Sustainable Cities and Society 99 (2023) 104890

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Operational analysis and optimization of a water-based municipal solid waste management system with hybrid simulation modeling

Yvonne Kummer [a,*], Lena Youhanan [b], Patrick Hirsch [a]

[a] *Institute of Production and Logistics, University of Natural Resources and Life Sciences Vienna, Feistmantelstraße 4, Vienna 1180, Austria*
[b] *Recycling Unit, Stockholm Vatten och Avfall, Bryggerivägen 10, Stockholm 106 36, Sweden*

ARTICLE INFO

Keywords:
Municipal solid waste management
Hybrid simulation model
Water-based infrastructure
Emission reduction
Operations management
Real-world data

ABSTRACT

Waste generation is continuously increasing, like the global population and urbanization. This is accompanied by emissions and externalities, making municipal solid waste management (MSWM) a central subject for sustainable urban development. Therefore, a novel logistics concept of a water-based MSWM system was piloted in Stockholm (Sweden). A recycling barge was used to collect waste, reuse items, and provide reuse items for citizens to take home. A hybrid simulation model based on real-world data from the pilot study is developed in this paper. This combined agent-based and discrete-event model simulates the customers' and workers' behavior, including loading operations on the recycling barge, filling a methodological gap in MSWM. The research focuses on elaborating the system boundaries and optimizing the operational processes to evaluate the sustainability and accessibility of the system. The computations with 58 different experimental settings identify capacity limits and determine optimal operational conditions. Further, modifying processes could reduce the number of transports up to 55%. Another added value of the model is the extension beyond the pilot study and its flexible application to procedural changes. Based on the presented findings, implementation in other cities can be enforced and thus increase recycling rates, reduce land use, and save transport kilometers.

1. Introduction

Global greenhouse gas (GHG) emissions have increased by over 30% from 2000 to 2019 (The World Bank, 2022), and around 70% are caused by cities (Dasgupta et al., 2022). At the same time, urbanization is accelerating as the world's population grows to an estimated 8.5 billion in 2030 (United Nations, 2019), representing an expansion of 7.2% since 2022. Concurrent, urbanization affects the environment and social life on various levels, both positively and negatively (Bloom et al., 2008; Henderson, 2003). The waste production in cities intensifies, making waste an unavoidable by-product of human activities (Fidelis & Colmenero, 2018; Bogner et al., 2007). An increase of almost 70% from 2016 until 2050 in the generated amount of municipal solid waste (MSW) is predicted by Kaza et al. (2018). MSW is defined as "household waste and waste similar in nature and composition to household waste" (European Commission, 2017), like commercial waste, waste from street cleaning, and non-process waste from industries (Baeumler et al., 2012). In 2019, 3.3% of global GHG emissions originated from wastewater, landfills, and incineration (Ritchie et al., 2020). Therefore, in addition to waste prevention, municipal solid waste management (MSWM) must adjust to changing structures to minimize emissions. The waste sector releases GHG emissions throughout the entire process chain, from waste generation, collection, recycling, disposal, and after that; however, these are hard to capture and monitor. Transportation between and within the individual process stages has various direct and indirect impacts, thus, is an integral and essential element in the overall MSWM system (Mohsenizadeh et al., 2020). Almost one-third of the total GHG emissions in cities result from road transport (Wei et al., 2021). Other prominent externalities of road transport are air- and noise pollution, vibrations, accidents, and land use (Russo et al., 2021). In addition, the overall urban emissions may continue to increase because of extensive land use changes and the significant influence of built-up areas on local emissions (Zhou et al., 2021).

MSWM affects the environment, economy, and social life in various ways and globally (e.g., climate change, resource security, or public health) (Chen & Gao, 2022). The importance of waste management, especially in cities, is given on the one hand by the extensive emission pollution caused by it and on the other hand by expanding urbanization and the associated growth in the amount of waste (Xu et al., 2022). Therefore, MSWM concerns diverse sustainable development goals

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* Corresponding author.
E-mail address: yvonne.kummer@boku.ac.at (Y. Kummer).

https://doi.org/10.1016/j.scs.2023.104890
Received 6 May 2023; Received in revised form 26 July 2023; Accepted 21 August 2023

(SDGs) as defined by the United Nations (2023) like SDG 6 – clean water and sanitation, SDG 11 – sustainable cities and communities, or SDG 12 – responsible consumption and production, where (municipal solid) waste is directly addressed. Many other parallels and indirect impacts are identified to SDG 3 – good life and well-being, SDG 13 – climate action, SDG 14 – life below water, or SDG 15 – life on land. These linkages, also recognized by Hannan et al. (2020), emphasize the importance of sustainable MSWM approaches.

The European Union Waste Framework Directive (2008/98) and especially the embodied waste hierarchy should be addressed when looking at mitigation strategies for the waste sector. Therein, prevention is the most critical mitigation measure, followed by preparing for reuse, recycling, recovery, and at the very last level, waste disposal. The segregation of waste fractions is crucial for recycling and significantly improves the quality of recyclables (Baeumler et al., 2012). Further, recycling, e.g., steel, paper, or plastics, increases material efficiency, diminishes GHG emissions (Bogner et al., 2007), and economically represents the most viable waste management approach (Hosseinalizadeh et al., 2021). According to IPCC (2021), waste should be managed as close as possible to the point of generation to minimize transport-related emissions. Considering this, sustainable and user-friendly waste management systems are needed. One central point is to address public acceptance and awareness of residents to prepare their waste correctly. Since residents are the primary producers of MSW, they significantly influence the amount and quality of separated waste.

1.1. Research objectives

Given the aforementioned background, the question arises of how MSWM systems can be designed to motivate the population to reuse and recycle, and support efficient operations. To address this, the city of Stockholm (Stockholms stad) with Stockholm Vatten och Avfall (SVOA), Stockholm's municipal water and waste company, performed a pilot study in May 2022 in Stockholm's inner city testing the use of a recycling barge. Sweco Sverige AB, an architecture and engineering consultancy, evaluated the pilot study primarily regarding its profitability and social acceptability based on data and customer preferences collected during the operation of the recycling barge. The underlying idea is to use water-based logistics to collect MSW from residents at several docks in the city by providing convenient and attractive access. Waste and reuse items that the residents themselves can carry are collected, except residual and packaging waste. At the same time, it is possible to take reuse items for free from a shop area on the recycling barge. This is intended to facilitate awareness and behavioral change concerning reuse. In parallel to the pilot study, a hybrid simulation (HS) model, presented in this paper, was developed in close cooperation with the providers of the recycling barge and the responsible authorities to evaluate the operational procedures and provide the computational basis for optimizing processes.

The conducted literature review (Section 1.2) exhibits several applications of HS and a variety of studies in waste management. However, micro-level planning of operational processes in waste collection centers and the application of HS in MSWM have not been found in the literature so far. In addition, the assessment of urban use of water-based infrastructure is highly underrepresented in the literature. The substantial innovative contribution of the present paper lies in the real-world, data-based HS study, which models a water-based MSWM system, including processes of collecting waste and reuse items and their take away. Following the results of the pilot study and the developed model, this novel MSWM system may contribute to the solution of current urban problems in terms of emissions, land consumption, and social equity. This paper addresses the following research objectives (RO): 1) analyzing the capacity limits of the recycling barge, 2) optimizing and modifying the operational processes at the recycling barge, and 3) assessing the sustainability of a water-based MSWM system and its applicability for other cities and operational procedures. Section 2 outlines the model development and the simulation approach, including an overview of waste management in Stockholm and details about the pilot study, followed by the numerical results and their discussion in Section 3. Finally, the main usage opportunities and an outlook for further research are presented in Section 4.

1.2. Literature review

To underpin the study's novelties and to embed it in the current state of research, this section provides a literature review of existing water-based logistics projects in European cities, the evolvement and state of the art of HS modeling, and studies dealing with MSWM.

1.2.1. Water-based logistics projects in European cities

Since transport causes significant negative externalities and road is the most used infrastructure in cities for urban freight transport (Janjevic & Ndiaye, 2014), the research on alternatives for more sustainable logistics advanced in previous years. Considering that inland waterways are often the only infrastructure in cities that are not fully utilized and, therefore, not associated with traffic congestion, they are more frequently used for freight transport in Europe (Janjevic & Ndiaye, 2014). However, only a small share of total inland freight transport is operated on waterways (Carlén et al., 2013). Looking at examples in European cities that use waterways for transport, it is noticeable that water-based transport is mainly used for bulky goods and products that are unhandy and, therefore, challenging to transport on other infrastructures (Diziain et al., 2014). Schachenhofer et al. (2023) examined barriers and usage opportunities of neglected routes, e.g., waterways in urban areas. The authors mention the necessity to recognize waterways as valuable infrastructure in cities due to their potential to reduce congestion, free up public space, and avoid emissions (Schachenhofer et al., 2023).

Due to the presented research topic, the literature review, summarized in Table 1, focuses on waterborne waste management and waste collection projects in Europe. One of the first water-based waste logistics projects was initiated in Lille, France. Since the system was first applied in 1999, it has been in operation and successfully transports MSW. Other possibilities for the use of waterways are construction logistics, parcel logistics, and passenger transport. These applications are tested in various projects in Belgium, England, Germany, and the Netherlands. Some of these projects also involve designing and constructing autonomous, zero-emission vessels. A pilot project in Gothenburg has been instrumental in identifying framework conditions and critical success factors of urban logistics concepts.

1.2.2. State of the art of hybrid simulation modeling

There are three prevalent simulation methods which are system dynamics (SD), discrete-event-simulation (DES), and agent-based modeling (ABM) (Howard et al., 2023). Combining at least two of them is called a HS (Barbosa & Azevedo, 2017). In addition, these simulation methods are often accompanied by other mathematical models or GIS models (e.g., Kerdlap et al. 2023; Ding et al. 2022). Brailsford et al. (2019) declare that the establishment of HS in operations research started more than 60 years ago. An extensive overview of each simulation method and their implementation related to sustainable manufacturing and supply chains, their historical evolvement, and relevant sources classified by modeling method and planning level is provided by Khan and Abonyi (2022). DES is the most widespread method of predicting and analyzing production processes (e.g., Negahban & Smith 2014). However, the increasing complexity of systems has encouraged the adoption of HS studies (Farsi et al., 2019; Negahban & Smith, 2014). Huanhuan et al. (2013) exemplify the evolution of combining DES and ABM based on optimizing and integrating human decision making within operational simulation models. Various sources encompass the implementation of HS (e.g., Howard et al. 2023; Katsigiannis et al. 2023; Hao & Shen 2008). Since this method has multiple

Table 1
Selected overview of water-based logistics projects in Europe.

City, Country	Name	Description	Status	Commodities	Source
Lille, France	n.a.	Transportation of MSW by barge to landfills and incinerators	Operating since 1999	MSW	CCNR (2022)
London, England	n.a.	Using the river Thames as a transport mode and offering water-based services for companies	Operating since 2005	MSW and construction waste	Gille (2011)
Berlin, Germany	A-swarm	Development and optimization of autonomous electrical vessels on inland waterways	Project 2019–2022	Parcels, food, and drinks for shops and restaurants, MSW, unitized cargo	SVA (2022)
Hamburg, Germany; Ghent and Leuven, Belgium; Delft, Netherlands	Avatar	Last mile delivery and reverse logistics by emission-free and automated water-based mode of transport	Project 2020–2023	Parcels, retail logistics, building materials, MSW	AVATAR (2022)
Leiden and Delft, Netherlands	Citybarge	Combination of an emission-free tug boat and barge for city logistics	Operating since 2020	Building materials, MSW, parcels	van den Heuvel (2021)
Gothenburg, Sweden	DenCity	Test of different sustainable and space-efficient transport solutions, e.g., recycling barge	Project since 2019	MSW	DenCity (n.d.)
Utrecht, Netherlands	Ecoboot	Disposal boat collecting waste along the canal	Operating since 2012	MSW	Brauner et al. (2021)
Lyon, France	River'tri	Barge regularly docks on the waterfront for waste collection from citizens	Operating since 2016	MSW	Velez (2021)
Amsterdam, Netherlands	Roboat	Fully autonomous, zero emissions boat operating on inland waterways	Project since 2017	Passenger, MSW, parcels, and packages	Leoni (2022)

applications in a broad spectrum of research fields, a selection of sources combining DES and ABM is presented in the following paragraph.

In the area of manufacturing processes, Sadeghi et al. (2016) use real-world data to model and evaluate the production of semiconductors mixing DES and ABM. Kukushkin et al. (2016) developed a model for producing a filling and packaging line for PET bottles wherein DES replicates the process at the production line, and ABM demonstrates the machine behavior. A use case in the healthcare sector is presented by Terning et al. (2022). The authors set up a computational model of the patient flow and behavior in an emergency department under pandemic conditions. Other applications are recognized in the agricultural sector, e.g., Kummer et al. (2022) model the Austrian pork supply chain based on real-world data and outbreaks of a viral animal disease to evaluate control strategies and identify bottlenecks in the supply chain. The validation of such models often relies on case studies and data availability. Roci et al. (2022) demonstrate the applicability of their HS by a case study of a washing machine manufacturing company declaring their significant contribution to current research by providing a highly adaptable decision support tool. Likewise, Terning et al. (2022) validate their model using secondary real-world data from a hospital in Norway. However, Brailsford et al. (2019) describe the implementation of HS models in practice as not yet advanced and the acquisition of data for simulation studies as complex. Sargent (2010) also states that the time-intensive and frequently complex acquisition of data is a common problem when constituting models, which is why their validation often fails due data availability and quality.

1.2.3. *Municipal solid waste management system studies*

Most scientific studies (e.g., Erdem 2022; Blazquez & Paredes-Belmar 2020; Hannan et al. 2018; Faccio et al. 2011; Benjamin & Beasley 2010) focus on optimizing waste collection services in terms of routing and resource scheduling. Yadav and Karmakar (2020) discuss the efficient collection and transportation of MSW for different urban areas and elaborate on mathematical modeling approaches applied within this field of research. The authors identified three main modeling approaches adapted for such problems: vehicle routing, facility location, and flow allocation (Yadav & Karmakar, 2020). The objectives of such models are primarily total costs, distance, time, and GHG emissions. On a strategic planning level, for instance, Eghbali et al. (2022) derive recommendations for planning waste management facilities based on a mixed integer linear programming model considering costs, GHG emissions, and other environmental impacts. Further, a study conducted in Jakarta, Indonesia, by Suryawan and Lee (2023) provides an assessment framework for adaptive MSWM systems and policy recommendations for implementation under different scenarios. Suryawan and Lee (2023) mention the design of collection points and infrastructure investments as crucial to providing sustainable and adaptive MSWM systems. Additionally, some literature examines recycling behavior and policy measures to increase recycling rates and waste management efficiency (e.g., Meng et al. 2018; Boonrod et al. 2015; Barr et al. 2003). Other research concentrates on improving waste collection (e.g., Fernández-Braña & Dias-Ferreira 2023; Iqbal et al. 2022). Several other literature references analyze different waste collection systems concerning their functioning and administrative structure (e.g., Degli-Esposti et al. 2023; Salazar-Adams 2021). Rodrigues et al. (2016) reviewed five components of waste collection services, summarizing previous literature sources on container type, vehicle type, collection method, waste type, and service type. It is noticeable that none of these categories include the design of the waste collection center itself. A couple of papers include an extensive literature review and overview of existing models in the field of waste management (e.g., Eghbali et al. 2022; Li et al. 2022). Most of these models, mainly using stochastic modeling and heuristic solution methods, concern the optimization of waste treatment plants, the planning of MSWM systems concerning the structure and type of the collection system, tactical planning of waste streams, alternative treatment methods, or entire supply chain models. A comprehensive analysis of the entire MSW supply chain is conducted by Xie et al. (2023). By modeling the waste supply chain and considering seasonal variations, the authors conclude that transportation costs are crucial for minimizing total costs (Xie et al., 2023).

In the field of social sciences, recycling behavior and its determining aspects are examined. Rousta et al. (2017) performed a literature review on research concerning the design of MSWM systems focusing on waste sorting behavior and collection systems. They categorized the influencing factors of recycling behavior into nine subcategories, e.g., physical infrastructure, user convenience, or intrinsic factors. Refsgaard and Magnussen (2009) state that, in addition to institutional frameworks, technological structures (e.g., an easily accessible and user-friendly collection facility) also contribute to positive recycling behavior among citizens.

Beyond all the aforementioned research foci, which are highly relevant for MSWM, the design of the waste collection facilities is also of great importance to make MSW collection more attractive and sustainable. To the best of the authors' knowledge, there are currently no published articles that present models of the collection sites and their operational processes. Although HS modeling is an advanced and sophisticated approach for operational planning in many research areas, the authors identified an application gap in the waste sector. Further, sufficient data availability is mentioned several times in the literature as critical and limiting to the validation of HS models. Therefore, the paper's main novelties are providing an HS model to numerically evaluate the operations of a water-based MSWM system in an urban environment with comprehensive real-world data and identifying optimal operational procedures under different parameter settings to enhance the sustainability of the concept. The presented RO provide relevant insights into the optimal design of such systems.

2. Model development and hybrid simulation approach

When introducing a new MSWM system, several planning steps and setting long- and short-term goals on a strategic, tactical, and operational level are essential. This study's background and planning process is briefly described in Section 2.1 before the HS approach is elaborated in Section 2.2.

2.1. Waste management and pilot study in Stockholm

Currently, there are several recycling options for residents in Stockholm. In addition to stationary recycling centers for citizens and businesses, land-based pop-up containers, located at different places in the city from April to October on weekends, collect MSW and reuse items and provide reuse items for citizens to take home for free. Staff is present at these pop-up containers to support visitors. The pop-up containers were provided on the water for a pilot study to free up valuable public space and advance the MSWM in Stockholm. Therefore, a recycling barge visited three quays in Stockholm from the 14th to 19th of May 2022, between 10 a.m. and 4 p.m. on weekends and 2 p.m. and 8 p.m. on weekdays. A theoretical feasibility study was carried out to identify possible docking points for the recycling barge. For the pilot study, a 29.40 × 11.38 m barge with a loading capacity of 545 m^3 was contracted. Due to diverse equipment, the available area is limited to 26 × 8 m. Several requirements concerning the operation of the recycling barge are provided. For example, a maximum of 200 kg of hazardous waste may be stored on the recycling barge at any time. In addition, collected waste has to be stored in locked and inaccessible facilities overnight. Therefore, two pop-up containers (same as those used on land) of 6 × 5 meters each, one for receiving waste and reuse items (drop-off container) and one for providing reuse items to take away (store container), are placed next to each other on the recycling barge. The hatched area in Fig. 1 represents a wall of the pop-up containers, which functions as a floor surface when open. A ramp provides the only access. During the pilot study, three workers were employed on the recycling barge to handle the dropped-off items, sort waste, and serve customers. After operating hours, the pop-up containers store the collected waste, which is kept in three different collection containers, depending on the fraction. Roll containers for collecting, e.g., wood, glass, textiles, and bulky waste, pallet containers for e-waste and metal, and separate hazardous waste containers. The recycling barge remained for two days at a quay from where trucks transport the reuse items (for sorting and preparation) and the collected waste to a stationary recycling center. The sorted reuse items are then partly used to restock the store container on the recycling barge. An electric truck and a hydrogenated vegetable oil (HVO) truck were used for the transports during the pilot study. The loading capacity of the HVO truck is 700 kg, while the e-truck has a loading capacity of 600 kg. The HVO truck must only remove the hazardous waste before closing the recycling barge and take as much dropped-off waste and items as possible. Quantitative data were collected during the pilot study, such as the number of customers per day, the amount of waste dropped off per fraction, the number of reuse items taken from the store container, and the number of transports. In addition, a survey was conducted with 9.4% of the customers to ask, for example, about their motivation to come to the recycling barge and their means of transport to arrive there.

2.2. Hybrid simulation model implementation

The operational planning level of the recycling barge was evaluated in a HS model implemented in the software AnyLogic 8, University. The recycling barge is modeled to scale in the same setup as in the pilot study (Fig. 1). The system boundaries include the processes on the recycling barge; therefore, the surroundings of the quay and the access conditions are not considered. A combination of ABM and DES was applied in close cooperation with the providers of the water-based MSWM system. ABM

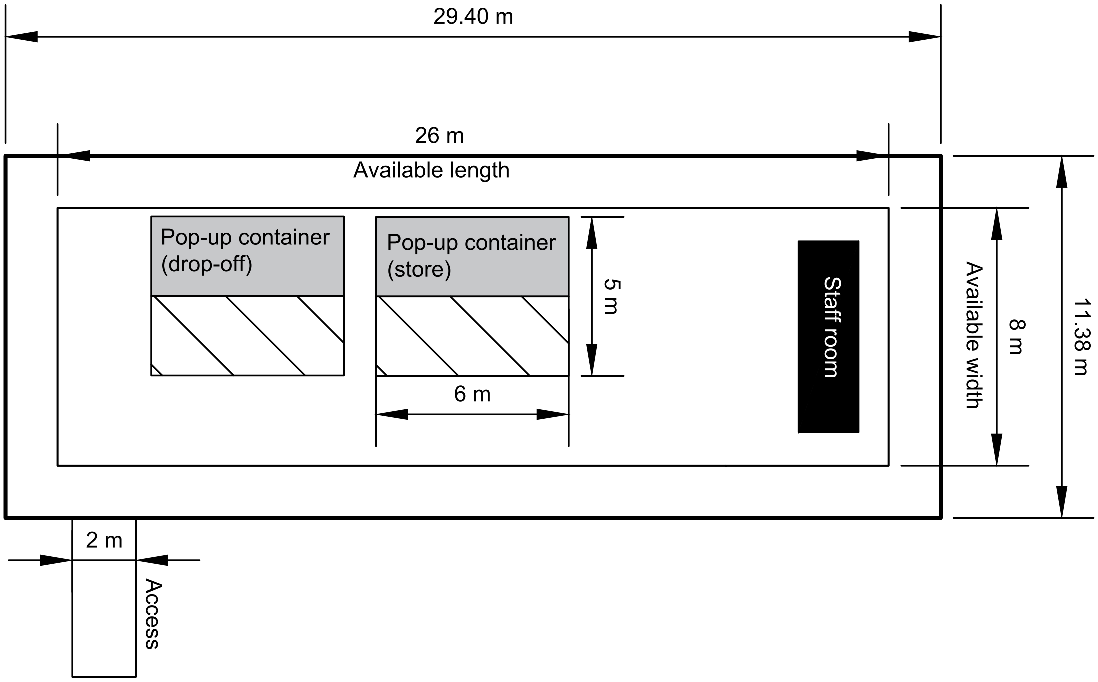


Fig. 1. Layout of the recycling barge.

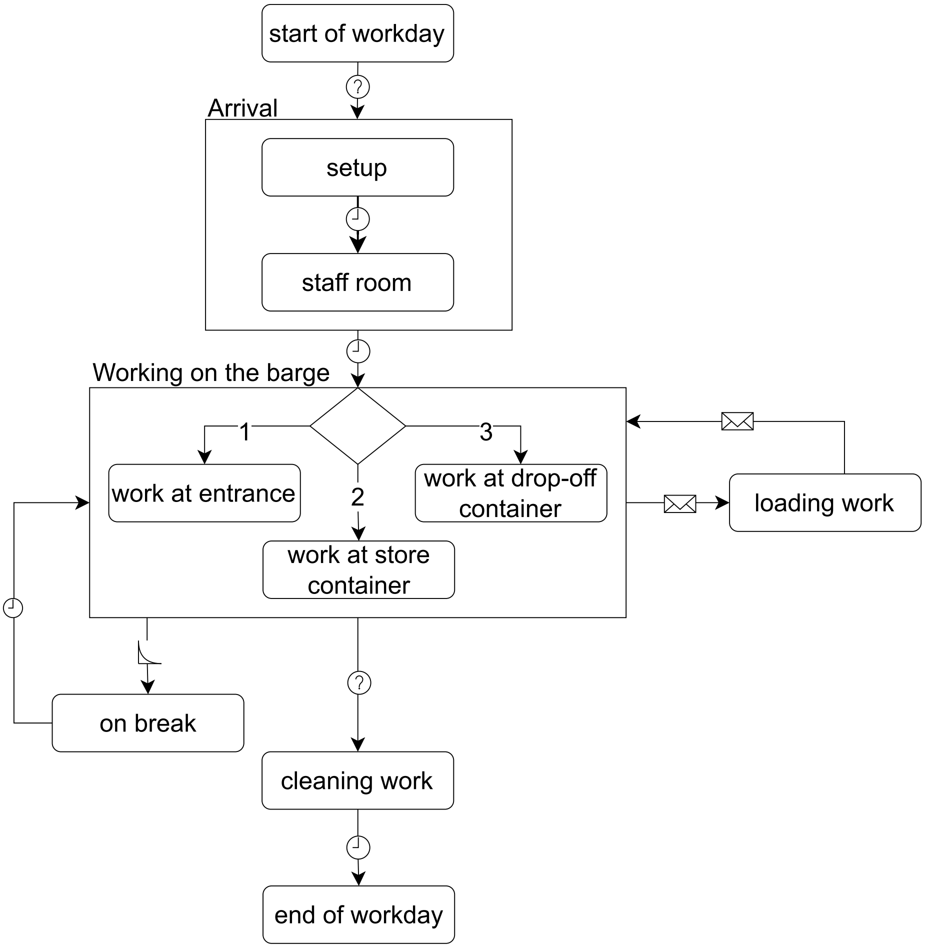
is about behavior-driven and interacting agents, which can be people and other resources like vehicles or products (Macal & North, 2005). DES is about modeling a process as a sequence of events performed by the entity passing through the process (Borshchev, 2013). Such events occur at discrete time steps and may instantly alter the system's state (Law, 2014). Katsigiannis et al. (2023) state that very robust and high-fidelity models can be implemented by combining DES and ABM. Since DES in AnyLogic also requires a (passive) agent to pass through the process, four agent types are used in the prevailing simulation, described in the following sections.

2.2.1. *Worker agent*

Fig. 2 illustrates the worker's event- or time-driven behavior using ABM. Before the recycling barge opens for customers, preparations are needed, e.g., the pop-up containers need to be opened, and the roll containers must be placed suitably. This is considered after arriving at the workplace in the state *setup*. The workers may have time to go to the staff room before proceeding to their workplace. When the recycling barge opens, two workers can work in the drop-off container and one in the store container or at the entrance as a first contact for the customers. Depending on the number of customers on the recycling barge and the allocation of the workers, the workplace is chosen according to the following prioritization: the presence of a worker in the drop-off container is mandatory, if there are more than ten people on the recycling barge, a worker must be at the entrance to instruct the customers and reduce congestion, and occupying the workplace in the store container is not mandatory. The initial allocation consists of two workers in the drop-off container and one in the store container. During the work shift, each worker takes breaks according to a triangular distribution whereby a break is taken on average 0.1 and at maximum once per hour. Each break can last up to 30 minutes, with an average of 10 minutes. As soon as a loading process, i.e., the movement of collection containers, has to be carried out, an available worker changes to the status *loading work* and then returns to one of the three workplaces. After the opening hours, the workers must store and lock all used collection containers (*cleaning work*) and then complete their workday.

2.2.2. *Customer agent*

Queueing theory, which concerns the effectiveness of queueing systems and helps to optimize them (Cruz & van Woensel, 2014), is used to model the customers' arrival on the recycling barge. Various queueing models exist, differing mainly in the assumed distributions for arrival



Arc	**Decision rule**
1	Number of customers on the recycling barge is more than threshold and no worker is already at entrance
2	Drop-off container is staffed and no worker is already at store container
3	Default transition - is taken if 1 and 2 are false

Fig. 2. ABM of the workers.

rate, interarrival rate, and service time. Service time is the time a customer takes to complete the service. The applied model assumes the number of customers to be finite and their arrival rate Poisson distributed with an exponential distribution for the service time (Hillier & Lieberman, 2010; Gans et al., 2003). Customers have a particular motivation for coming to the recycling barge, obtained from the empirical survey during the pilot study. Therefore, a customer either comes to drop off waste or reuse items, shop in the store container, look around, or combine the preceding. The number of workplaces defines the number of services in the model. When customers have to wait in a queue for service, they follow the first-in-first-out rule. The literature shows that the maximum waiting tolerance of individual customers is difficult to determine (Bolandifar et al., 2023). This time depends on the type of service and the information provided to the waiting customers. Several studies by companies use surveys to find out the maximum waiting tolerance of their customers (Waitwhile, 2022; Wethered, 2020; American Express, 2017; TimeTrade Systems, 2013). These show that 15 minutes can be assumed as the maximum tolerable waiting time in most cases. An exponential distribution models the waiting tolerances (Batt & Terwiesch, 2015). Customers will leave early if their waiting time in a queue exceeds their maximum waiting tolerance. The customers follow a DES, which determines the sequence of their movements in the system (Fig. 3). The weight brought or taken by customers has been calculated based on the pilot study results by determining the average quantity per customer.

2.2.3. *Container agent*

The roll, pallet, and hazardous waste collection containers are filled with dropped-off waste and reuse items during the opening hours and are considered full when they reach a maximum fill level and thus require movement. They are either moved by a worker to another place on the recycling barge or to the truck to be emptied. An essential component within the modeling is the conversion from weight to volume regarding the amount of waste per fraction and collection containers. This depends on the density of the waste but also the size of the collection containers and the compaction measures and is therefore different in each country or MSWM system. Several fractions are separated in the model, each requiring a different conversion factor. For example, the density of bulky waste collected in roll containers is assumed to be 0.1 kg/l, which means a maximum loading weight of 170 kg for the roll container. The assumed values (Table 2) have been taken under best conscience from several sources (e.g., AbfallScout GmbH, 2023; Bayrisches Landesamt für Statistik, 2018) and discussions with the operators of the recycling barge.

2.2.4. *Truck agent*

During operating hours, the means of transport is always the e-truck, while the last transport is executed with the HVO truck. In the simulation, four conditions were defined to trigger a transport with the e-truck: 1) the maximum quantity of stored hazardous waste is exceeded, 2) the amount of reuse items in the store has fallen below a threshold, 3) the quantity of bulky waste stored on the recycling barge has reached a threshold, or 4) the maximum loading quantity is reached in all available collection containers. The first condition is based on a legal requirement. The second is about restocking the store container if 20% of the total capacity is empty. Further, the third condition is based on the experience of the pilot study, where some bigger bulky items, e.g., chairs, were dropped off. Since such items reserve much space, the threshold ensures regular removal of such bulky items. The fourth condition is met when all available collection containers on the recycling barge are full. Transport is triggered as soon as one of these conditions is met. If possible, the truck is always filled to the maximum loading capacity. Table 2 summarizes all input parameters of the model and describes their characteristics.

3. Results and discussion

This chapter provides the numerical results of six scenarios and associated 58 experimental settings, as well as a discussion of their results. Table 3 lists the parameters of interest regarding the RO and their range for Scenarios 1 to 6. Each experimental setting was computed 100 times to deal with the stochasticity of the parameters. Therefore, the stated numerical output is the mean value over 100 replications. The simulation was performed on a 60 GB RAM computer with an intel® Core ™ i7–3903 L CPU, 3.20 GHz. The computation time of one simulation run is less than one second.

Verifying the model's logic and identifying the system boundaries is vital and examined in Sections 3.1 and 3.2. Concerning the applicability to other cities and their legal and technical conditions, the optimization potential is analyzed and validated by several scenario computations in Section 3.3. The evaluation of the numerical outcome and its interpretation regarding the system's sustainability is presented in Section 3.4.

3.1. *Model verification and validation*

Verifying the simulation models' logic is necessary to provide information on whether the implemented algorithms reflect the pilot study's output and are appropriate for further calculations. Validation and verification techniques for simulation models as the animation of operational behavior, event validity, face validity, historical data validation, internal validity, operational graphics, parameter variability - sensitivity analysis, and traces, which are commonly used in practice and described in the literature (Sargent, 2010), were applied in this study. Validation of simulation results based on real-world data is commonly practiced if feasible (Farsi et al., 2019). Table 4 summarizes the numerical output of Scenario 1, reproducing the pilot study's conditions. The calculations result in an average of two transports with the e-truck and one with the HVO truck per day, reflecting the pilot study results. The output related to HVO transports is not relevant for further calculations as it is always once at the end of the workday. In the

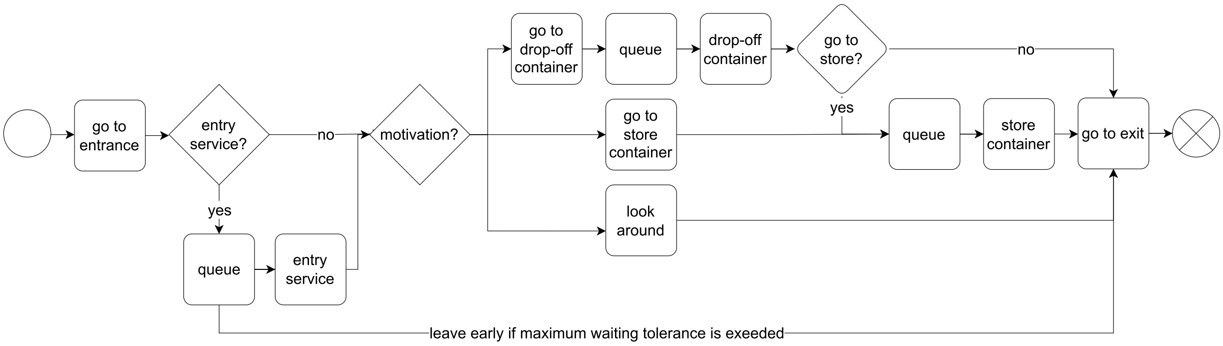


Fig. 3. DES of the customer process flow.

Table 2
Model parameters.

Parameter	Value [unit]	Characteristics
Simulation run time	10 [h]	Period of one working day plus buffer (setup and cleaning work).
Number of workers	3 [person]	Obtained data from pilot study.
Threshold number of customers to work at the entrance	10 [person]	When reached, the workplace at the entrance must be staffed. Estimation by providers of pilot study.
Average number of customers per day	479 [person]	Obtained data from pilot study.
Customer arrival rate	Poisson (lambda ∈ (17, 250), per hour)	Lambda is calculated based on the number of customers per day.
Motivation	leave waste 28.63%, leave items for reuse 28.63%, store container 31.23%, other 11.51%	The main reason why people come to the recycling barge. Obtained data from pilot study.
Average reuse items dropped off per customer	2.50 [kg]	Obtained data from pilot study.
Average other fractions dropped off per customer	2.70 [kg]	Obtained data from pilot study.
Average e-waste and metal dropped off per customer	0.60 [kg]	Obtained data from pilot study.
Average hazardous waste dropped off per customer	1.00 [kg]	Obtained data from pilot study.
Average reuse items taken per customer	3 [item]	Obtained data from pilot study.
Weight distribution	Uniform discrete (0, 2)	Factor how much weight each customer drops off and takes away.
Shopping preference	Triangular (1, 4, 2)	Defines whether a customer wants to go to the store container after dropping off waste: 1 - not interested, 2 - interested but not taking items, 3 - interested and taking items.
Service time entry	Exponential (3.3, 0.1) [min]	Time each customer needs at entrance service (if available).
Service time drop-off	Exponential (1.25, 0.3) [min]	Time each customer needs at drop-off container.
Service time take away	Exponential (0.5, 0.5) [min]	Time each customer needs at store container.
Service time drop-off after entrance service	Exponential (3.3, 0.1) [min]	Time each customer needs at drop-off container after entrance service (if available).
Max. waiting time	Exponential (0.23, 1.5) [min]	Time each customer is willing to wait in line.
Number of pallet containers	2	Used for e-waste and metal. Obtained data from pilot study.
Number of roll containers	10	Used for reuse items and other fractions (wood, glass, textiles, and bulky waste). Obtained data from pilot study.
Number of hazardous waste containers	2	Used for hazardous waste. Obtained data from pilot study.
Volume roll container	1.70 [m^3]	Standard roll container.
Volume pallet container	1.12 [m^3]	Standard pallet container.
Volume of hazardous waste container	0.24 [m^3]	Standard recycling container.
Conversion roll container - bulky waste	0.10	Conversion factor from volume to weight.
Conversion roll container – all other fractions	0.40	Conversion factor from volume to weight.
Conversion pallet container - e-waste and metal	0.20	Conversion factor from volume to weight.
Conversion factor hazardous waste	0.80	Conversion factor from volume to weight.
Threshold reuse items taken	20%	Percentage of the total capacity of the store container. When reached, new reuse items must be brought to the store.
Threshold hazardous waste	200 [kg]	Max. amount allowed on the recycling barge at one time. When reached, hazardous waste must be removed.
Threshold bulky waste	200 [kg]	When reached, bulky waste must be removed.

experimental setting, the main reason a transport was initiated was to bring reuse items to the recycling barge, which is hard to compare with the data from the pilot study as this was not sufficiently recorded. However, discussions with the operators confirm that this was similar during the pilot study. Furthermore, the results were analyzed on collected waste quantities per fraction and in total. The assumed distributions could be successfully evaluated compared to the pilot study data. Accordingly, verifying and validating the model's logic justifies its reliable use for calculating further experimental settings and addressing the RO.

3.2. *Capacity analysis (RO-1)*

In order to investigate the capacity limits of the recycling barge, two determining indicators were considered: the number of customers per day (Scenario 2) and the weight dropped-off (Scenario 3). On average, the maximum waiting tolerance of the customers' overall experimental settings of Scenario 2 (Table 5) is 7.05 minutes. The time each customer spent in the system, meaning the time between entering and leaving the recycling barge, rises from 8.5 to 14.6 minutes from $N = 100$ to $N = 1500$, increasing by 72%. The relatively long mean residence time is mainly influenced by the time spent in the store container. Up to $N = 400$, all customers could be served. From $N = 500$ onwards, on average, 0.2 customers left the queue early; from $N = 1000$ onwards, the average percentage of customers who left the system early is above 6%; at $N = 1500$, it is 38% on average. These calculations show that an adequate number of customers exists up to $N = 800$. When this threshold is exceeded, the number of dissatisfied customers, as measured by people who leave the system before receiving service, increases tremendously. The amount of waste and reuse items brought and taken away decreases slightly after $N = 1100$, which correlates with the increasing number of customers not served. The average number of transports and the average loading quantity also display this causality. From $N = 100$ to $N = 1500$, the average number of e-truck transports increased from 0 to 4.2, whereas the average tons loaded per day raised by 739%. The primary reason transportation was initiated remains to bring reuse items from the stationary recycling center to the recycling barge across all experimental settings.

Fig. 4 shows the effects on worker utilization by measuring how long the workers are deployed at the respective workplaces (entrance, drop-off container, store container) and how often they need to change

Table 3
Parameter setting for Scenarios 1 to 6.

Scenario	Number of experimental settings	Number of customers (N)	Weight factor	Number of pallet containers	Number of roll containers	Threshold bulky waste [kg]	Percentage of items dropped off reused directly at the store cont. [%]
1	1	479	1	2	10	200	0
2	15	100–1500	1	2	10	200	0
3	24	500–1000	2–5	2	10	200	0
4	6	500–1000	2	3	14	400	0
5	6	500–1000	2	2	10	200	10
6	6	500–1000	2	3	14	400	10

Table 4
Numerical output Scenario 1.

Parameter	Value
number of customers (N)	479
mean time customer queue at entrance [min]	0.03
mean time customer queue at drop-off container [min]	0.23
mean time customer queue at store container [min]	0.01
mean time customer in system [min]	8.92
mean number of customers left early	0.00
mean number of e-transports	1.96
mean number of HVO transports	1.00
mean loading quantity [tons]	0.91
mean collected reuse items [tons]	0.36
mean collected other fractions [tons]	0.37
mean collected e-waste and metal [tons]	0.08
mean collected hazardous waste [tons]	0.14
mean reuse items taken [tons]	0.18

workplaces. The implemented algorithm achieves a constant average working time in the drop-off container, assigning the highest priority to this workplace. At the same time, the average working time in the store container declines rapidly as soon as more than 400 customers visit the recycling barge. Simultaneously, the time spent working at the entrance increases, which is justified by the limit of 10 customers allowed to be on the recycling barge, which is reached more frequently. The time spent on loading activities, i.e., moving collection containers on the recycling barge or transporting them to and from the truck, also increases with the number of customers, as this correlates with the amount dropped off. The time spent on break remains almost constant, decreasing by 15 minutes from $N = 100$ to $N = 1500$. Another indicator to measure workers` utilization is the average number of state changes, meaning that each time a worker leaves the workplace, it is counted as one change. This indicator has a 700% overall rise (16 to 130) from $N = 100$ to $N = 1500$. This suggests greater stress for the workers. A further breakdown of the data by work location shows that most changes had to be made between the store container and the entrance (Fig. 4, right).

For further analysis, Scenario 3 considers the impact of increasing waste and reuse item volumes. Therefore, the quantities customers drop off are multiplied by a constant weight factor. The results are shown in Table 6. With a weight factor of 2, the mean number of transports increases by 100%. When applying the weight factor of 5, an 239% increase is reported compared to Scenario 2. The main reason for transport shifts from an average of 60% to bring reuse items to the recycling barge when applying the weight factor of 2 to 75% to remove bulky waste for the weight factor of 5. Further, statistics on the distribution of working hours among workplaces show a significant increase in time consumption for loading activities when more waste is dropped off, which correlates with the number of transports. The average number of state changes remains almost the same as in Scenario 2 and thus indicates no additional impact on the workers' utilization.

The results were compared with data from the stationary recycling center Roslagstull in Stockholm, which accepts MSW from private households. The average quantities of each collected fraction are comparable to the calculated quantities with the weight factor of 2. Hence, this weight factor is used for the subsequent calculations of Scenarios 4 to 6.

3.3. *Operational optimization and extension (RO-2)*

The results of Scenario 3 indicate that the amount of waste collected is not a limiting factor, as it does not exceed the capacity of the collection containers. This is mainly related to the rules for a transport trigger programmed in the model. Especially bulky items that require much space must be picked up more often than other fractions. Accordingly, the impact of increased storage capacity is considered in Scenario 4.

Table 5
Numerical output Scenario 2 (all times in [min]).

Number of customers (N)	Mean time customer queue at entrance	Mean time customer queue at drop-off cont.	Mean time customer queue at store cont.	Mean time customer in system	Mean number of customers left early	Mean number of e-transports	Mean loading quantity [tons]	Mean collected reuse items [tons]	Mean collected other fractions [tons]	Mean collected e-waste and metal [tons]	Mean collected hazardous waste [tons]	Mean reuse items taken [tons]
100	0.00	0.02	0.00	8.51	0.00	0.00	0.19	0.07	0.07	0.02	0.03	0.04
200	0.00	0.05	0.00	8.68	0.00	0.86	0.38	0.15	0.15	0.03	0.06	0.08
300	0.00	0.12	0.00	8.74	0.00	1.02	0.58	0.22	0.23	0.05	0.09	0.11
400	0.01	0.17	0.01	8.85	0.00	1.45	0.72	0.29	0.31	0.07	0.12	0.15
500	0.04	0.22	0.02	8.92	0.20	2.01	0.95	0.38	0.38	0.08	0.14	0.19
600	0.10	0.23	0.04	8.98	0.41	2.15	1.10	0.45	0.46	0.10	0.17	0.23
700	0.21	0.26	0.09	9.13	1.96	2.72	1.27	0.52	0.53	0.12	0.20	0.26
800	0.42	0.28	0.14	9.31	7.14	3.44	1.48	0.59	0.60	0.14	0.23	0.30
900	0.82	0.32	0.23	9.74	25.03	3.98	1.59	0.65	0.65	0.15	0.25	0.33
1000	1.40	0.40	0.32	10.32	64.05	4.21	1.68	0.68	0.69	0.16	0.26	0.36
1100	2.16	0.49	0.43	11.03	135.25	4.35	1.69	0.69	0.70	0.16	0.26	0.38
1200	2.96	0.59	0.50	11.73	226.79	4.39	1.68	0.68	0.69	0.16	0.26	0.39
1300	3.86	0.75	0.62	12.62	331.77	4.45	1.66	0.67	0.69	0.15	0.26	0.39
1400	4.93	0.78	0.58	13.41	451.20	4.29	1.62	0.66	0.68	0.15	0.26	0.38
1500	6.30	0.90	0.55	14.61	573.42	4.20	1.63	0.65	0.67	0.15	0.25	0.37

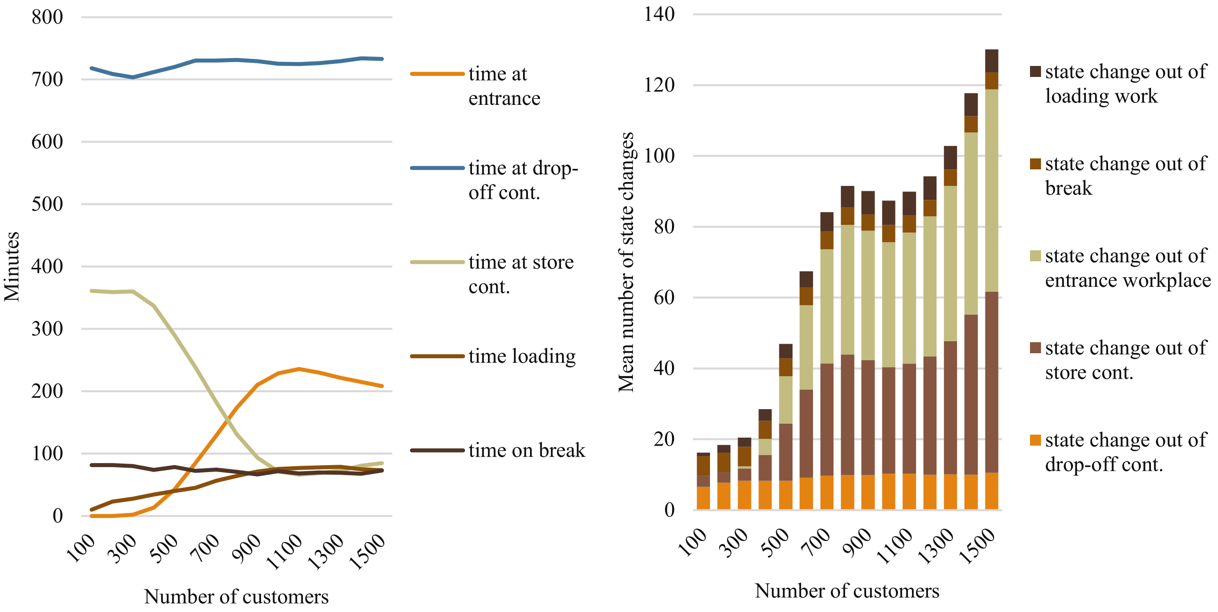


Fig. 4. Statistics for all workers Scenario 2 – average working time at each working place (left), average number of state changes per workplace (right).

Table 6
Numerical output Scenario 3 (all times in [min]).

Number of customers (*N*)	Weight factor	Mean number of e-transports	Mean loading quantity [tons]	Mean time worker at entrance	Mean time worker at drop-off cont.	Mean time worker at store cont.	Mean time worker loading	Mean time worker on break	Mean number of workers state changes
500	2	4.56	1.86	42.69	709.08	265.14	83.72	71.43	51.16
600		5.30	2.19	81.27	717.58	215.83	92.17	65.43	68.84
700		6.04	2.49	126.18	714.57	158.70	102.18	70.52	84.05
800		6.57	2.83	167.20	717.15	114.54	112.09	61.07	89.38
900		7.14	3.10	197.86	715.79	83.66	119.22	55.16	84.94
1000		7.52	3.28	214.52	710.96	64.35	126.96	55.85	82.08
500	3	6.34	2.71	40.36	704.67	254.28	107.97	65.18	53.16
600		7.40	3.21	77.28	710.71	202.92	122.74	59.23	69.96
700		8.47	3.70	117.19	713.60	149.46	135.38	56.43	82.72
800		9.07	4.07	153.56	713.50	105.62	145.16	54.72	87.30
900		9.23	4.44	185.62	704.32	72.93	152.88	56.70	82.55
1000		9.64	4.66	204.02	703.04	57.07	156.22	51.87	77.37
500	4	8.22	3.57	39.62	697.49	239.56	132.99	62.63	54.43
600		8.97	4.19	75.54	704.95	186.47	145.32	60.56	69.66
700		9.53	4.64	118.25	704.57	143.67	154.07	52.81	81.83
800		10.02	5.17	153.32	703.58	101.20	161.41	53.62	85.94
900		10.27	5.62	183.10	699.46	72.51	164.13	52.83	82.69
1000		10.64	5.83	198.68	703.13	54.67	166.07	50.21	79.01
500	5	9.03	4.32	39.27	695.35	232.72	147.80	56.71	55.84
600		9.92	5.02	75.83	704.01	184.52	156.66	51.84	71.17
700		10.39	5.55	115.32	704.86	138.28	162.70	50.83	83.25
800		10.85	6.17	152.97	703.57	99.82	165.41	50.38	87.57
900		11.06	6.71	184.83	701.20	70.91	162.64	53.90	86.37
1000		11.47	6.95	200.60	702.89	56.71	164.47	49.03	84.51

Table 7
Numerical output Scenario 4.

Number of customers (*N*)	Mean number of e-transports	Mean loading quantity [tons]	Reason for transport: hazardous waste (mean)	Reason for transport: bring reuse items (mean)	Reason for transport: bulky waste (mean)	Reason for transport: full collection container (mean)
500	4.25	1.86	1.46	3.79	0.00	0.00
600	4.73	2.24	1.69	4.04	0.00	0.00
700	5.10	2.58	1.49	4.59	0.02	0.00
800	5.56	2.90	1.60	4.92	0.04	0.00
900	6.00	3.21	1.89	5.09	0.02	0.00
1000	6.34	3.30	1.93	5.32	0.09	0.00

Places on the recycling barge, primarily used as open spaces and common areas, can be used as additional storage space for collection containers. Therefore, four roll containers and one pallet container were added to the simulation setting. Simultaneously, the threshold for bulky waste stored on the recycling barge is increased by 200 kg to 400 kg, reflecting the increased storage capacity. As a result, the total trips required were reduced by an average of 14% compared to Scenario 3 with a weight factor of 2. The numerical output related to transport statistics is presented in Table 7. Transports with the main reason for picking up hazardous waste or bringing reuse items increase slightly by 7% and 10% in Scenario 4 compared to Scenario 3 with the weight factor of 2. In contrast, the transports intended to remove bulky waste are reduced to almost zero.

As the simulation model is not limited to the requirements of the pilot study, it is investigated how the water-based MSWM system can be optimized regarding its operational processes. Hence, Scenario 5 considers, in particular, the accessibility and extension of the system for other cities and regulations. Therefore, it is assumed that several items dropped off will be directly reused on the recycling barge by being taken away by customers. The current conditions in Stockholm do not allow such a material flow, as careful sorting must be carried out by skilled personnel in a stationary recycling center. However, if more or specially trained workers are employed on the recycling barge, these system boundaries could be relaxed. The model extension includes the additional material flow between drop-off and store container, whereby 10% of the dropped-off reuse items are classified as suitable for direct forwarding. The other items must continue to be handled through the stationary recycling center. This is because some reuse items need to be repaired or provided to charitable organizations. The numerical output of the transport statistics is shown in Table 8. On average, 22% fewer transport operations are required compared to Scenario 3 with a weight factor of 2. The main reason for transport is to remove bulky waste.

Combining the results from Scenarios 4 and 5, in Scenario 6, an increased storage capacity and the possibility of sorting reuse items directly on the recycling barge are simulated. The results show that the total transport operations could be reduced by 55% on average compared to Scenario 3 with these combined modifications. The distribution of the reasons for transport in Scenario 6 is as follows: 53.2% to remove hazardous waste, 44.4% to remove bulky waste, and 2.4% to empty the collection containers (Table 9).

Scenarios 2 to 6 were also computed with a higher loading capacity of the e-truck of one ton (+ 0.4 tons) to extend the system's boundaries. However, the number of required transports was not influenced compared to the base scenarios. This indicates that the reasons for transport are more crucial than the loading capacity.

3.4. *Outcome evaluation and sustainability assessment (RO-3)*

The calculated experimental settings have contributed to identifying the system boundaries of the water-based MSWM system and analyzing its optimization potential. The main results are analyzed hereafter to assess the results in the scope of the RO and the context of economic, social, and environmental sustainability.

The economic applicability of a water-based MSWM system was evaluated during the pilot study. It was observed that the service was well received by the residents and frequently used. This is assumed to be the fundamental premise for all further considerations within the scope of this research. The dimension of the barge is crucial for its capacity limit and is highly dependent on the operator's economic resources and technical requirements at the quays. Therefore, the concept must be adapted to the on-site technical conditions when considering broader extensions of the service, including other cities. Within this research, the recycling barge dimensions and constraints were derived from real-world data and the financial and technical requirements of the pilot study in Stockholm. However, costs for renting the barge, quays, containers, and other equipment are decisive factors to be considered in the planning stage of such a service. Further, Schachenhofer et al. (2023) mention the necessity to address technical and technological as well as infrastructural obstacles to better utilize waterways in cities.

Regarding social sustainability, it is essential to prevent inequalities and provide unconditional access to public facilities to ensure spatial justice (Pitarch-Garrido, 2018). The results addressed social sustainability by providing an optimal level of service, above which a service expansion should be considered to maintain customer accessibility. Exceeding waiting times were measured mainly at the entrance, where customers would most likely abandon the service and leave the system early. However, to increase recycling rates and improve service quality, it is necessary to make the service accessible to all population groups. Thus, waiting times should be minimized, e.g., by installing two entrance ramps, one for the store and another for the drop-off container, to utilize the space better. The number of workplace changes was evaluated to address the workers` utilization, assuming that more changes indicate more stress for the workers. Across all scenarios, only minor deviations in the number of workplace changes were observed. A further breakdown of the working time per workplace shows hardly any difference per scenario. On average, most of the time, 61%, is spent in the drop-off container, reflecting that two workers can be assigned to it simultaneously. 13% and 12% are spent in the store container and at the entrance, respectively. 8% of the working time is needed for loading activities, and the remaining 6% is spent on breaks.

When modifying the operational procedures in Scenarios 5 and 6, the e-truck trips could be drastically reduced, consequently reducing emissions. The "Transport and Environment Report 2022″ by the European Environment Agency (2022) quantifies the various environmental impacts of transport and mentions that the increase in transport activity is responsible for increasing emissions in this sector. Although the life-cycle GHG emissions of e-vehicles are already drastically diminished compared to fossil-fueled vehicles under most conditions of driving speed and payload (Zhou et al., 2017), reducing vehicles on the road is an ambitious goal to reduce other emissions and negative externalities such as, e.g., particulate matter, noise emissions, congestion costs, accident costs, and the like. The computations with a higher loading

Table 8
Numerical output Scenario 5.

Number of customers (*N*)	Mean number of e-transports	Mean loading quantity [tons]	Reason for transport: hazardous waste (mean)	Reason for transport: bring reuse items (mean)	Reason for transport: bulky waste (mean)	Reason for transport: full collection container (mean)
500	3.24	1.51	1.62	0.00	2.62	0.00
600	4.04	1.75	1.58	0.01	3.45	0.00
700	4.59	2.04	1.53	0.02	4.04	0.00
800	5.15	2.31	1.54	0.01	4.60	0.00
900	5.71	2.45	1.70	0.00	5.01	0.00
1000	6.15	2.62	1.66	0.00	5.49	0.00

Table 9
Numerical output Scenario 6.

Number of customers (*N*)	Mean number of e-transports	Mean loading quantity [tons]	Reason for transport: hazardous waste (mean)	Reason for transport: bring reuse items (mean)	Reason for transport: bulky waste (mean)	Reason for transport: full collection container (mean)
500	1.97	1.59	1.94	0.00	1.03	0.02
600	2.17	1.86	1.73	0.00	1.44	0.14
700	2.47	2.07	1.59	0.00	1.88	0.08
800	3.02	2.37	1.96	0.00	2.06	0.11
900	3.44	2.60	2.29	0.00	2.15	0.10
1000	3.59	2.73	2.44	0.00	2.15	0.08

capacity of the e-truck did not affect the number of transports required, meaning that the assumed size is sufficient. Since the mass of a vehicle correlates with energy consumption (Weiss et al., 2020), the system's environmental sustainability is enhanced by using small, fully loaded vehicles with lower curb weight and reduced externalities. Further, the storage area for bulky waste and the restocking procedure of the store container are defined as essential parameters for operational optimization. Encouraging people to use other MSWM facilities for large items may also help to utilize the storage space more optimally and must be counterbalanced with the potential consequences of decreasing recycling rates. An important aspect, mainly to save transport and emissions, is the direct flow of reuse items from the drop-off to the store container.

4. Conclusion and outlook

The paper presents a solution to use alternative infrastructures in cities for MSWM. A water-based MSWM system combines convenient access to waste collection for citizens and creates awareness and motivation for reuse and recycling, while not occupying valuable public space. We use HS modeling for optimizing the operational processes on a recycling barge. Based on the developed verified and validated model, the recycling barge's system limits were calculated, demonstrating practical approaches to expanding the system's capacity. Consequently, the operational procedures were adapted to identify the relevant parameters which are significant for the utilization of the system and the performance in terms of sustainability. For instance, the calculated scenarios show enormous potential for transport bundling and thus possibilities to reduce negative externalities of road transport.

The simulation model can be flexibly modified for other conditions and therefore helps to implement sustainable MSWM systems in cities. A notable usage opportunity of the introduced MSWM system is the utilization of underused waterways while facilitating recycling, reducing land consumption, and reaching other sustainability goals if applied on a larger scale. A relevant strength of the HS method is the possibility for decision makers to vary the simulation parameters to represent different objectives. Therefore, various scenarios can be evaluated before expensive investments are undertaken, and decision makers may become aware of outcomes not considered in advance. Future research might deal with large-scale network-flow models to compare different transportation modes and routes of the water-based MSWM systems. Transportation by the barge itself may be compared with that by road, and optimal (multimodal) route planning could be determined. Furthermore, simultaneously using several barges can provide additional benefits and open future research fields. This research's quantitative evaluation of a water-based MSWM system significantly contributes to future developments and applications in other cities. By implementing sustainable MSWM systems, cities are significantly contributing to fulfilling the SDGs.

Funding

This work was written within the research project "ASAP - Awaken Sleeping Assets Project", which is supported by the Austrian Research Promotion Agency [project number 887519] and funded with federal public funds by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK), by the Swedish Energy Agency, Formas and Vinnova [project number 51974–1] and by the European Commission under the Horizon 2020 ERA-NET Co-fund on Urban Accessibility and Connectivity (ENUAC) [grant agreement 875022]. Open access funding provided by University of Natural Resources and Life Sciences, Vienna (BOKU).

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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