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Unlocking system transitions for municipal solid waste infrastructure: A model for mapping interdependencies in a local context

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ABSTRACT

Rapid global urbanization, urban renewal and changes in people's lifestyles have led to both an increase in waste generation and more complex waste types. In response to these changes, many local governments have invested in municipal solid waste infrastructure (MSWI) to implement circular strategies. However, matching and bridging the costly and logistically complex MSWI with the dynamic social context is a central challenge. In this paper we aim to explore the interdependencies between MSWI and the local social system, and then conceptualize and empirically validate the systemic nature of MSWI. We first review the current MSW treatment methods, corresponding infrastructure, and the challenges facing them. Then, we interrogate system-oriented concepts and use two key insights to set up a conceptual model for mapping the interdependencies in a MSWI system (MSWIS). Finally, a case study of the Dutch city of Almere is used to empirically validate the MSWIS model and identify the social systems that contribute to the development of the MSWIS. The analysis reveals that the development of MSWIS is beyond the municipality's control: efficient resource recovery facilities established by businesses under market rules and waste reuse facilities constructed by social organizations/individuals based on their own needs are key pieces of the puzzle to complete the MSWIS. This highlights the ability of the framework to capture interdependencies that go further than just the formal municipal sphere of influence.

1. Introduction

Worldwide, the urgency for circular changes has been called for in numerous international agreements (such as the Circular Economy Action Plan in Europe) and national policies (such as Circular Economy 2050 in the Netherlands). This requires cities to make drastic changes to their municipal solid waste (MSW) management, such as better recycling capabilities, more accurate waste sorting, and more frequent repurposing of resources after use. For such circular changes to be effective, cities need to make significant changes to the underlying hardware, also referred to as the municipal solid waste infrastructure (MSWI). Despite the clear urgency this hasn't proven to lead to effective changes.

A few key reasons surface as to why MSWI is not yet equipped for these urgent changes. On the external side, the needs of MSW management are constantly changing. Rapid global urbanization (Egidi et al., 2020) and urban renewal have seen economic development and enabled people to consume resources more rapidly, thereby resulting in an increase in the amount of waste and the complexity of waste types (Rootes, 2009). Developed countries are dealing with these needs side through legislation. For example, "The Waste Framework Directive (WFD)" (EU, 2008) is seen as a milestone in sustainable waste management in the EU, introducing a waste hierarchy. It clarifies that waste should first be prevented from being generated; then the generated waste should be reused, recycled, or recovered, and finally the remaining waste that cannot be recycled due to resource loss and health hazards should be handled through incineration or landfill. Since landfilling is the least preferred option, the EU has ordered a reduction in landfilled waste from 24% in 2018 to 10% in 2035 (EU, 2018). The implementation of the EU waste hierarchy has raised stricter requirements on the separation of MSW streams, highlighting the need for investment in modern MSWI.

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On the internal side, existing MSWI is experiencing lock-in caused by high costs, lagging legislation, and normative social constraints. Looking at the state of MSWI worldwide, landfill and incineration still dominate waste disposal in most cities, particularly in developing countries (Ferdous et al., 2021). Previous studies have revealed part of the reason why the lock-in is difficult to unlock. First, many local governments cannot afford the financial costs (Subagio et al., 2020) and technical requirements (Chalfin, 2017) for large-scale upgrading of MSWI. Second, lagging legislation (Patil & Ramakrishna, 2020) and lack of monitoring (Kůdelaa et al., 2020) have hindered the enforcement of renovating MSWI. Third, the construction of new MSWI is often opposed by nearby residents due to their potential pollution problems (Rootes, 2009). Fourth, some residents and businesses are reluctant to cooperate in the proper use of waste sorting facilities because it takes up extra time and private space (Burgess et al., 2021).

These issues all point out one fact: modern MSWI is not a group of stand-alone facilities that can perform their function independently (like flood-control facility), their development and functionality strongly depend on support and participation of various actors in society. Meanwhile, the MSWI in cities can shape the social habits of people using these facilities and the accompanying business models for handling the waste streams. Therefore, in order to unlock the sustainable transition of existing MSWI, cities first need to systematically identify the interdependencies among both the physical components of MSWI and those at the physical-social interface. Only on this basis can a city prepare a MSWI from a system optimization perspective to adapt to the external changes and internal needs. However, a systemic tool to map such interdependencies has not yet been developed.

This paper aims to fill this gap by answering the following question: how can a city systematically prepare its existing MSWI in order to meet evolving waste management demands? In doing so, Section 2 first reviews the challenges faced by current MSW treatment and academic debates about MSWI, then discusses the academic added value of a systems perspective and frames theoretical underpinnings of such a perspective in the context of MSWI. Synthesizing two promising system theories, i.e. socio-technical systems (STS) and systems of systems (SoS), Section 3 proposes a conceptual model as a basis to identify and assess in-situ elements of an MSWI system (MSWIS) in a city. This model is then empirically demonstrated in Section 4 to map and assess the MSWI of the city of Almere in the Netherlands. Section 5 discusses the insights to support the systematic transformation of the MSWIS to meet future demands. Section 6 concludes with the theoretical and empirical contributions and limitations of this study.

2. Literature review

2.1. Municipal solid waste infrastructure

MSW includes waste generated from households, small businesses, institutions (schools, hospitals, government buildings) and some public spaces (parks and streets) (OECD, 2020). Current MSW treatment methods fall into three main categories: (i) waste-to-resource conversion, including recycling materials from old paper, plastics, metals, and glass (Ferdous et al., 2021; Shamsuyeva & Endres, 2021), and composting with bio-waste (Zabaleta & Rodic, 2015); (ii) waste-to-energy recovery, including recovery of combustible gases and thermal energy by incineration (Corvellec et al., 2013; Purnell, 2019), gasification (Sikarwar et al., 2016), pyrolysis (Xia et al., 2021), and anaerobic digestion (Xu et al., 2018); and (iii) landfill (Di Trapani et al., 2013). MSWI is a series of facilities that collect and treat MSW by the above methods (Fig. 1). To give an overview of current MSWI, we conducted a literature review to identify the MSW treatment procedures, associated MSWI, main actors, and external influencing factors and present them in Appendix A.

Current research on MSWI is mostly focused on centralized treatment of MSW after collection, especially on how to improve MSW-to-

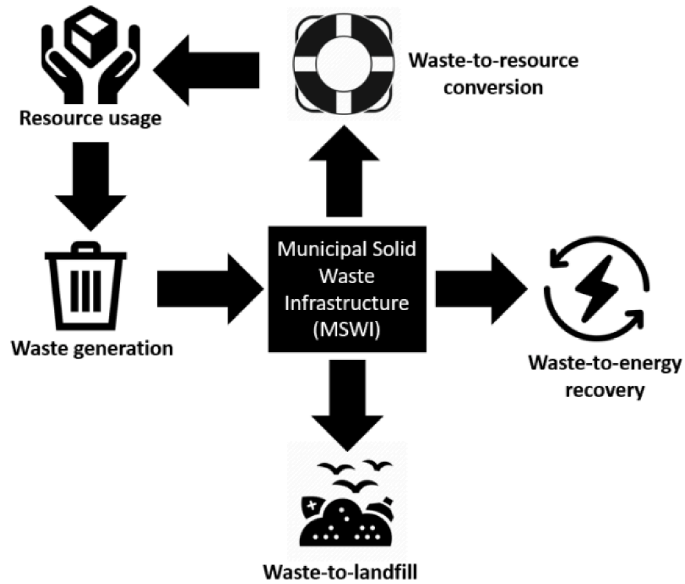

Fig. 1. Schematic representation of the operational context of MSWI.

resource/energy efficiency and reduce environmental impacts through new technologies and equipment (Soltanian et al., 2022; Sondh et al., 2022). However, there are bottlenecks in solving the MSW problem solely through upgrading technologies. For example, mixed plastic products with different chemical structures make the recycling process cumbersome and inefficient (Ferdous et al., 2021; Shamsuyeva & Endres, 2021); incineration, gasification and pyrolysis technologies show limited performance when they process MSW with high humidity (Leng et al., 2020). To break through the dilemma of these technologies, we believe that MSWI should be viewed with a top-level systems approach – i.e., not only focusing on centralized recycling and resource conversion of MSW, but also by controlling its generation and source-separation; not only focusing on technological innovation, but also through involving of actors in the social networks.

However, there is a dearth of systematic analysis with a primary focus on MSWI. One notable exception to this is the study by Piton and Nurcahyo (2021) who examine the e-waste management infrastructure in Jakarta-Indonesia from a supply chain perspective. Another definition of "the infrastructure of the waste processing cluster" was proposed by Serebryakova et al. (2020): "a complex of facilities and organizations that implement environmental, economic, technological and social tasks in the field of education and disposal of waste" (p. 4). In essence, these two studies initially identified the systemic nature of MSWI, but this remained limited to the physical system and lacked an exploration of the dependencies between technical and social systems.

Therefore, we believe that for MSWI research to truly benefit from a systems approach, it is necessary to (1) identify the technical and social elements of MSWI, the interfaces and operating rules between them, and how they are influenced by the external environment; (2) connect the entire process from MSW generation to final processing, viewing each process as a subsystem, so that MSWI can be observed at different levels and scales. In the next section we will use these insights to explore relevant concepts from a systems theoretic perspective to help in identifying and assessing MSWI.

2.2. System concepts

A variety of system theories have been applied to describe and analyze infrastructure systems, such as complex adaptive systems theory to analyze the evolution and resilience of infrastructures (Brown et al., 2004; Grus et al., 2010), the use of entropy theory to indicate the degree of disorder or uncertainty in a infrastructure system (Tamvakis &

Xenidis, 2013), and integrated systems theory to understand and optimize the interfaces of components in an infrastructure system (Saidi et al., 2018). In response to the features and research state of MSWI discussed in Section 2.1, we select two pertinent system concepts and discuss how they can systematically analyze the structure, operational mechanisms, and evolution of MSWI.

2.2.1. Socio-technical systems

Trist and Bamforth (1951) pioneered the interdependency of social structures and technological content in coal mining work systems. Subsequently, Emery and Trist (1960) coined the term "socio-technical systems (STS)" to describe systems involving complex interactions between people, machines, and contexts of the work system. Studies on socio-technical systems can be carried out at three levels from micro to macro: primary work systems (e.g., a coal mining project), whole organization systems (e.g., a software development company), and macrosocial systems (e.g., an education system) (Trist, 1981). Many studies have applied STS as a design approach on manufacturing industries (Clegg, 2000; Sony & Naik, 2020) and computer-supported information systems (Clegg & Shepherd, 2007; Eason, 2007). Baxter and Sommerville (2011) argued that STS should not be just a design approach, but a system engineering mindset that considers socio-technical factors at all stages of the system life cycle.

MSWI has two key characteristics in common with an STS (Baxter & Sommerville, 2011; Wolsink & Devilee, 2009): first, MSWI has an internal environment that consists of separate physical facilities and social actors, while they are linked through waste streams and waste treatment actions (Kirkman & Voulvoulis, 2017; Sin et al., 2017). Second, the performance of MSWI relies on the joint optimization of the technical and social subsystems; only focusing on part of them may lead to a decrease in system utility (Oehman et al., 2022). Therefore, in this research we apply STS to the conceptualization and modeling of system components, structure, and operational mechanisms of the MSWI.

2.2.2. System of systems

Definitions of System of Systems (SoS) vary depending on the application domain (Carlock & Fenton, 2001; Jamshidi, 2008; Maier, 1998; Mo & Beckett, 2019; USDoD, 2008), the main principal characteristic of an SoS being the ability of its subsystems to operate independently and by cooperating to achieve additional capabilities (Jamshidi, 2008; Mo & Beckett, 2019). SoS offers the prospect of improving system performance by realizing synergy between independent (sub)systems: thinking of the system as a configurable multilevel network of multiple subsystems, adjusting the rules and procedures for the operation of this network can regulate the interaction and functional realization of the subsystems and thus control the overall performance of the system (Keating et al., 2003).

On top of that, Dagli and Kilicay-Ergin (2008) have described the idea of evolutionary SoS architecting: the dynamically changing external environment and societal needs are reorientating the mission of the system, and SoS offers a new strategy for responding to this new challenge – instead of designing the systems from scratch, companies or governments become system integrators, responding to mission changes by adapting the existing system architecture (adding, removing, and modifying components and functionality). It has been successfully applied to develop product-service systems based on customer needs and this system allows for the evolution of industry networks for sustainable operations (Peruzzini et al., 2015).

In this research, we regard the MSWI as an SoS, where each waste treatment procedure (including both physical and social components) can be considered as a subsystem to offer waste services and meanwhile cooperating to contribute to the dynamic sustainable goals of the city. SoS offers the prospect of adapting subsystems from a system integrator's perspective in order to break the architectural constraints imposed by the existing MSWI.

2.2.3. Synthesis: integrating STS and SoS in developing an MSWIS model

We integrate the insights and strengths of STS and SoS to provide a strong conceptual basis for developing a model of the MSWIS: STS can well help identify the internal components (technical elements, social elements, and the waste treatment modules they comprise), the structure (the interface and operational rules between the components), and the external context (system goals, external influences) of the MSWIS. On this basis, SoS is used to analyze the collaborative mechanisms of these subsystems, including the balance between the capability of the facilities (technical subsystems) and the corresponding behavioral patterns (social subsystems). Additionally, for observing the evolution of existing MSWIS and redesigning them for future scenarios, SoS brings in insights on how the components and functionality can be adjusted, instead of rebuilding from scratch, to dynamic environmental and operational conditions.

3. A conceptual model of the MSWIS

3.1. Subsystems and structure of the MSWIS

Based on the discussion above, we define MSWIS as a complex, open socio-technical system consisting of several chained or parallel MSW treatment subsystems. Each subsystem is an MSW treatment procedure module that delivers one or more functions through interactions between physical facilities and actors, and is influenced by external factors (Fig. 2). Multiple such subsystems connected by waste streams and action flows comprise the MSWIS (Fig. 3).

The physical facilities and actors in the modules, their interactions in MSWIS, the technical and social subsystems in MSWIS, and the external factors are described as follows:

- Physical facility – is the man-made physical infrastructure (e.g., buildings, containers, vehicles, material recovery facilities, incinerators, and landfill sites) associated with the waste stream. Waste streams are processed through the infrastructure and then become products or materials with specific categories and properties; or transferred to the next waste treatment module for further processing.
- Actors – are civil (e.g., municipality, regional authorities), public (e.g., local community, NGOs), and private (e.g., residents, businesses) individuals or organizations, that are involved in the design, planning, investment, use, and maintenance of the waste infrastructure. Actors are also influenced by the physical facilities and their functions in different ways, such as a clean living-environment, employment, and recyclable resources.
- Technical subsystem – consists of all the physical facilities in the waste treatment modules. It is the physical structure that enables actors to share and use knowledge, techniques, equipment, and facilities.
- Social subsystem – consists of all actors from the civil, public, and private sectors involved in or influenced by the waste treatment procedures. It is the social network that enables actors to formally or informally participate, organize, and coordinate in waste treatment activities, resulting in orderly action flows.
- External factors – are regulations including laws, policies, rules that regulate actors' activities and the process of developing and using physical facilities (e.g., environmental taxes, landfill restrictions); local culture that shapes the interactions, awareness, and behaviors of actors in relation to waste treatment (e.g., community climate, environmental awareness); and technologies that are applied in physical facilities and social activities (e.g., automated waste separation, waste sorting apps).

3.2. Methodology for implementing the MSWIS model

The MSWIS model depicts how the technical and social components

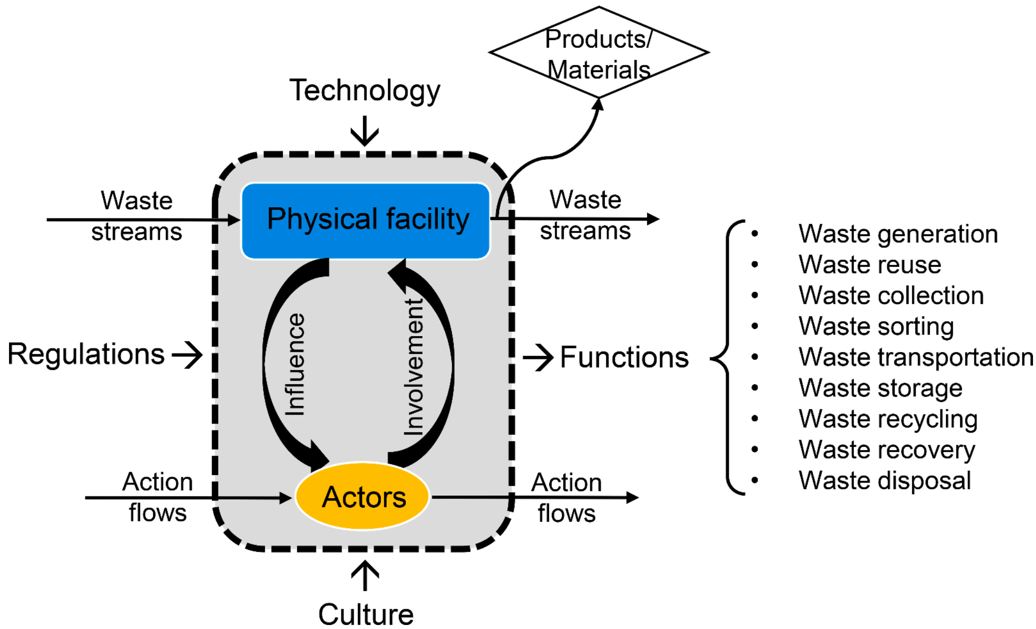

Fig. 2. The module of one waste treatment procedure: a socio-technical subsystem in an MSWIS.

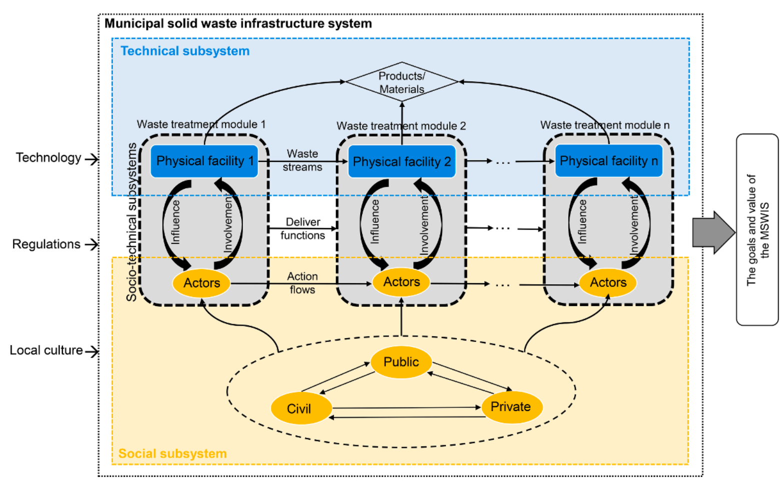

Fig. 3. Conceptual model of a municipal solid waste infrastructure system (MSWIS).

interact and form subsystems and ultimately enable the operation of the MSWI in cities. If all the facilities and actors associated with MSW in a city are viewed as scattered puzzle pieces, the MSWIS explains how these pieces can be related to each other and stitched together into a complete picture. This model can be used at different stages of MSWI development as a tool for planning, evaluation, and monitoring following three steps (Fig. 4):

Step 1: Build the MSWIS model with basic data, including the list of MSW treatment procedures, list of MSW streams, list of physical facilities for MSW treatment, and list of actors involved and how they get involved.

Step 2: Collect specific data according to the scenarios of applying the model.

- Present scenario: To evaluate the current performance of the MSWIS in a city. To achieve this, we need to select indicators for evaluating the system performance (e.g., MSW recycling rate, etc.), and collect specific data accordingly.
- Future scenario: To make decisions for the construction or adaption of a waste treatment facility. To achieve this, the new facility's connectivity to adjacent facilities and its impact on waste streams and actors need to be comprehensively examined.
- Dynamic scenario: To monitor the system transformation over time and find enablers and barriers. To achieve this, we need to track the dynamics of the data listed in Step 1 and identify the internal/external factors and then map out a developmental trajectory.

Step 3: Analyze parts or the entire system and draw lessons for future research and practice.

4. Validation of implementing the MSWIS in Almere

To validate the feasibility of applying the MSWIS model to real-world problems, we chose the city of Almere, the Netherlands (hereinafter referred to as Almere) as our laboratory.

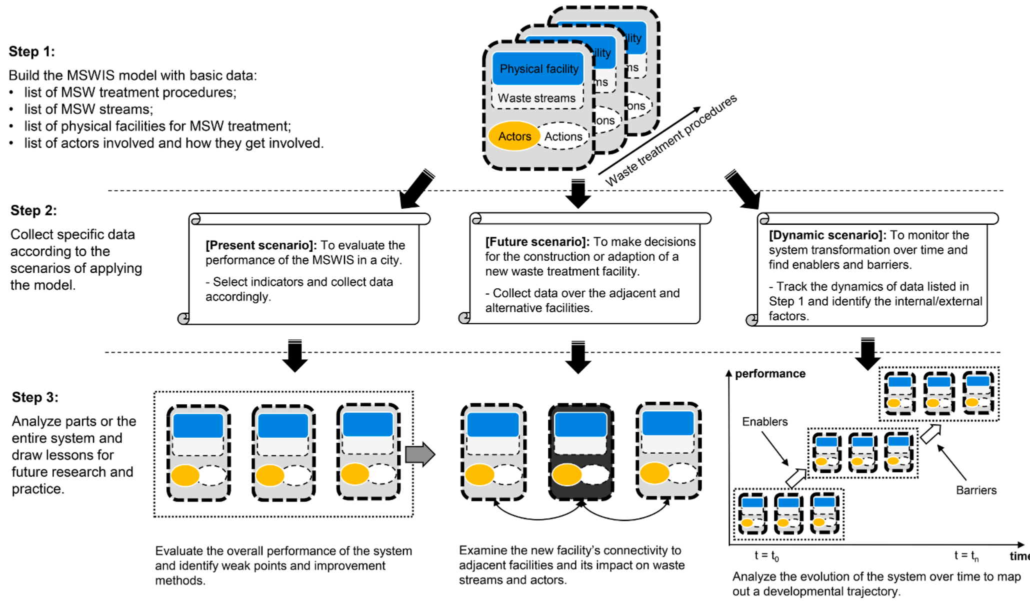

Fig. 4. Implementation methodology of the MSWIS model.

4.1. Introduction to the city of Almere

Located in Flevoland province in the Netherlands, Almere was reclaimed from the sea as agricultural land in 1976. Since 1984, it has grown rapidly to address overpopulation and housing shortages in neighboring large cities such as Amsterdam, with approximately 220,000 citizens in 2022 and expected to expand to 350,000 by 2030. To overcome the waste management challenges that accompany urban expansion, the Municipality of Almere has undertaken actions on improving waste-related infrastructures and calling for public participation and innovation with various initiatives and projects, such as the "City Deal Circular City", "Almere Green & Healthy", and "Inclusive City of Almere". These attempts have put Almere at the forefront of pursuing resource circularity and social inclusion in the Netherlands as well as in Europe, and they have made it a "living laboratory" for analyzing the MSWIS at the city level.

4.2. Three steps for implementing the MSWIS model

4.2.1. Step 1: build the MSWIS model with basic data

We first reviewed the Almere municipality website, conducted a preliminary interview with the leaders of the waste sector in Almere Municipality and identified seven waste treatment procedures in Almere in 2022: generation, reuse and upcycle, on-site disposal (collection and sorting), transportation, storage, recycling and recovery, and landfill. For each procedure, we collected data on the type of physical facilities (with photographs), the type of waste streams, the main actors and their activities related to waste treatment (see Appendix B) and visualized the

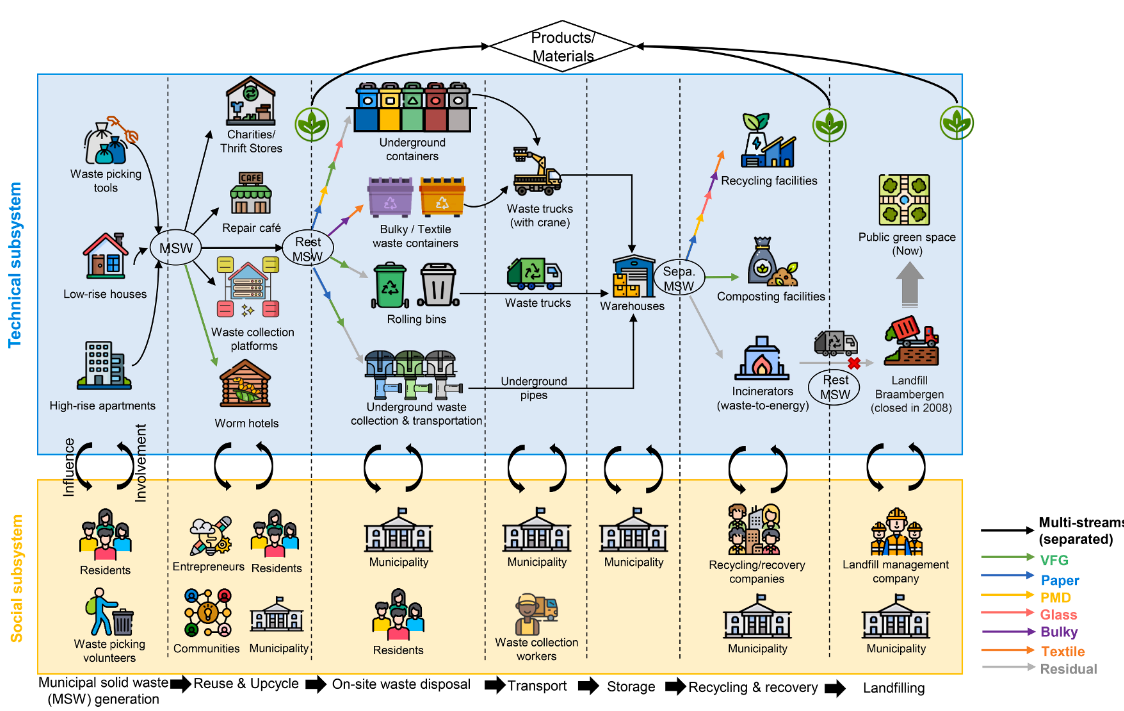

Fig. 5. The MSWIS in Almere in 2022.

MSWIS of Almere in Fig. 5.

4.2.2. Step 2: collect specific data according to the purposes

Based on Almere's urban development goals, we decided to apply the MSWIS model with the purpose of mapping and visualizing Almere's current MSWIS and qualitatively examining the impact of the current MSWIS on the circularity and inclusiveness of the city. In this study, we define urban circularity as the circular performance regarding MSW within an urban context following the principles of the circular economy; urban inclusiveness is defined as the possibility for all actors to participate and to benefit equally from the MSWIS in social, economic, and environmental terms. In this case we focus on the internal components and interactions of the MSWIS in Almere, so the external factors such as national policies, technological development, and social culture are not discussed.

According to the purpose, we then selected indicators for qualitative evaluation of urban circularity and urban inclusiveness. A literature review was conducted to learn how previous work has examined the impact of waste infrastructure on urban circularity and inclusiveness (Table 1). Based on the indicators identified during the literature review, we collected specific data about the impact of the MSWIS on urban circularity in terms of waste reduction, reuse, and recycling; as well as its impact on urban inclusiveness in terms of environmental and related health risks, social acceptance and participation, and equal benefits for different stakeholders.

All the data reflect the status of the MSWIS in Almere in 2022. The data were collected through on-site surveys and interviews with people working in the waste sector and those running waste-related businesses, and subsequently triangulated and supplemented with government websites and reports.

4.2.3. Step 3: evaluate the performance of the entire system

We consider each MSW treatment procedure as a socio-technical subsystem, and Almere's MSWIS consists of seven such subsystems, connected through waste streams and action flows. Then the qualitative indicators of urban circularity and inclusiveness (Table 1) are applied to provide a narrative of how they have been influenced by the MSWIS. We have combined procedures that are closely related and overlap in facilities, so MSW generation and on-site disposal are presented together in 4.2.3.1, and waste transport and storage are presented together in 4.2.3.3.

4.2.3.1. Waste generation and on-site disposal. The two subsystems of MSW generation and on-site disposal are closely interrelated and interact with each other: residents' living habits and environmental awareness determine the amount of MSW they generate and how they dispose of it, while the accessibility, aesthetics, and convenience of waste facilities also influence the specific actions they take to reduce and separate waste. In Almere, high-rise residents currently use public underground containers for VFG, PMD, paper, and residual waste, while low-rise residents use three rolling bins in their own yards for waste separation: VFG and residual waste in a bin with built-in compartments (called a 'duobak'), and PMD and paper in two separate bins. Other MSW, such as glass and textiles, needs to be taken to site-specific containers for disposal. For bulky waste, such as old furniture, residents need to make an appointment to have it picked up by the municipality or take it to the waste collection platforms themselves.

With 77% of the residual waste disposed by Almere residents being recyclable materials (VFG, PMD, glass, paper, and textiles), there is significant room for improvement in waste separation. On the one hand, brightly colored bins and containers in yards and streets can remind residents to conserve resources and increase the respectability and responsibility of waste separation; on the other hand, containers that are too far away and bins that take up too much space in homes can also trigger reluctance. In addition, new residents, especially immigrants, may be unfamiliar with local sorting rules, resulting in incorrect waste separation.

Table 1
Examples from the literature on how waste infrastructures influence urban circularity and inclusiveness.

Aspects	Qualitative indicators	Examples
Urban circularity	(i) Symbolic role of waste infrastructure in influencing circular awareness	Messy and smelly waste collection facilities create a negative image of waste management and discourage waste recycling behaviors (Wolsink & Devilee, 2009). Modern waste separation and recycling facilities become part of the community culture, reminding households at an early stage to 'refuse, reduce, and reuse' (Metcalfe et al., 2012). Waste-to-energy incinerators may evolve into a lock-in that slows the transition towards waste recycling (Corvellec et al., 2013).
	(ii) Impact on the reuse of MSW	Repair cafes provide free product repair services to residents and recycle parts of obsolete products (Keiller & Charter, 2014). Thrift stores in cities attracts consumers to exchange or buy used products, extending the life of products (Machado et al., 2019).
	(iii) Impact on the effective separation and recycling of MSW	Household waste separation can be improved by higher density and better location of waste collection facilities (Higgs, 2006). Automatic MSW separation facilities can achieve over 90% accuracy in sorting metal, plastic, and paper waste (Gundupalli et al., 2017; Rahman et al., 2011). Single-stream waste systems can increase the recycling rate by up to 50% compared to dual-stream systems (Fitzgerald et al., 2012).
Urban inclusiveness	(i) Environmental and related health risks of waste infrastructure to certain groups	The siting and emissions of waste incineration led to increasing public concern and protest (Rootes, 2009). Landfill leachate contaminates soil and groundwater for decades, threatening the public health (Salem et al., 2008).
	(ii) Social acceptance and participation	Public acceptance of waste infrastructure depends on local culture and environmental awareness (Gallagher et al., 2008), as well as the transparency of the decision-making and implementation process (Kirkman & Voulvoulis, 2017). Waste infrastructures that are perceived to mitigate climate change and address employment, resource, energy, and other local issues are generally accepted (Wolsink, 2010). Waste infrastructure that ignores public input and participation may fail by undermining cooperation (Wolsink & Devilee, 2009).
	(iii) Equal benefits for different stakeholders	The transformation of waste infrastructure reshapes the scale and pathways of waste streams, thereby influencing the value derived from or impacted by different actors (Butt, 2020). Competition exists between the informal sector and formal institutions for facility assets and waste ownership (Scheinberg et al., 2016). Residents have different access to waste facilities and services due to their location and mobility (Liu et al., 2023)

4.2.3.2. Reuse and upcycle. In Almere's MSWIS, we identified an overlooked subsystem consisting of thrift stores, repair cafés, worm hotels, and businesses run by entrepreneurs in the *Upcycle centrum*. It is the "Reuse and Upcycle" module after MSW generation and before municipal collection. The facilities in this subsystem are primarily invested in, used, and maintained by residents and businesses on their own initiative. This subsystem allows residents to reuse and upcycle MSW as early as possible with less resource input by trading and exchanging used items, free repair services, and small-scale composting, thereby reducing the amount of waste going to the next waste treatment procedure, and thus reduce energy consumption and carbon emission in the waste transportation and recycling.

In particular, *Upcyclecentrum*, a waste collection platform built by the Municipality in 2018 from recycled materials, can collect forty-eight types of waste. Residents bring their MSW here and sort it under the guidance of the staff, while entrepreneurs upcycle raw materials from there to make new products. In addition, workshops and educational activities are organized here to share circular concepts, knowledge, and experiences.

In this subsystem, we note the issue of inclusiveness related to waste ownership and access. Raw materials and by-products collected directly from waste have a certain economic value, but their utilization requires specific technologies and costs, and their use may pose safety and health risks. Therefore, who has the right to collect, how it should be used, and how the benefits and risks should be distributed remain to be specified and regulated.

4.2.3.3. Waste transport and storage. The waste collected by bins and containers is transferred by waste trucks organized by the municipality. The truck's inner space is partitioned to be able to transfer multiple waste streams. The frequency and route of truck transport is influenced by the on-site disposal subsystem: sensors in the underground containers can measure the percentage of containers filled, transmit these data to the control center via the Internet; then the control center will identify the locations of nearly full containers and plan the timing and optimal routing for waste transport. However, even if this is optimized, the smart truck transport system still poses health and safety concerns for residents due to its massive size, odor, and noise.

Since 2003, an underground waste transport system (in Dutch: ondergronds afvaltransportsysteem, OAT) has been in place in the center of Almere. It consists of a network of underground steel pipes with a diameter of 50 cm, using air currents to transport sorted VFG, paper, and residual waste at a speed of 70 km/h to a the storage building called 'The Vacuum Cleaner' for further processing. About 1400 households, 300 businesses, and 100 bins in the city center have been connected to the system, which can be turned on and off individually in different areas. Since the system monitors and empties waste at the collection points in real time, residents can use it 24/7 without worrying about full containers and without the nuisance of odors and truck noise. However, the establishment of an underground network requires a high initial investment, so the residents of Almere bear a higher waste tax compared to other city residents.

4.2.3.4. Waste recycling and recovery. The waste streams collected and transferred by the municipality will reach the waste recycling and recovery facilities and be transformed into raw materials or energy. For example, plastics, old paper, glass, and textile are further sorted, decomposed, and turned into new raw materials at recycling company Cirwinn. The VFG stream is dewatered, digested, composted, and eventually converted into green energy and bio-based products at organic waste company Orgaworld. These facilities are mostly developed and operated by enterprises and benefit from governmental investments or policy incentives. This subsystem is the key component of the MSWIS for the direct conversion of waste into resources, but its effective operation depends on residents properly sorting MSW, while mixed or "contaminated" waste streams (e.g., old paper with oil, VFG covered by plastic packaging) incur additional separation costs or even cannot be recycled.

The Municipality of Almere invested in and uses the incinerator at Alkmaar, located about 60 km from downtown Almere. Residual waste that cannot be recycled is transported here for incineration to produce electricity and hot water for more than 100,000 inhabitants and the industrial park nearby. The facility has received certain public support for its ability to provide an inexpensive source of energy, but this has also raised concerns because of the potential polluting emissions. In addition, the transportation of MSW over long distances from Almere to Alkmaar consumes energy and produces greenhouse gas emissions.

4.2.3.5. Landfill and restoration. The Braambergen landfill covers 50 hectares and is located approximately 8 km from the center of Almere. It was used for dumping residual MSW and closed in 2008. Since 2016 the site has become one of three pilots in a ten-year national project called "Sustainable Landfill Management". The municipality, waste management company Afvalzorg, energy company HVC, and the National Forestry Administration (In Dutch: Staatsbosbeheer) are working together to restore the site as a multifunctional area with natural landscaping, recreation, and sustainable energy production.

A gas extraction plant and approximately 15,000 linear meters of gas pipeline were built here to extract and process landfill gas from the stored waste. About ten hectares of the site is used for a solar park with 26,000 solar panels and a peak power generation capacity of over 14 megawatts. The perennial landfill created a unique hilly landscape in the flat Flevoland area, which has been transformed into a 7.2-kilometer asphalt-paved mountain bike trail. The restored site will also become a public green space for residents and educating and inspiring them about sustainable development. These facility modifications make the long, costly aftermath of traditional closed landfills outdated. It not only helps to reduce environmental and health risks by decontaminating the landfill, but also but also creates considerable economic and social value.

5. Discussion

Building an MSWIS that can adapt to urban development is a systemic challenge influenced by regulations (Kůdelaa et al., 2020; Patil & Ramakrishna, 2020), finance (Subagio et al., 2020), technology (Chalfin, 2017), and social acceptance (Burgess et al., 2021; Rootes, 2009), but a systemic perspective to dissect this dilemma has been lacking so far. By introducing STS and SoS systems thinking into MSWIS, we have designed and validated a model for outlining a complete MSWIS, and based on this we present the following insights to support the systematic transformation of the MSWIS.

First, balancing the capability of the facilities (technical subsystems) and the corresponding behavioral patterns (social subsystems) is crucial for the realization of the system functionality. For instance, despite the establishment of modern waste sorting facilities, residents placing food waste with plastic packaging in the bio-waste bins (inefficiency of the action flow) can reduce the quality of bio-waste received by the composting facility, thus leading to a hindrance in its functioning. Therefore, we need to recognize that the evolution of MSWIS is not just about physical changes, but also about how society understands and participates. Urban policymakers need to build cross-agency knowledge sharing and collaboration networks to break down cognitive, cultural, and linguistic barriers to improve the overall performance of MSWIS and enhance the social subsystem's ability.

Second, the oft-overlooked informal MSW processing facilities created by individuals and social organizations are an important part of MSWIS. Unlike the traditional view that defines infrastructure as top-down initiated, centrally controlled facilities for providing public services, we recognize that some small-scale facilities led by social innovation (e.g., worm hotels and repair cafes), can provide services beyond waste-to-resource – i.e., reuse and upcycling at the early stage of waste management. This subsystem functions to extend the life of products, reduce the cost of waste treatment, and provide social spaces and entrepreneurial opportunities for residents and entrepreneurs. Therefore, urban policymakers should not ignore these informal facilities and actors when identifying and planning an MSWIS. In addition, current regulations on waste-use may limit the space for entrepreneurs to upcycle waste, and future regulations should accommodate both safety and innovation of waste reuse.

Third, when system tasks are repositioned to meet societal needs, MSWIS can respond to changes by adapting its system architecture (adding, removing, and modifying components and functions) from a system integration perspective. In Almere, for example, when the Dutch government implemented *Waste Hierarchy* and landfill volumes dropped dramatically, Almere closed the Braambergen landfill and repurposed it into a cycling ground and solar park based on special topography to accommodate the outdoor activities and energy needs of residents. When the population density in the city center increased, Almere added an underground waste transport system (OAT) to reduce the safety risks of trucking waste in crowed areas. These adjustments to the subsystems not only adapted to the changing external environment and social needs, but also improved the overall circular performance of the MSWIS system.

Fourth, the MSWIS model gives guidance on how to align the design of MSW facilities with regional and seasonal variations in MSW. To give some examples, Chinese cities with high population and boost economy generate large amounts of kitchen waste and packaging waste (cupboard and plastic) (Ding et al., 2021), so the planning of MSWIS focuses on efficient collection systems, automated sorting systems, large-scale incineration, and landfills. In terms of seasonal variation, historical data from the United States (Rhyner, 1992) and Europe (den Boer et al., 2010; Denafas et al., 2014) show that in summer MSW is generated more than average and contain more kitchen and garden waste, these areas should therefore increase the capacity or frequency of bio-waste bins in summer and design bins that can prevent odor and mosquito problems caused by high temperatures. The case of Greece (Gidarakos et al., 2006) also shows that MSW volume increases steeply during the tourist season, especially for packaging waste and disposable items, so tourist cities need to design expandable waste collection and transportation facilities or temporary waste storage facilities.

Fifth, the MSWIS model can contribute to quantitively assessing urban circularity. The assessment of circularity at the city/regional level has strongly focused on material flows, while MSW is a vital subset of it. Previous research has applied Life Cycle Analysis (LCA), Material Flow Analysis (MFA), and multi-regional input-output (MRIO) on cities but provided limited lessons for monitoring circularity with indicators (Harris et al., 2021). Meanwhile, despite the plethora of circularity indicators (e.g., the Material Circularity Indicator (EMF, 2015), the Circular Economy Toolkit (Evans & Bocken, 2017), and the Circular Economy Indicator Prototype (Cayzer et al., 2017)), there has been limited testing of the correlation with environmental performance (Saidani et al., 2019). This may risk driving "circularity for circularity's sake", resulting in long-term and/or cross-regional environmental burdens. The MSWIS model may help to standardize elements of urban systems for circularity monitoring – considering an MSW treatment procedure module with certain facilities, techniques, and behavior patterns as a standardized unit for quantitative assessment. Combining circularity metrics with LCA, the MSWIS model has the potential to enhance efficiency and comparability of circularity assessment across regions and to provide evidences on which specific urban circularity practices can really improve environmental performance.

6. Conclusions

The MSWIS model provides a novel approach to systematically map the complex and dynamic network of infrastructure and associated actors that serve urban MSW treatment. We developed and validated the MSWIS model in three steps: first by reviewing the challenges faced by current MSW treatment and academic debates about MSWI, then by adopting system concepts to dissect the components and operational mechanism of the MSWIS, and finally by applying it to a Dutch city to illustrate how the MSWIS affects transition interventions in the urban context, with examples of circularity and inclusiveness.

Theoretically, the MSWIS model refines the stereotypical view of existing studies (Piton & Nurcahyo, 2021; Serebryakova et al., 2020) defining waste infrastructure as a collection of physical facilities by introducing the STS view of the interdependence of facilities and actors in engineering systems. It points out the importance of balancing between the capability of the facilities and the corresponding behavioral patterns. Additionally, the insights from SoS have guided us to view MSWIS as a three-level embedded system: from the smallest MSW treatment module through the mid-level technical/social subsystem, to the entire MSWIS. This perspective gives researchers a tool aiding them to narrow down their view to observe facility/behavioral details or rather zoom out and study the whole picture of the MSWIS.

In practice, the MSWIS model is widely applicable to cities in various contexts, with the advantage of finding and integrating the pieces of MSWIS beyond the control of the authorities. The case of Almere draws the lesson of a highly developed European city: the municipality took the lead in developing a highly centralized, large-scale MSWI, while waste reuse/upcycle facilities built by social organizations and individuals based on their own needs are key pieces of the puzzle to complete the MSWIS. In the Global South (e.g., Brazil, China, and Africa), waste pickers and small waste traders are important actors in waste treatment (Steuer et al., 2018; Zisopoulos et al., 2023). The MSWIS model can help compensate for the absence of informal waste facilities (such as small scrapyards and community waste composting facilities) in the official maps by mining the corresponding physical facilities (in technical subsystems) through the social network of actors (in social subsystems).

This study has certain limitations. First, due to the limited data collected in Almere, we focused only on MSW generated from residential buildings but not on other MSW sources (e.g., small businesses) and non-MSW streams (e.g., construction and demolition waste) that may pass through Almere's MSWIS. Future research could include more sources of MSW generation and analyze how the treatment of other waste (e.g., construction waste, agricultural waste) may impact the development of MSWIS. Second, we applied the model in Almere to map the current state of its MSWIS without thoroughly analyzing the impact of external factors, since including all these factors touches on more evolutionary processes. We will explore the impact of external factors, such as national policies (e.g., Circular Economy 2050 in the Netherlands) and new technologies (e.g., automatic waste separation), on the evolution path of Almere's MSWIS in a follow-up study. Third, we did not quantify the interdependencies of different components in the MSWIS, such as the contribution of people's reuse and waste sorting behaviors to the efficiency of subsequent recycling subsystems. Future research can combine MSWIS model with agent-based modeling that excels in simulating complex system scenarios (Tong et al., 2023) to quantitatively analyze interconnectedness, reciprocity, and feedback loops between facilities and actors.

CRediT authorship contribution statement

Zhaowen Liu: Conceptualization, Data curation, Methodology, Visualization, Writing – original draft. **Daan Schraven:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Martin de Jong:** Conceptualization, Writing – review & editing, Supervision. **Marcel Hertogh:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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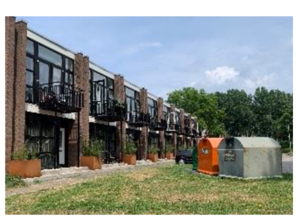
Appendix A. Examples of municipal solid waste infrastructure by literature review

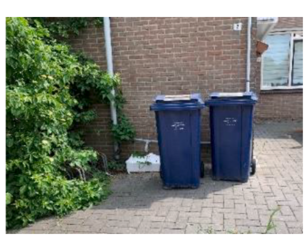
MSW treatment procedures	Physical facilities	Main actors	External influencing factors
Waste generation	Residential houses, small businesses, institutions (schools, hospitals, government buildings) and some public spaces (parks and streets) (OECD, 2020)	Households; industries and businesses (if their waste is managed by municipalities)	Culture/Social norm, e.g., social learning (Chen & Gao, 2021); peer pressure (Botetzagias et al., 2015) Regulations, e.g., waste tax (Sahlin et al., 2007)
Waste reuse and upcycle	Thrift stores (Machado et al., 2019); repair cafés (Keiller & Charter, 2014)	Households; business owners; second-hand products traders.	Culture/Social norm, e.g., environmental awareness (Meng et al., 2019) Regulations, e.g., restrictions on waste reuse (Hargreaves et al., 2008)
Waste collection	Rolling/duo bins (Burgess et al., 2021; Metcalfe et al., 2012); underground containers, source-separation containers (Nevrly et al., 2019; Rives et al., 2010); curbside collection (Wilson & Williams, 2007)	Municipality; households; business owners; local communities	Culture/Social norm, e.g., initiatives at the community level (Tong & Tao, 2016) Technology, e.g., Online recycling platforms (Wang et al., 2018); intelligent waste collection facilities (Tong et al., 2023) Regulations, e.g., Mandatory waste separation rules (Wang et al., 2021)
Waste sorting	Post-separation equipment (Gundupalli et al., 2017); mechanical-biological treatment facilities (Cook et al., 2015)	Waste sorting companies; municipality	Technology, e.g., automated waste sorting (Gundupalli et al., 2017)
Waste transportation	Waste trucks (with or without crane) (Karadimas et al., 2008; Nguyen-Trong et al., 2017)	Municipality; waste disposal companies	Technology, e.g., GIS analysis for routing optimization (Karadimas et al., 2008)
Waste storage	Property type and space to store waste (Zhu et al., 2009); temporary storage facilities (Wagner & Bilitewski, 2009)	Municipality; warehouse owners	Technology, e.g., underground waste storage (Kumar & Verma, 2022) Regulations, e.g., ordinance on long-term storage facilities (Wagner & Bilitewski, 2009)
Waste-to-resource conversion	Plastic/Paper/Glass recycling facilities (Ferdous et al., 2021); bio-waste composting facilities (Zabaleta & Rodic, 2015)	Waste recycling companies; waste recovery companies; municipality	Technology, e.g., chemical recycling of plastic (Garcia & Robertson, 2017) Regulations, e.g., industry standards for using recycled material (Hargreaves et al., 2008)
Waste-to-energy recover	Incinerator (Corvellec et al., 2013; Purnell, 2019); gasification facility (Sikarwar et al., 2016), pyrolysis facility (Xia et al., 2021); anaerobic digestion facility (Xu et al., 2018)		Technology, e.g., waste incinerators for district heating (Corvellec et al., 2013) Regulations, e.g., waste incineration tax (Sahlin et al., 2007)
Landfill	Landfill sites (Sin et al., 2017); gas extraction facility (Di Trapani et al., 2013); leachate treatment (Salem et al., 2008)	Landfill management company; municipality	Technology, e.g., methane generation in landfills (Themelis & Ulloa, 2007) Regulations, e.g., landfill tax (Purnell, 2019); ban on landfills for all recyclable waste (EU, 2018)

Appendix B. An overview of the components of the MSWIS in Almere

MSW treatment procedures	Physical facilities	Photograph of examples	Waste streams	Main actors and activities	Source
Generation	Low-rise houses and high-rise apartments		VFG (vegetable, fruit, and garden waste), paper, PMD (plastic, metal, and drink packaging), glass, residual waste	Residents consume products and generate waste.	On-site survey
	Streets and waste picking tools		Residual waste	Municipality offers tools, staffs and volunteers clean the streets.	On-site survey

(continued on next page)

(*continued*)

MSW treatment procedures	Physical facilities	Photograph of examples	Waste streams	Main actors and activities	Source
Reuse and upcycle	Charities/Thrift stores		Textile, electrical devices, furniture/wooden objects, books, etc.	The entrepreneurs run a second-hand goods trade.	On-site survey
	Repair cafés (in community centers)		Textile; bicycles; electrical devices; furniture/wooden objects	Entrepreneurs offer free repair services to residents.	On-site survey and website (https://www.repaircafe-almere.nl/html/)
	Three waste collection platforms		48 types of sorted recyclable waste in Upcyclecentrum, 35 types of sorted recyclable waste in Almere Buiten Recycling Platform and Almere Poort Recycling Platform	Municipality invests and operates the facility; entrepreneurs reuse the recyclable materials.	On-site survey, interview with the Municipality of Almere, and website (https://www.almere.nl/afval/recyclingperrons)
	Worm hotels		VFG	Residents and communities build and maintain the worm hotels.	On-site survey
On-site disposal (collection and sorting)	Underground containers		VFG, paper, PMD, glass, residual waste	Municipality invests and maintains the facility, and residents sort their waste.	On-site survey and interview with the Municipality of Almere
	Rolling bins		VFG, residual waste, PMD (from low-rise housing)	Residents in low-rise houses separate VFG and residual waste in duo-bin, and PMD in another bin.	On-site survey and interview with the Municipality of Almere

(*continued on next page*)

(*continued*)

MSW treatment procedures	Physical facilities	Photograph of examples	Waste streams	Main actors and activities	Source
	Aboveground containers		VFG, paper, PMD, textile	Municipality invests and maintain the facility.	On-site survey
Transportation	Trucks (with or without crane)		VFG, paper, PMD, glass, residual waste	Municipality invests trucks and organizes workers to transport both sorted and mixed waste.	On-site survey and interview with the Municipality of Almere
	Underground waste transport system		VFG, paper, residual waste (with plastic)	Municipality invests and maintains the facility, and residents sort their waste.	Interview with the Municipality of Almere. The photo is produced and authorized by Jorrit Lousberg and Dura Vermeer.
Storage	Warehouses		VFG, paper, PMD, glass, residual waste	Municipality has contracts with some warehouses.	Interview with the Municipality of Almere
Recycling and recovery	Recycling facilities	(No photo)	Paper, plastic, glass, bulky waste, textile	Recycling companies have contracts with the municipality.	Interview with the Municipality of Almere and websites of recycling company Cirwinn
	Composting facilities	(No photo)	VFG	Composting companies have contracts with the municipality.	Interview with Municipality of Almere and websites of composting company Orgaworld
	Waste-to-energy incinerator in Alkmaar	(No photo)	Residual waste	Municipality and a company invested an incineration factory out of the city.	Interview with Municipality of Almere and news report about waste management company HVC
Landfill	Braambergen (closed in 2008)	(No photo)	Residual waste	Municipality works with a landfill management company to extract gas and restore the landfill site to a green public space and solar park.	Interview with Municipality of Almere and website of waste management company Afvalzorg and HVC.

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