used to make new plastic bottles, containers, bags, and clothing materials. Another application of recycled plastic is in manufacturing plastic

Table 7
Main products and by-products of each type of food waste to energy technology (Pham et al., 2015).

Conversion process	Products	By-products
Anaerobic digestion	Gas (CH_4 and CO_2)	Sludge that can be used as a fertilizer after being treated
Ethanol fermentation	Ethanol, CO_2	Animal feed
Incineration	Heat, electricity	Ash
Pyrolysis	Char, oil or tar, gas (CO, CH_4, hydrocarbons, H2, CO_2)	Char that can be used as an oil amendment, activated coal or sorbent
Gasification	Gas (CO, CH_4, N_2, H_2, CO_2)	Ash
Hydrothermal carbonization	Hydrochar and gas (mainly CO_2)	Crude oil and process water (contains value-added chemicals)

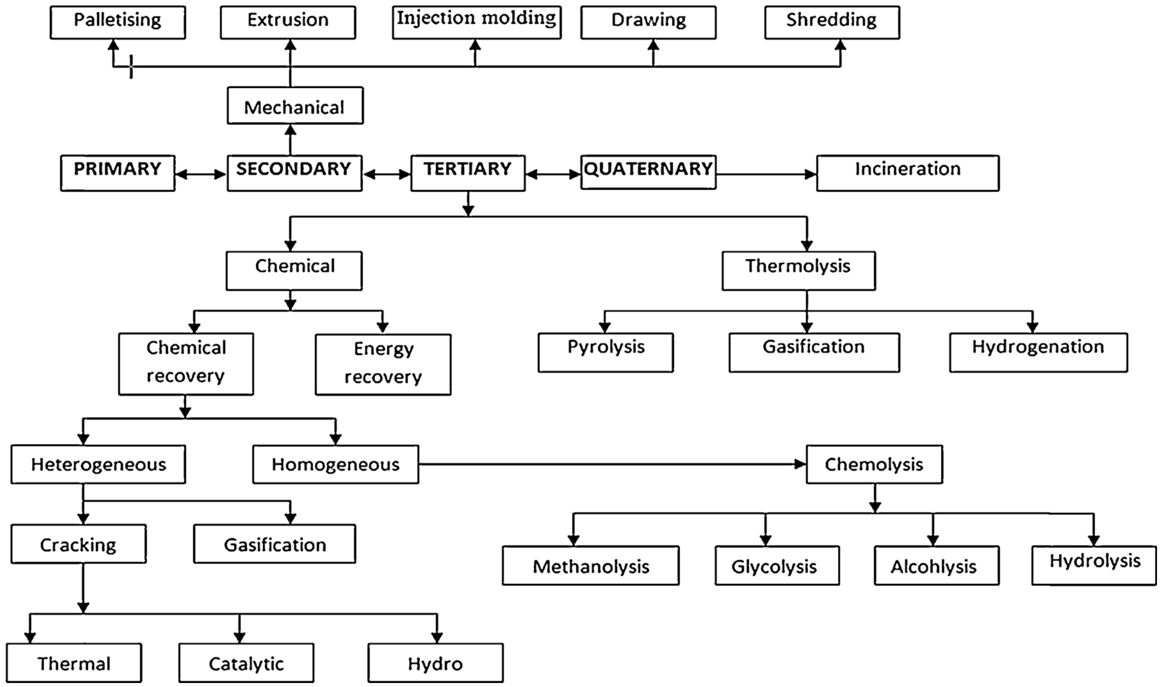

Fig. 9. Classification of plastic waste recycling methods (Singh et al., 2016).

lumber which can be used to construct pier and dock surfaces, marine piling, fences, park benches, and outdoor decking. Plastic lumber mostly uses HDPE, LDPE, and PP as the feedstock. Another application of recycled plastic is in producing plastic filament for 3D printing. Several companies have developed machines that are able to shred and grind post-consumer plastic, specifically HDPE, which is then melted, extruded, and then spooled into the plastic filament. 3D printers then use the filament to make new plastic products. The variety of applications available for recycled plastic material drives the demand to collect and recycle post-consumer plastic through the different conversion methods.

3.6.4. *Electronic waste*

Waste electrical and electronic equipment, also known as e-waste, has become a pressing environmental problem globally due to the rapid uptake of electrical and electronic equipment by consumers. In 2016, global e-waste generation reached 44.7 million metric tonnes and only 20% was recycled (Baldé et al., 2017). Asia generated the most e-waste followed by Europe, the Americas, Africa, and Oceana. The biggest challenge is that a majority of e-waste is not tracked and documented adequately and waste equipment is not recycled or treated properly. E-waste recycling is currently driven by prevention of hazardous heavy metals from damaging ecosystems and human health and capturing precious metals such as copper, steel, aluminum, and gold. Traditional e-waste recycling starts with manual disassembly and separation of the different components. Then the components are categorized into parts that can be reused or need to be further processed for recycling. Parts that are unable to be disassembled are then sent through size reduction processes, removal of dust and debris, and then separation of metallic contents through magnets.

Pyrometallurgical and hydrometallurgical processes are currently practiced in industry to extract valuable metals from e-waste. Pyrometallurgical processes extract metals by directly burning e-waste in a blast furnace resulting in a product with 70–80% black copper by weight. The black copper is then put through a converter to be oxidized and then reduced in an anode furnace. Afterwards, the copper anode produced is further purified in a sulfuric acid electrolyte with other elements such as nickel, zinc, and iron. An issue with pyrometallurgical recovery is that huge amounts of wastewater and residues are produced which can cause serious pollution if the wastes are not handled properly. Furthermore, it is hard to recover metals other than copper through incineration and non-metallic materials cannot be recycled during the process. In hydrometallurgy, strong acids such as HNO_3, HCl, or $HClO_4$ are commonly used as leaching solvents to extract metals such as copper, lead, and zinc from e-waste. Cyanide leaching has also been done to extract gold from e-waste components. The challenge with these traditional methods of incineration and acid leaching is that the processes have low metal recovery rates and the chemicals used and wastes produced are hazardous to human health and the environment.

More advanced methods of e-waste recycling exist that can achieve higher metal recovery rates, lower costs and resource inputs, and reduce impacts to the environment and human health (Zhang and Xu, 2016). The challenges of some advanced methods are that they are still immature and have only shown successful results at the lab or pilot level and have high investment costs. The processes, inputs, and products extracted through different methods of e-waste recycling are summarized in Table 8.

3.6.5. *Remanufacturing*

Remanufacturing is another form of waste to resource conversion that focuses on bringing used products back to original or better conditions (Center for Remanufacturing and Reuse, 2017). Products that are easy to disassemble enable efficient remanufacturing. Steps in the remanufacturing process are illustrated in Fig. 10.

Most remanufactured products are required to pass a set of quality standards before they are resent out for sale. Companies around the world that conduct remanufacturing activities are listed in Table 9.

Remanufacturing has been an undervalued part of the sustainable industries landscape with activities promoted only on a sector-by-sector basis. The prices of remanufactured products are also typically 60–80% lower compared to the cost of a new product (Centre for Remanufacturing and Reuse, 2017). The European Remanufacturing Network conducted a Remanufacturing Market Study to estimate the level of remanufacturing in the European Union and understand the barriers that need to be addressed to advance remanufacturing. Countries covered in this landscape review were Brazil, China,

Table 8
E-waste metal recovery processes, inputs, and products.

E-waste metal recovery method	Process details and inputs	Products extracted
Pyrometallurgy	Main processes include dismantling, smelting in a plasma arc furnace, drossing, sintering, melting and reactions in a gas phase at high temperatures. Crushed scraps containing base and precious metals are burned in a high temperature furnace. Metals are then volatilized by a chemical reaction or by heat, and impurities are converted into slags. Improved treatment of pollutants from incineration and purification process compared to traditional pyrometallurgy.	High quality copper. Other pure solid metals that have been extracted include silver, gold, palladium, nickel, selenium, and zinc.
Hydrometallurgy	Can achieve more targeted metal recovery and pre-treatment, better control of chemical reaction and produces less pollution. Uses more mild leaching agents such as chlorinate, ammonia-ammonium, non-cyanide lixiviants, and organic acids (i.e. citric acid and hydrogen peroxide). Metal extraction rates as high as 98% at lab/pilot scale.	Copper, gold, silver, palladium extracted in solution
Biometallurgy	Bioleaching and biosorption are the two main techniques for metal recovery. Bioleaching uses acidophilic group of bacteria to bioleach heavy metals. Biosorption uses biological materials to remove substances from solution in a physico-chemical and metabolism independent process. Microorganisms used as biosorbents include bacteria, fungi, algae, actinomycetes, yeasts and some biowaste materials. Technology currently successful at laboratory scale and has not been industrialized yet.	Copper, nickel, zinc, chromium, gold, silver extracted in solution
Electrochemical technology	Highly energy efficiency process and uses a minimal amount of chemicals to dissolve and recover metals on a cathode for further processing. An electrochemical cell maximizes energy efficiency of the process. The process of electrorecycling generates oxidizing agents at an anode in order to dissolve metals from the scrap matrix. The dissolved metals are then reduced at the cathode. Technology has not been commercialized yet.	Pure solid copper, gold, silver
Supercritical technology	An environmentally friendly method that decomposes organic polymers and recycles metals since supercritical substances have unique properties such as low viscosities, high mass transport coefficient, high diffusivity, and high solubility. Example supercritical substances used are supercritical water, supercritical methanol. Technology has not been commercialized yet.	Almost all metals can be extracted at a high recovery rate. Output is a solid mixture of metals.
Vacuum metallurgical technology	Metals are separated based on difference in water pressure of the metal elements at the same temperature. Can separate and recycle different metals from waste printed circuit boards under the guidance of separation criteria. Four crucial processes of vacuum distillation of metals are heat transfer, evaporation, mass transfer and condensation. Main environmental benefit is wastewater pollution is not produced. Technology is still immature and has not been commercialized yet.	Cadmium, zinc, lead

Denmark, India, Japan, South Korea, Malaysia, Singapore, United Kingdom, and United States (European Commission, 2015). From the study, the major challenges of remanufacturing identified were:

1 Logistics chain: Costly and complicated collection of cores.
2 Compliance with quality requirements: Costly to ensure the quality of remanufactured products.
3 Long-term investment: Cost intensive research and development is required for remanufacturing and has a long payback period that can be too risky for some companies.
4 Too much transparency: Remanufacturing requires cooperation between suppliers and customers, as well as an open value chain. This can give competitors an advantage and increase espionage.
5 Sales versus leasing: To counter customers' skepticism of remanufactured products, some companies lease their products to the customers. The inability to lease some product types was seen to be a potential barrier.
6 Complex with seemingly overlapping authorities and contradictory regulations from governments have deterred remanufacturing progress in certain countries.
7 In middle income or developing countries, the remanufacturing sector is largely unregulated, quality varies, and counterfeiting is common.

Advancing research and implementation of technologies for recycling food, paper, cardboard, plastic, e-waste, and other post-consumer products contributes to building a ZWM ecosystem by increasing the amount of waste recovered for use as resources in other supply chains and reduces reliance on virgin materials in manufacturing. Greater waste to resource conversion also reduces stress on the limited landfill capacity in different countries and also reduces the amount of waste shipped abroad for disposal.

4. Discussion

4.1. Integrating ZWM technologies

The review of state-of-the-art industry technologies and research revealed that there are many technology options that waste value chain stakeholders in Singapore and other countries can adopt to achieve ZWM. Applications of Internet-of-Things (IoT) technologies was found in the review to be an enabling factor for connecting different stakeholders along the waste value chain. IoT is the connection of all technologies to the internet and to each other that builds off cloud computing and networks of sensors that continuously collect and monitor data. Devices in IoT are not limited to smartphones, but also include everyday equipment such as coffee makers, washing machines, household lighting, vehicles, and cash registers (Risteska Stojkoska and Trivodaliev, 2017). IoT has risen due to swift expansion of basic and affordable internet access and growth in smartphone adoption. Smart waste collection systems demonstrated the application of IoT in cities through the use of the internet to connect sensors, smart bins, waste hauling trucks, and the waste management system. IoT technologies are also applicable to collaborative platforms for industrial symbiosis. This is because data covering waste volume, type, and cost from waste producers and recyclers can be shared between stakeholders to

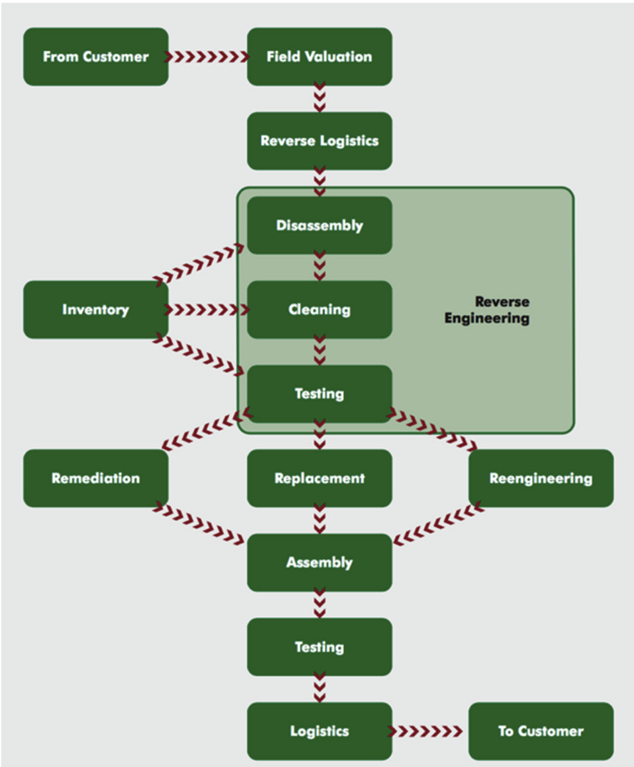

Fig. 10. Remanufacturing process diagram (Centre for Remanufacturing and Reuse, 2017).

Table 9
Companies engaged in remanufacturing organized by product sector.

Product sector	Company
Machine tools	Jones & Shipman, Millbrook, Douglas-Curtis, Marrill
Pumps	Weir, Plenty, Sulzer, Johnson
Compressors	Comptec, Flatwoods, J&E Hall, ThermoCom
Refrigeration installations	Bond Group, Manor Concepts
Starter motors	Sovereign
Automatic transmissions	Mitchell-Cotts, ATP
Car and truck engines	Autocraft, Ivor Searle, Perkins, Caterpillar
Photocopiers and printer consumables	Xerox, Danwood, Greenstrike
Excavation equipment	Powerhire, Blackhill Engineering
Power turbines	Alstom
Defense equipment	Vickers, BAe Systems, ABRO
Computer and telecoms equipment	Sony, Solectron

facilitate feasible waste to resource matches and exchanges.

4.2. Feasibility of ZWM technologies in Singapore

Applying the ZWM framework introduced in this study can help decision-makers explore the technology options that can improve waste reduction in manufacturing and increase reuse, sorting, collection, and recycling along the entire waste value chain. However, there are several limitations existing ZWM technologies may face during implementation in the manufacturing and waste management sectors in dense urban cities such as Singapore. This section briefly revisits Singapore's manufacturing and waste management sectors and discusses the practical feasibility of implementing the technologies reviewed under the ZWM themes. Based on the barriers identified in implementing ZWM technologies, future areas of research are recommended to help Singapore and other dense urban regions overcome them to transition to a circular economy.

4.2.1. Manufacturing and waste management sectors

Similar to many other nations and cities across the world, Singapore seeks to transition to a circular economy to meet their national zero waste goals while also advancing its manufacturing sector to boost economic growth. Singapore's manufacturing sector is dominated by the key industry clusters of electronics, chemicals, biomedical sciences, logistics, and transport engineering that contribute to 20–25% of the country's GDP (Enterprise Singapore, 2019). Singapore is globally ranked as the fourth largest exporter of high-tech goods and many leading multinational companies across different industrial sectors have chosen Singapore as a strategic manufacturing hub (Economic Development Board of Singapore, 2018). In terms of sustainability, the Singapore Institute of Manufacturing Technology operates a Sustainable Manufacturing Centre that assists companies in Singapore improve energy, water, and material efficiency and waste reduction across their entire manufacturing supply chain using both hardware and software solutions.

Singapore currently operates a well-organized waste collection and disposal system to manage waste generated across all economic activities, but it still requires improvements to boost its overall recycling rate. Wastes are collected by four public waste collector companies which are Colex Environmental Pte. Ltd, SembWaste Pte. Ltd, Veolia ES Singapore Pte Ltd, and 800 Super Waste Management Pte. Ltd. Waste collection in Singapore is divided into six regions of which the four companies are responsible for managing separately. The waste collected are sent to sorting facilities where recyclables are separated, and the rest is sent to Singapore's four waste-to-energy incineration plants. The incineration ash and waste deemed unrecyclable are sent to Semakau Landfill for final disposal. Singapore's main goal in becoming a zero waste nation is to increase its recycling rate to 70% by 2030 from its current rate of 60%. Today, about 37% of waste generated in Singapore is incinerated and 3% of waste generated is sent to the landfill. As shown in Fig. 11, paper and cardboard, plastic, and food were the waste streams with the highest volumes, but lowest recycling rates.

As a result, paper and cardboard, plastic, and food waste as well as electronic wastes have become the target waste streams to be addressed in Singapore's Zero Waste Masterplan that is undergoing public consultation (MEWR, 2019a,b). One large scale project the Government of Singapore has invested in to improve waste management is development of an integrated waste management facility (IWMF) that is expected to start operating in 2022. The key waste streams to be handled at the IWMF are incinerable wastes at 5800 tonnes/day, household recyclables at 250 tonnes/day, food waste at 400 tonnes/day, and dewatered sludge at 800 tonnes/day (National Environment Agency of Singapore, 2018b). To address e-wastes, the Government of Singapore will implement extended producer responsibility system to cover five categories which are information and communications technology, such as mobile phones and computers; solar panels; batteries; lamps and large household appliances such as refrigerators, air-conditioners, washing machines and dryers (NEA, 2018a).

4.2.2. Implementation barriers of ZWM technologies

Opportunities exist to reduce waste generation and recover value from the high volumes of waste sent to the incinerator, but several barriers need to be overcome with regards to the feasibility of technologies reviewed under the ZWM themes. Specific technologies under the ZWM themes face fewer implementation barriers compared to others in Singapore to help transition to a circular economy. In the theme of design for zero waste, the feasibility of design for disassembly to impact existing products consumed in Singapore varies depending on the specific technology. In the case of building construction, modular construction of buildings has already demonstrated high feasibility. In the case of Singapore, the Housing Development Board (HDB) has already committed to having 35% of all new public housing projects be

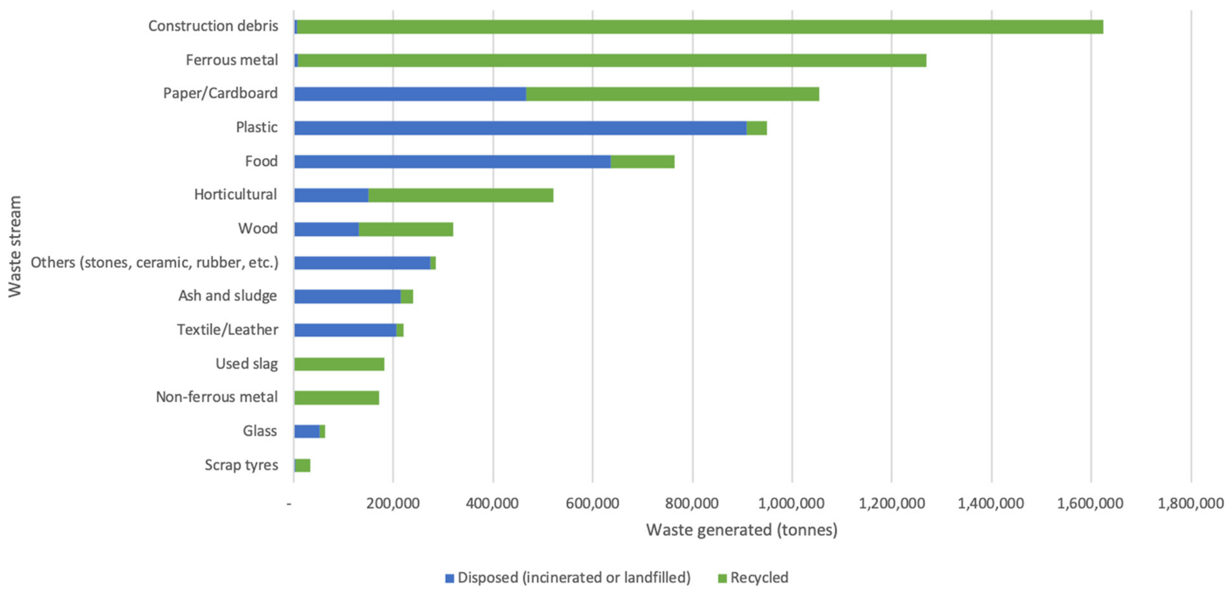

Fig. 11. Volume of waste disposed and recycled in Singapore in 2018.

constructed by using modular units produced at the factory instead of onsite construction (HDB, 2017). The benefits the HDB will gain from using prefabricated prefinished volumetric construction technology is improvement in productivity by 50% (HDB, 2017) and reduced waste generation from construction, reduced noise and dust at the construction site, and fewer incidences of wet construction joints all while having a higher quality home. Using modular construction is expected to increase costs by about 8%, but the higher construction costs will be offset by manpower savings (Channel NewsAsia, 2017).

Implementation of additive manufacturing technology in Singapore is being actively researched and developed (National Research Foundation, 2018) which will reduce generation of waste plastics, construction materials, and metals as well as improve energy efficiency in manufacturing processes in Singapore. Individual products designed for disassembly are feasible to produce in Singapore due to the country' capabilities in high-performance manufacturing technology. However, even if products designed for disassembly are produced in Singapore, the waste reduction benefits within the country would be dependent on whether a majority of those products are used in Singapore or exported abroad. As shown in Table 10, an analysis of Singapore's 2012 input output tables, the latest dataset publicly available, reveals that 75% of the goods and services households in Singapore consumed from the manufacturing sector were imported from abroad (Singapore Department of Statistics, 2012).

At the product group level, over 90% of the food products consumed in Singapore are imported from overseas (Agri-Food and Veterinary Authority of Singapore, 2019). Therefore, although Singapore is highly capable of manufacturing products designed for disassembly, the waste reduction benefits would be limited in the case where an overwhelming majority of households in Singapore consume products imported from abroad that are not designed for disassembly instead of equivalent products designed for disassembly and manufactured in Singapore.

Smart waste audit and reduction technologies are feasible to implement on the software side for waste data management and benchmarking. However, the physical process of waste data collection is the technical barrier that needs to be overcome. Unlike countries such as Japan, the U.S., and the UK that typically sort their wastes on site through specialized bins, a majority of post-consumer waste generated in Singapore's residential and commercial premises is commingled and therefore highly heterogenous in composition. State-of-the-art smart waste bins are able to measure the overall volume of waste generated, but they lack the ability to measure the volumes of waste by material type, which is information that is more valuable for detailed waste reduction planning. Countries and other dense urban centers such as Singapore require hardware technologies that are able to efficiently measure the volume of waste generated and estimate its material composition.

Smart waste collection technologies have been highly feasible to implement in Singapore's waste collection system. One of Singapore's four public waste collectors 800 Super has already implemented smart waste collection sensors at its compacters in bin centers in the towns of Tampines and Pasar Ris (Channel NewsAsia, 2018). The NEA has stated

Table 10
Private consumption of goods and services in Singapore, 2012.

Sector	Domestic	Imports	Domestic and Imports	Domestic share	Import share
Manufacturing	5.4	16.6	22	25%	75%
Utilities	2.7	0	2.7	100%	0%
Construction	0	0	0	0%	0%
Other goods	0	1.5	1.5	0%	100%
Wholesale and retail trade	12.7	0	12.7	100%	0%
transportation and storage	6.7	1.3	8	84%	16%
Accommodation and food services	12.4	0	12.4	100%	0%
Information and communications	2.9	0.1	3	97%	3%
Finance and insurance	8.3	0	8.3	100%	0%
Business services	22.3	0	22.3	100%	0%
Other services	24.8	−0.2	24.6	101%	−1%
Total	98.2	19.3	117.5	84%	16%

Values in billion U.S. dollars.

Fig. 12. Single-stream recycling collection bin in Singapore.

that the new smart waste collection systems have improved efficiency and will not result in increases in domestic waste collection fees. Furthermore, NEA will progressively roll out smart waste collection system through public waste collection companies by the end of 2021. Smart waste bins have not faced technical barriers in implementation. Many commercial premises in Singapore have already set up smart waste bins (Big Belly Solar, 2018).

The feasibility of implementing technologies for high-value mixed waste processing has not been an issue in Singapore since the country currently has several material recovery facilities operating which have helped the country maintain its recycling rate at 60%. However, the remaining 40% of mixed waste that is not recycled is of very low quality and as a result it is sent to the incinerators. Increasing the quality of the remaining 40% of mixed waste is necessary to increase the overall recycling rate. As shown in Fig. 12, Singapore provides blue bins for residents to mix together all recyclables.

Similar to other countries around the world, many non-recyclable materials are often mixed in with the recyclables in Singapore which causes contamination. According to the NEA, 40% of waste disposed in bins is contaminated and is not recoverable for recycling (Channel NewsAsia, 2019b). In residential settings, waste chutes are provided where residents are able to conveniently mix all wastes in a bag and throw it away (MEWR, 2019a,b). Although this practice enables an efficient waste collection system, it increases contamination of materials that are then no longer recoverable for recycling. Research is therefore needed to determine methods or technologies that would prevent contamination of recyclable waste streams. Smaller scale sorting facilities that are suitable for dense urban and residential areas that consumers can conveniently access would be able to reduce the amount of recyclable materials that get sent to the incinerator due to contamination.

Collaborative platforms for industrial symbiosis face few technical barriers for implementation in Singapore. This technology relies primarily on digital systems and would require minimal to nearly no changes in physical infrastructure to implement (Yeo et al., 2019). Many sharing economy-based services are already actively used in Singapore and so a similar digital platform focused on waste to resource matching and exchanges between individuals and companies is technically feasible. One of the challenges that may arise during the initial stages of implementation would be achieving a critical mass of users for the collaborative platform to successfully facilitate industrial symbiosis exchanges. The impact on Singapore's waste management system through implementing collaborative platforms for industrial symbiosis would be a reduction in the amount of waste materials that get mixed in with waste sent to incinerators. Instead, users would be directly matched to a market where their waste could be recycled to gain value and not need to rely on the existing waste collection and recycling system.

Singapore's severe lack of land space for development presents a major limitation in feasibility of implementing the technologies reviewed under the theme of waste to resource conversion and recycling (Zhou and Zhao, 2016; Murakami, 2018). With a total land area of 720 square kilometers, Singapore has the third highest population density in the world at 7,916 people per square kilometer (World Bank Group, 2017). Competition for land is therefore tough and offers little opportunity to implement new large-scale mixed-waste processing and segregation facilities, recycling centers, and waste digestors. As Singapore's population is 100% urbanized, implementation of these large-scale technologies in urban space-constrained environments could encounter public backlash due to the disruptive effects of waste conversion technologies such as foul odors and loud noises. In the case of food waste, Singapore has a high potential for improvement as only 16% of it is recycled and the volume of food waste generated continues to grow annually as shown in Fig. 13.

The new IWMF that will begin operating in 2022 is expected to treat 400 tonnes of food waste per day alone which would only increase the recycling rate to at most 34%, which still leaves more room for improvement. However, large scale food waste recycling facilities designed to treat as high as 800 tonnes of food waste per day have proven to be unsuccessful in Singapore due to contamination and poor logistics in food waste collection (Eco-Business, 2011). Food waste is typically generated in many distributed locations. Therefore, implementation of additional food waste digesters to successfully increase the amount of

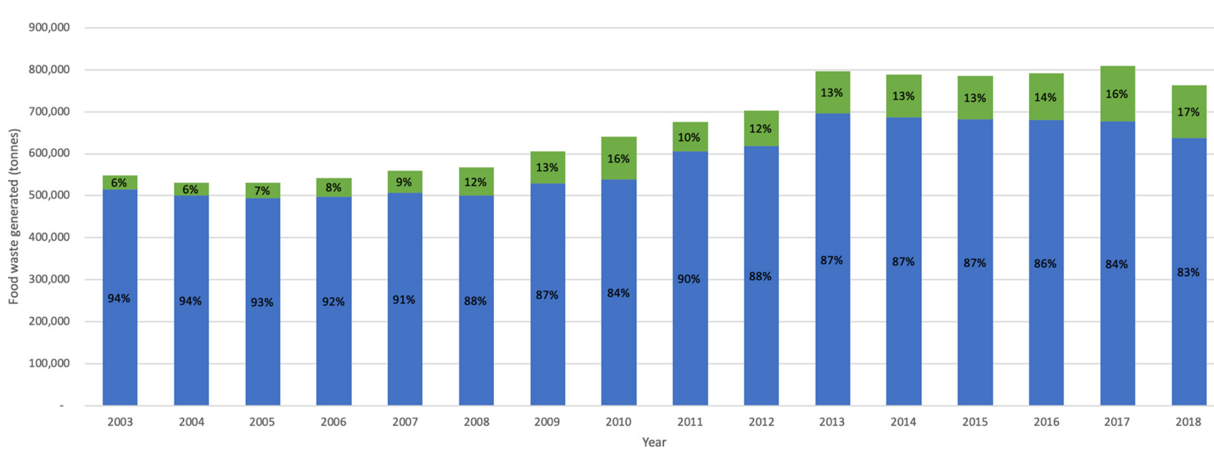

Fig. 13. Food waste generation in Singapore between 2003–2018.

food waste recycled will require conventional large scale technologies to be scaled down to match the volumes generated at the different sites and also be located closer to the source to avoid logistical issues (Lou et al., 2012). Systems will need to be designed in a way that have a very low level of disturbance to people in residential and commercial areas.

Paper recycling currently stands at 50% and offers more potential for increasing waste recovery. In Singapore, waste paper that is recyclable is sorted, baled, and shipped overseas for recycling since there are no paper mills in Singapore. Restrictions in land use does not make it feasible for implementing new paper recycling facilities in Singapore. However, the amount of waste paper disposed can be reduced by increasing the amount of waste paper collected, sorted, and baled. Existing technologies for collecting and sorting paper include conveyor belts, balers, trucks, which are all very large in size. The space occupied by such equipment and storage space are limitations to increasing the rate of waste paper recovery in highly dense urban regions such as Singapore.

Plastic recycling currently stands at 4% which presents a high opportunity for improvement. Currently, a majority of the plastic that Singapore recycles is done outside of the country. In 2016, Singapore exported nearly 42,000 tonnes of plastic waste to China, Malaysia, Vietnam and Indonesia (United Nations, 2016) representing about 81% of the plastic waste Singapore recycled and 5% of the total plastic waste generated. Singapore has therefore relied on its larger neighboring countries with large scale facilities to deal the process of shredding and washing waste plastics for recycling or through chemical recycling. The processes of collection and sorting of waste plastics however is taken care of by public waste collectors and other companies in Singapore. Even if Singapore were able to implement large scale plastic facilities to create products from recycled plastic waste, other than electricity and fuel, the issue of plastic waste contamination would still need to be resolved. More than 50% of waste plastics collected by recycling facilities in Singapore are incinerated because they are highly contaminated (Today, 2018). Therefore, the issue of preventing contamination of waste plastics should be addressed if mechanical recycling methods are to be used to boost the plastic recycling rate in Singapore far beyond 4%. Tertiary plastic recycling to high value fuels through thermochemical conversion methods could also serve as alternative to mechanical plastic recycling to deal with the high mixture and impurities in Singapore's plastic waste streams (Khoo, 2019).

For e-waste streams, using pyrometallurgical methods to recycle the 60,000 tonnes of e-waste produced in Singapore annually will face implementation barriers due to high costs, high energy intensity, and toxic fumes that pollute the environment. Voluntary programs led by industry currently exist where companies accept different types of e-wastes and send them off to partner companies for recycling (NEA, 2019a). A total of 15 companies in Singapore are listed as official partners for e-waste recycling (NEA, 2019a) of which two of these companies publicly state that they use hydrometallurgical methods to recover valuable materials in e-waste. These companies carry out their operations in facilities sited on industrial premises. Hydrometallurgical methods have attracted more attention in research and development in Singapore. Nanyang Technological University, the French Alternative Energies and Atomic Energy Commission, and NEA have invested USD14.8 million to develop a research center focused on less toxic e-waste recycling using hydrometallurgical methods along with other non-pyrometallurgical techniques (Channel NewsAsia, 2019a,b). Remanufacturing would also be a feasible method Singapore can use to reduce the amount of electronics and electrical equipment that have to be recycled. Research and development and implementation of remanufacturing in industry is already active in Singapore at research institutes such as the Advanced Remanufacturing and Technology Centre (ARTC) that collaborates with 65 members ranging from global multinational corporations to small and medium enterprises (ARTC, 2019).

5. Future research areas in ZWM

To overcome the limitations that current ZWM technologies may face during implementation in Singapore and other dense urban settings around the world, several areas of research are recommended.

1. **Smart bins that measure waste material composition:** To advance smart waste audit and reduction planning, smart waste bins need to be able to collect data about the material composition of the waste disposed in the bin. This type of data is valuable for organizations to monitor the type of waste they produce and then make strategic waste reduction plans that target specific waste streams. Identifying the waste composition in a smart waste bin would be especially useful for countries and cities that typically use single bins for disposing both wastes and recyclable items.
2. **Small and medium sized waste sorting technologies:** Although the global mixed waste processing industry is moving towards large regional single-stream facilities, small and medium sized sorting facilities are still needed in urban centers that have higher waste generation levels. Research is needed to design waste sorting and material recovery facilities and equipment that have lower space requirements so that they can be sited within or closer to urban centers. Having smaller waste sorting facilities distributed in urban centers could reduce the logistical demands as the facilities would be closer to the sources of waste generation.
3. **Matching consumers with remanufacturing services:** Households that use products produced domestically or imported from abroad may not know that their product can be repaired or refurbished to extend its useful life and may not know where to access such services. Certain company-specific products imported from abroad that can be remanufactured may not have their company's service available in the country the product is used in. However, there may be small-medium enterprises that have the technical capability to remanufacture different products regardless of the company the product is manufactured from. Industrial symbiosis platforms should not only focus on waste to resource exchanges, but also help match consumers with remanufacturing service providers. These types of matches would help facilitate remanufacturing of products that are designed to be repaired or disassembled regardless of whether the product was imported or produced domestically.
4. **Life cycle impact evaluation models for IS platforms:** Multilevel models that evaluate the life cycle impacts of all waste to resource exchanges in closing the resource loop are needed in industrial symbiosis platforms to prevent environmental burden shifting. These models can help businesses and other stakeholders of a collaborative platform understand and design better systems to gain both environmental and economic costs and benefits from closing resource loops (Low et al., 2016, 2014, 2012; Low et al., 2018). Government entities and city planners can also use these models to measure performance in meeting environmental sustainability targets.
5. **Small scale food waste digesters:** Dense urban settings present space limitations for implementing large scale digesters for recycling a region's food waste. Implementation experience has shown that large scale digesters in urban settings face financial issues due to logistical challenges. Research is therefore needed in developing smaller food waste digestion systems that can be sited close to the source of generation such as residential areas or commercial dining areas and sized for the specific daily food waste volumes. The technical issues that need to be overcome are reducing odor and noise from the small scale digesters to avoid disturbance to people nearby.
6. **Reducing contamination of consumer waste streams:** Technologies for recycling waste such as plastics and paper and cardboard are already mature, but recycling rates are still low. One

major cause of this is that many recyclable materials become highly contaminated when mixed with other waste streams. The contaminated recyclable materials are sent to the landfill or incinerator because they are no longer economic to recycle. Research is needed in developing technologies that are able to recycle materials that are contaminated or technologies that can reduce the contamination of disposed materials to overcome this issue which would help boost the volume of materials that are recycled.

6. Conclusion

As more nations continue to implement waste import bans, governments and businesses that were highly reliant on exporting their wastes abroad are now faced with the challenge of finding alternative solutions to manage their growing volumes of wastes. Moving beyond traditional end-of-pipe waste disposal methods and transitioning to a circular economy is critical to overcoming the global waste challenge in a holistic manner. ZWM can aid in the transition by developing manufacturing systems that minimize waste generation across entire value chains and maximizing the use of wastes as resources in other supply chains. To enable ZWM, stakeholders such as generators, collectors, and converters and recyclers will need to know what technologies they can implement to fulfill their role in the waste value chain. This study proposes a framework for ZWM comprising six themes of (i) design for zero waste; (ii) smart waste audit and reduction planning; (iii) smart waste collection; (iv) high-value mixed waste processing; (v) collaborative platform for industrial symbiosis; (vi) waste to resource conversion and recycling. The framework aims to help stakeholders in the waste value chain identify the technologies they can implement to achieve ZWM.

Through a systematic review approach, state-of-the-art technologies and research literature under the six themes of the ZWM framework were identified and examined. The findings of the review revealed that there are many mature technologies under each theme of ZWM that stakeholders can implement to address their challenges. The technologies include additive manufacturing, design for disassembly, modular products and buildings, smart waste auditing tools, smart waste bins and smart waste collection systems, material recovery and mixed waste processing technologies and facilities, digital platforms for enabling industrial symbiosis, remanufacturing, and technologies for recycling waste streams of food, paper and cardboard, plastics, and electronics and electrical equipment. The use of IoT technologies in smart waste collection systems showed that IoT technologies should be applied to ZWM overall so that waste generators, collectors, and converters can be integrated on a single system that shares data to facilitate greater waste to resource exchanges. The feasibility and technical limitations of implementing the ZWM technologies in highly dense urban centers were then discussed by using the case of Singapore. To overcome the technical limitations of ZWM technologies and make them more feasible to implement in urban centers, it is recommended that future research is pursued in scaling down waste sorting facilities and food waste digesters, developing smart waste bins that collect data about waste material composition, and improving collaborative platforms for industrial symbiosis so that they can measure the life cycle impacts of waste to resource exchanges and match consumers with product remanufacturing services. The findings of this study can be used by countries and cities to develop a roadmap for ZWM. In Singapore and other similar countries and urban settings, implementing the technologies and conducting activities that contribute to the themes of ZWM through a roadmap will help transform the manufacturing sector by decoupling economic growth from environmental degradation and bolster resource security.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104438.

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