International Journal of Social Ecology and Sustainable Development
Volume 15 • Issue 1 • January-December 2024

Towards a Smarter Waste Management:
Developing and Evaluating a Smart Waste Management Decision Support Framework

Inna Sosunova
Lappeenranta–Lahti University of Technology, Finland

Ari Happonen
https://orcid.org/0000-0003-0744-1776
Lappeenranta–Lahti University of Technology, Finland

Annika Wolff
Lappeenranta–Lahti University of Technology, Finland

Jari Porras
Lappeenranta–Lahti University of Technology, Finland

ABSTRACT

The study 1) explores how to develop an IoT-based smart waste management (SWM) system that improves the waste management processes of a city and 2) researches how to develop SWM system improvement and evaluation decision support framework (DSF), that guides how to achieve all major WM-related goals, applies to different types of cities with different contexts and is not restrained to a single country or region. This study combines in one framework theoretical research, surveys with key WM stakeholders, practical research from international projects and hackathons, and practical knowledge from interviews with city authorities and companies responsible for waste management in the world's greenest cities. The SWM DSF has been tested and evaluated in three stages: 1) by researchers, 2) by a panel of experts, and 3) by representatives of the city administration of two Finnish cities.

KEYWORDS

Decision Support Systems, Framework, IoT, Waste Management, Sustainability, Recycling, Software for Sustainability, SMW, SDG, Digitalization, Circular Economy, Reduce-Reuse-Recycle, Green ICT

INTRODUCTION

Waste management (WM) is a critical environmental concern (Vergara & Tchobanoglous, 2012), but many under-evaluated themes are present in current research (Khan et al., 2023). In society activity, WM presents a significant challenge for modern cities and municipalities (Bhargavi et al., 2020) and is also highly linked to the proper selection of processes and technologies (Khan et al., 2022; Kilpeläinen et al., 2021). Modern digitalization (Mondal et al., 2023; Happonen et al., 2023) does support these challenges (Ghoreishi et al., 2022), but digitalization and automation mean more technological implementations (Chen et al., 2023), which, in the long run, might be an extra source of electronic waste (e-waste; Jain et al., 2023; Minashkina & Happonen, 2022), alongside the boom in electric vehicles, which means the large-scale growth of car-based electronics and battery components cause more e-waste problems to solve (Happonen et al., 2024; Swapnil et al., 2024). With divergent

DOI: 10.4018/IJSESD.361770

living areas, divergent styles of infrastructure, financial capabilities, investment feasibilities (Happonen et al., 2021), needs, reporting demands (Happonen & Minashkina, 2020), and goals for implementing a WM system, cities and municipalities (or WM companies organizing activities on behalf of these actors; Farooq et al., 2022) require diverse WM services and technologies for emissions (Auvinen et al., 2020) and waste reduction solutions to build a successful and resource-effective WM system to improve circularity in cities (Maddalene et al., 2023) and nearby rural areas.

There are a large number of smart WM (SWM) systems (Sosunova & Porras, 2022) operating at different levels and solving different sets of problems: data analytics (Jadli & Hain, 2020; Bevish Jinila et al., 2019), waste separation behavior practice motivator systems (Arkorful et al., 2022; Zaikova et al., 2022), user support (Addabbo et al., 2019; Naskova, 2017), user engagement practices for recycling (Santti et al., 2020), route planning and optimization (Lozano et al., 2018; Anagnostopoulos et al., 2015), environmental problems on the city level (Jadli & Hain, 2020; Digiesi et al., 2015), and waste type identification, waste classification, and segregation on the smart garbage bin (SGB) level (Saranya et al., 2020; Subbulakshmi, 2019). Most existing frameworks rely only on literature or standards from a specific country (He et al., 2022; Shin et al., 2020) or data on specific topics (Thyberg & Tonjes, 2015; Verge & Kerry Rowe, 2013), which limits their applicable scope and real-world usefulness.

The study (1) explores how to develop an Internet of Things (IoT) SWM system that improves the WM processes of a city; (2) researches how to develop an SWM system improvement and evaluation decision support framework (DSF) that guides how to achieve all major WM-related goals, applies to different types of cities with different contexts and is not restrained to a single country or region; (3) discusses the framework plausibility and usability evaluation and testing results, by researchers working in the field of computer science and green information and communications technology (green ICT) and by a panel of field experts; and (4) discusses the framework impacts evaluation and testing results (by representatives of the city administration of two Finnish cities).

This paper presents an SWM DSF, incorporating (1) theoretical research obtained through a systematic literature review (SLR) of 173 primary studies (Sosunova & Porras, 2022); (2) surveys conducted with the main WM system stakeholders (Sosunova et al., 2023); (3) practical research conducted during international projects (bIoTope, 2018; CroBoDDIT project, 2021) and hackathons (International Hackathon in Disruptive Information Solutions, 2021); and (4) practical knowledge obtained from interviews with the representatives of the world's greenest cities authorities and companies responsible for WM. The proposed SWM DSF provides recommendations about WM in the city based on current tasks, the city's characteristics, and the city's context. Authors have evaluated and tested the framework's plausibility, usability, and impact on two Finnish cities, and our results demonstrate that the developed framework can significantly improve WM processes and promote sustainable development.

The study contributes to the current literature on WM by providing a DSF combining theoretical research, surveys with key stakeholders, practical research from international projects and hackathons, and practical knowledge from interviews with city authorities and companies responsible for WM in the world's greenest cities. The developed DSF solves a more comprehensive problem than existing frameworks, which are limited in scope, data sources, and real-world usability, as mentioned above. It provides guidance on achieving all major WM-related goals, applies to different types of cities with different contexts, and is not restricted to a single country or region. The DSF has an extensive structure of contextual parameters, goals, and challenges, making it possible to obtain relevant recommendations for a wide range of cities, from small technologically unequipped towns to megacities with developed WM infrastructures that use several modern WM technologies.

The proposed SWM DSF contributes to long-term environmental sustainability by offering and guiding towards optimization of WM processes to minimize resource consumption, reduce waste generation, and improve recycling rates. By providing tailored recommendations based on the city's specific context and needs, the framework promotes resource efficiency and supports sustainable urban development. Additionally, the framework considers social equity, ensuring that WM solutions are accessible and beneficial to all residents, regardless of city size, economic capabilities, or technological infrastructure. By fostering a holistic approach to sustainable development, the SWM DSF aids in realizing key environmental goals, including emission reduction, responsible resource use, and waste minimization, while also addressing social challenges such as community engagement and behavioral change. With the suggestions coming from the framework, it will be easier for waste managers and larger companies working directly with them to work together and improve both the social and economic sustainability of companies (Minashkina & Happonen, 2023), boosting worker and individual interest in contributing holistically to local waste reduction and recycling activities.

The rest of the paper is structured as follows: first is a review of related work on WM DSFs, highlighting a research gap. Next is an outline of the research methodology, followed by the results, obtained through a Microsoft Excel test tool and web versions of the developed SWM DSF. Following this, is a description of the evaluation and testing of the DSF. Finally, the paper concludes with discussions and analyses of the findings.

RELATED WORK

Frameworks (Zorpas, 2020; Elsaid & Aghezzaf, 2015) help to solve existing problems in diverse areas of WM and help to valorize waste streams (Cooney et al., 2023; Mainardis et al., 2024; Jones et al., 2022) can help stakeholders (city authorities, WM companies, municipalities) to plan WM in a city and related areas to solve various urban problems, in context of WM and environment. Such frameworks (see Table 1) exist in the areas of municipal solid WM (Pamučar et al., 2022; Antmann et al., 2013; Thyberg & Tonjes, 2015; He et al., 2022; Rybnytska et al., 2018), waste-to-energy (WTE) resource planning (Kaya et al., 2021), construction waste recycling (Bao & Lu, 2021), and industrial WM (Sarkkinen et al., 2019), agriculture and poultry waste (automated WM, waste minimization; Arun Gnanaraj & Gnana Jayanthi, 2017), reduce plastic waste generation (Shin et al., 2020), zero-WM (Ahmed et al., 2023), monitor violations prior to the waste collection process (Al-Masri et al., 2019), landfill design (Verge & Kerry Rowe, 2013), and waste in the textile industry (Chowdhury et al., 2023).

Most of these frameworks focus on authorities as stakeholders (Pamučar et al., 2022; Kaya et al., 2021; Bao & Lu, 2021; Sarkkinen et al., 2019; Antmann et al., 2013; Shin et al., 2020; Thyberg & Tonjes, 2015; He et al., 2022). Some frameworks are focused on both authorities and companies (Al-Masri et al., 2019; Arun Gnanaraj & Gnana Jayanthi, 2017; Verge & Kerry Rowe, 2013; Ahmed et al., 2023). The most common purposes of these frameworks are general WM and waste minimization planning (Arun Gnanaraj & Gnana Jayanthi, 2017; Shin et al., 2020; Ahmed et al., 2023; Rybnytska et al., 2018); resource planning (Kaya et al., 2021; Antmann et al., 2013); assessment of WM performance (Pamučar et al., 2022; Antmann et al., 2013); route optimization (Rybnytska et al., 2018); and waste generation prediction (Kaya et al., 2021; He et al., 2022). In this generated research, studies focus e.g., on waste recycling process planning (Bao & Lu, 2021), real-time violations before the waste collection process monitoring (Al-Masri et al., 2019), analysis of alternative WM scenarios (Sarkkinen et al., 2019), maximizing long-term landfill performance (Verge & Kerry Rowe, 2013), providing some theoretical general high-level guidance on WM process (Thyberg & Tonjes, 2015; He et al., 2022) and efficient monitoring and control of waste recovery.

The existing frameworks use literature on the framework subject area (Verge & Kerry Rowe, 2013; Ahmed et al., 2023; Thyberg & Tonjes, 2015), case studies (Bao & Lu, 2021; Sarkkinen et al., 2019; Antmann et al., 2013), expert knowledge, country case studies and governmental reports (Shin et al., 2020),(He et al., 2022; He et al., 2022), IoT-sensors (Al-Masri et al., 2019; Arun Gnanaraj & Gnana Jayanthi, 2017; Rybnytska et al., 2018), and real-world data (Kaya et al., 2021) as a data source.

Past research in WM frameworks has produced a variety of systems that address different aspects of WM, helping stakeholders to plan and solve urban WM and environmental problems. Notable frameworks include those focused on municipal solid WM, WTE resource planning, construction waste recycling, and industrial WM. Other frameworks address specific waste types and issues, such

Table 1. Frameworks in the field of WM

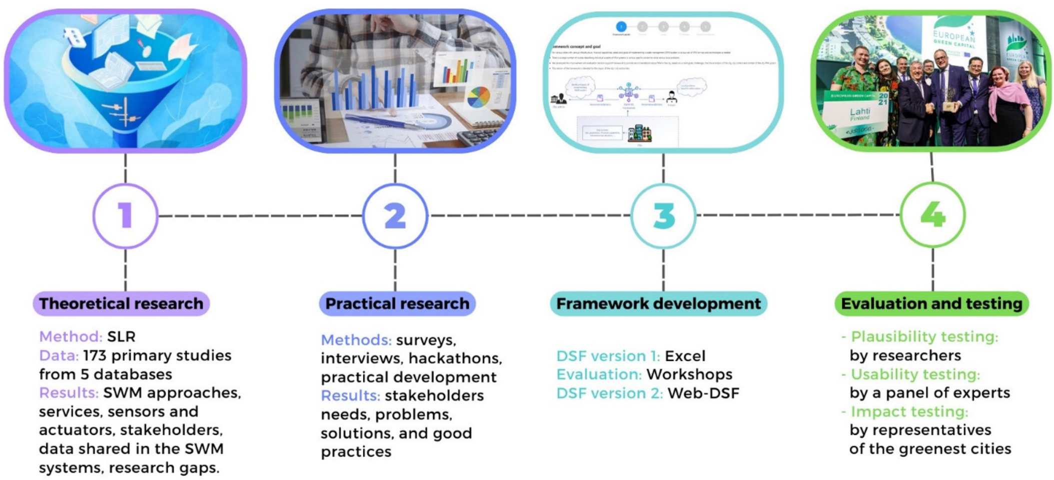
Reference	Topic	Data source	Methods	Features	Testing
Antmann et al., 2013	Solid WM	WM and recycling program analysis	Simulation-based decision-making and optimization	WM assessment, resource allocation optimization	Simulation, Florida, United States
Verge & Kerry Rowe, 2013	Landfill design	Textbooks on landfill design and WM	Algorithms for data processing and decision-making	Long-term performance and service life maximization	No
Thyberg & Tonjes, 2015	Municipal solid waste, food waste	Literature	Theoretical case study	Integration	Theoretical case study
Arun Gnanaraj & Gnana Jayanthi, 2017	Agriculture and poultry waste	IoT sensors	Real-time monitoring with IoT sensors	Automated WM, waste minimization	No
Rybnytska et al., 2018	Smart WM	IoT data from sensors, Melbourne City Council	Design science research, optimization model, heuristic algorithms (ALNS)	Sustainable garbage collection route planning and optimization, CO_2 emission reduction	Simulation, Melbourne, Australia
Sarkkinen et al., 2019	Industrial waste	Case study	Modified analytical hierarchy process	Alternative cover scenarios analysis with multi-criteria decision analysis	No
Al-Masri et al., 2019	Monitoring WM process violations	IoT sensors	Real-time monitoring with IoT sensors	Monitoring violations before WM	No
Shin et al., 2020	Plastic waste reduction	Data on plastic waste in South Korea	Government plastic waste control plan	Reduction in plastic waste generation and increased disposal	No
Kaya et al., 2021	WTE planning	Waste station data, Istanbul, Turkey	Machine learning	WTE resource planning, waste prediction	Simulation, real-world data
Bao & Lu, 2021	Construction waste recycling	Case studies, site visits, interviews in Shenzhen	Decision-support framework	On-site and off-site construction waste recycling planning	No
He et al., 2022	Municipal solid waste	Databases and government reports	Multivariate linear regression, additive models	Waste generation, composition, recovery rates related to demographics	Simulation, Florida, United States
Pamuèar et al., 2022	Integrated municipal solid WM	Model of solid WM stages and environmental impact	Fuzzy measuring attractiveness by a categorical based evaluation technique (MACBETH) multi-criteria decision-making	Performance assessment, uncertainty and inefficiency investigation	South European region
Ahmed et al., 2023	Zero-WM	Zero-WM studies	Conceptual framework	Zero-WM	No

continued on following page

Table 1. Continued

Reference	Topic	Data source	Methods	Features	Testing
Chowdhury et al., 2023	Textile industry waste	Literature, expert knowledge	Analytical network process model	Efficient monitoring and control of waste recovery	Case study

Figure 1. Research stages



as agriculture and poultry waste, plastic waste reduction, zero-WM, monitoring violations before waste collection, landfill design, and waste in the textile industry.

However, existing WM frameworks often have limited scope and applicability, relying predominantly on literature or standards from specific countries or narrow sets of data, which can constrain their real-world usability and effectiveness. Furthermore, many frameworks do not undergo extensive testing, reducing confidence in their practical implementation and impact. This highlights the need for a more comprehensive framework that can integrate a broader range of data and provide adaptable solutions. To confirm its reliability, the framework must also undergo a multi-stage evaluation and testing by both subject matter experts and key stakeholders.

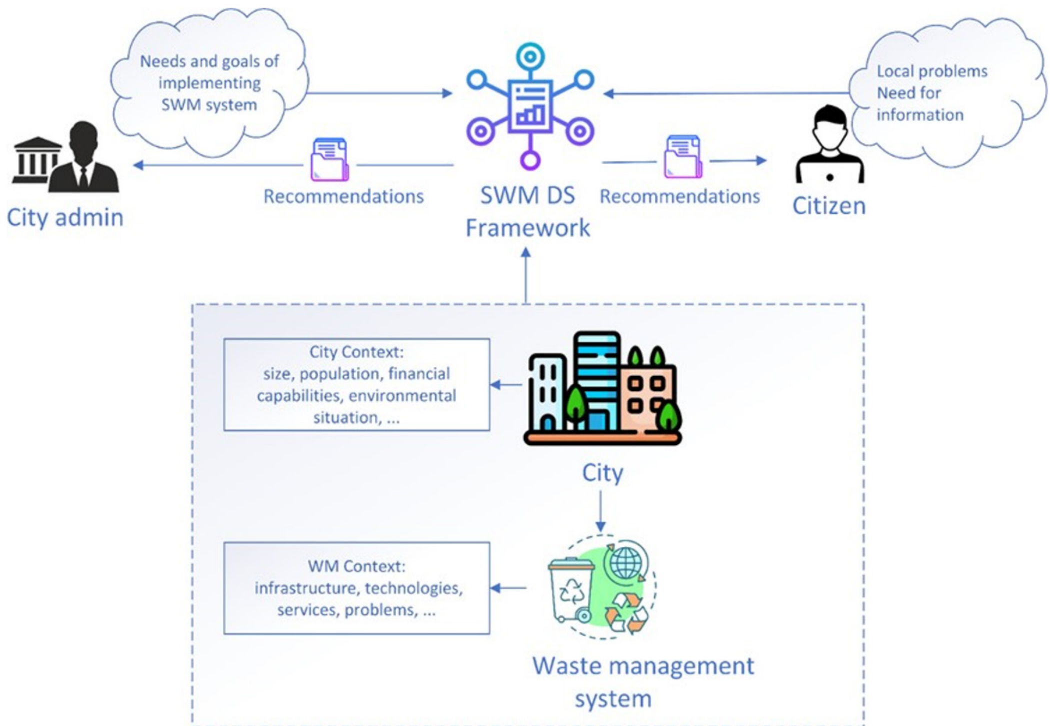
METHOD

The SWM DSF research methodology employs a mixed-methods approach that combines qualitative and quantitative data collection and analysis techniques. The method includes theoretical research (systematic literature reviews and the development of a knowledge base) and practical research (surveys, interviews, hackathons, and collaborative projects; see Figure 1). The SWM DSF was developed and tested based on the collected data.

THEORETICAL RESEARCH

The systematic literature study of the SWM subject area (Sosunova & Porras, 2022) included 173 primary studies selected for analysis and data extraction from the 3,732 initially retrieved studies from five databases: Institute of Electrical and Electronics Engineers (IEEE), Association for Computing Machinery (ACM), Elsevier, Springer, and Web of Science (WoS). We have analyzed the collected

Figure 2. DSF conception



data provided by the earlier study and created a knowledge base that connects and incorporates the following aspects of SWM systems: the main approaches and services that are applied in the high- and low-level SWM systems, sensors and actuators and their application in different types of SWM systems, the direct and indirect stakeholders of the SWM systems, the types of data shared between the SWM systems and stakeholders, and the main promising directions and research gaps in the field of SWM systems.

The key research gap identified (Sosunova & Porras, 2022) was that in the presence of numerous studies describing individual aspects of the design, development, and implementation of SWM systems in diverse locations to solve various problems, there is no general description that would unite all the accumulated results at any level of operations. Based on the identified research gap and the needs of the subject area, the SWM DSF concept was developed by combining the knowledge of area experts, academic studies, and the authors' knowledge into one consistent framework (see Figure 2).

The appendix in this paper contains links to online appendix resources. The framework provides recommendations to the city administration and other tool utilizers on achieving the goals (described in online Appendix B) associated with WM. To most effectively achieve the set goal, the framework must consider the context of the city and the WM system used in the city (described in online Appendix A), must have the means to identify specific problems and challenges that need to be solved to achieve the goal, and must have the means to evaluate the effectiveness of the application of recommendations. There will be a *citizen* role in the framework in the future, adjusted for private people to solve local WM-related problems.

PRACTICAL RESEARCH

The SWM DSF data collection process involved multiple complementary methods, which were (1) surveys for residents, authorities, and companies of three cities (Sosunova et al., 2023), (2) interviews for the representatives of the city authorities and companies responsible for WM, (3) hackathons (International Hackathon in Disruptive Information Solutions, 2021), and (4) practical SWM system elements development during two international projects (bIoTope, 2018; CroBoDDIT Project, 2021).

Surveys were used to gather information from a large number of participants. At the same time, interviews allowed for more in-depth discussions with Helsinki (the capital of Finland), Lappeenranta (a southeastern city near the eastern border), and Lahti (middle Finland city) WM authorities and companies. The Finnish cities were chosen because the research was conducted during the Finnish project at the Finnish university. Furthermore, Lappeenranta and Lahti were selected due to their status as some of the greenest cities in the world (Yle, 2021; Greenreality, 2021), despite their relatively average sizes for Finnish cities, while Helsinki was chosen for its large size, the fact that it is the capital, and its commendable environmental situation, advanced WM and recycling infrastructure, and widespread implementation of modern WM technologies. This study focuses on consumers (residents) and producers of the services (civic authorities and companies involved in waste collection and removal) as the main stakeholders. The questionnaires considered four topics: household waste sorting and urban WM, WM logistics, WM in public places (i.e., parks and recreational areas), and new technologies in WM. Self-administered online questions based on Google Forms were used to conduct the surveys. Detailed information regarding the survey methodology, questions, results, sample sizes, representativeness, validity, and limitations can be found in the work by Sosunova et al. (2023).

The interviews were conducted with the representatives of the city administration and companies operating the WM in the city. The goal of the interviews was to understand the WM in the city's problems and needs as well as to evaluate the framework. The set of interview questions is presented in the appendix (online Appendix C, Table C2). The demography of the interview participants is presented in Table 5. *Hackathons* provided a platform for collaborative problem-solving, and projects allowed for practical exploration of the issues. *Practical experience* in SWM systems development gave us an understanding of the fundamental technical and conceptual aspects of different SWM services. These methods were chosen for their ability to provide a diverse range of perspectives and insights, making the resulting data more robust.

FRAMEWORK DEVELOPMENT

The first version of the SWM DSF design was done with the help of a sustainability awareness framework (SusAF; Porras et al., 2021) in Excel. It was evaluated by researchers in software engineering, human–computer interaction, and green ICT during a series of internal workshops. The workshop tasks included technical work with data in Excel to check, refine, and verify the original data, brainstorming with the help of the Miro board and in creative tasks such as "You as a mayor of a city." The web version of the DSF was developed using Drupal and included five steps: framework guide, context, goals, challenges, and recommendations. In the end, on each step, there is a feedback form with a set of questions based on user role (see online Appendix C, Table C1), field experts (see online Appendix C, Table C1), or representatives of the city administration (online Appendix C, Table C2). The demography of the workshop participants is presented in Table 2.

FRAMEWORK EVALUATION AND TESTING

The SWM DSF has been tested and evaluated in three phases: (1) by researchers at a university (see online Appendix C, Table C1), (2) by a panel of experts in the field of SWM and decision support systems, including professors from leading universities of Finland and representatives of

Table 2. Demography of the internal workshop participants

No.	Job role	Research / professional sphere	Company type	Years of experience	
				in sphere	in company
1	Professor	Computer science, green ICT	University	32	32
2	Postdoctoral researcher	Computer science, software products sustainability design	University	13	7
3	Postdoctoral researcher	Behavioral science	University	7	2
4	Junior researcher	Computer science, agile, web development	University	8	2
5	Junior researcher	Computer science, software engineering	University	17	2
6	Junior researcher	Computer science, green ICT	University	3	3
7	Junior researcher	Computer science, green ICT, system analytics	University	12	2
8	Junior researcher	Computer science, DS frameworks development and evaluation	University	10	1
9	Junior researcher	Computer science, climate change, green ICT	University	1	1

Table 3. Demography of the testing researchers at the university

No.	Job role	Research / professional sphere	Company type	Years of experience	
				in sphere	in company
1	Assistant professor	Computer science, user-centered software engineering, semantic Web	University	23	6
2	Postdoctoral researcher	Behavioral science	University	7	2
3	Junior researcher	Computer science, agile, web developer	University	8	2
4	Junior researcher	Computer science, software engineering	University	17	2
5	Junior researcher	Computer science, green ICT, system analytics	University	12	2
6	Junior researcher	Computer science, business	University	2	2

companies specializing in SWM (see online Appendix C, Table C1), (3) by representatives of the city administration of two Finnish cities (see online Appendix C, Table C2). Tables 3–5 show the demography of testing participants.

RESULTS

The primary outcome of this study is the development of the SWM DSF, which generates recommendations at the city and local levels, providing technological and infrastructure solutions for implementing these improvements. Each recommendation is supported by a list of relevant literature describing how the proposed solutions can be developed, implemented, and tested, including evidence from pilot projects. The developed framework includes four action steps: (1) *context*—allows setting the context parameters of the city and city WM system; (2) *goals*—allows setting the goals of WM system development and improvement and setting key performance indicators (KPIs) for the evaluation of the results; (3) *challenges*—allows to specify the problems and challenges for every goal and set

Table 4. Demography of the testing panel of experts

No.	Job role	Research / professional sphere	Company type	Years of experience	
				in sphere	in company
1	Professor	Computer science, green ICT	University	32	32
2	Assistant professor	Computer science, user-centered software engineering, semantic Web	University	23	6
3	Innovation architect, business development specialist	Business, innovation management	Innovation company	21	4
4	Junior researcher	Computer science, DS frameworks development and evaluation	University	10	1

Table 5. Demography of the testing representatives of the city authorities

No.	Job role	Research / professional sphere	Company type	Years of experience	
				in sphere	in company
1	Director	Economic and urban development	City administration	27	21
2	Managing director	WM development	The company operating the WM in the city	19	19
3	Managing director	WM development	The company operating the WM in the city	17	3
4	Development manager	WM development	The company operating the WM in the city	19	2

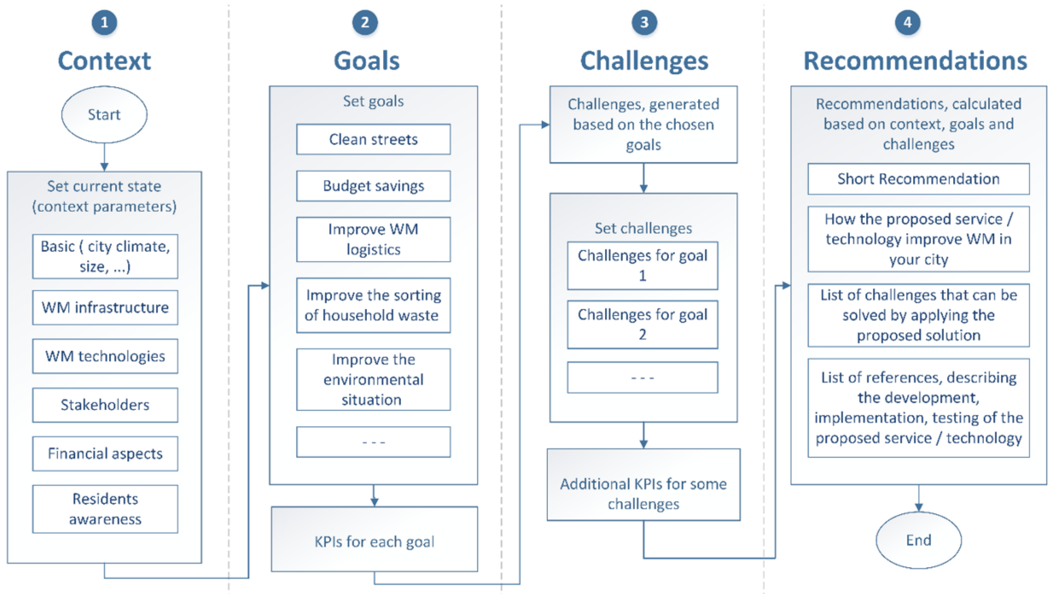
additional KPIs; and (4) *recommendations*—provides the recommendations for achieving the set goals and solving problems, taking into account the specific context of the city (Figure 3).

FRAMEWORK DESIGN AND DECISION-MAKING

The conceptual diagram of user interaction with the framework, framework reasoning engine data processing, and context-driven decision-making is shown in Figure 4. The user starts by setting the context parameters of the city and city WM system. Context parameters include basic city context (city size and population, climate), existing WM infrastructure (physical WM infrastructure, separate waste collection in the city), WM technologies (city-level WM services and technologies, SGB-level WM services and technologies), stakeholders (primary and secondary stakeholders involved in the WM process), financial aspects (annual city budget for tasks related to WM, annual city budget for solving current WM-related problems, average income of the citizens), and resident awareness (level of stakeholders awareness and engagement in WM activities and level of education of the residence). Online Appendix A presents the complete list of context parameters of the city and WM system.

Based on the *basic city context* parameters, as a future development area, we suggest DSS be developed to include features for giving references to pilot projects. With pilot project references, DSS users would see how the recommended technologies and services have been applied to solve similar sustainability challenges and with what sort of results, cost, and resource needs, potentially in highly similar-sized cities with similar climate zones, and so on. The authors are preparing to collect the data and add it to the knowledge base. Based on the existing WM infrastructure and WM technologies, we provide recommendations on the services that can be implemented using

Figure 3. Basic steps for using the framework



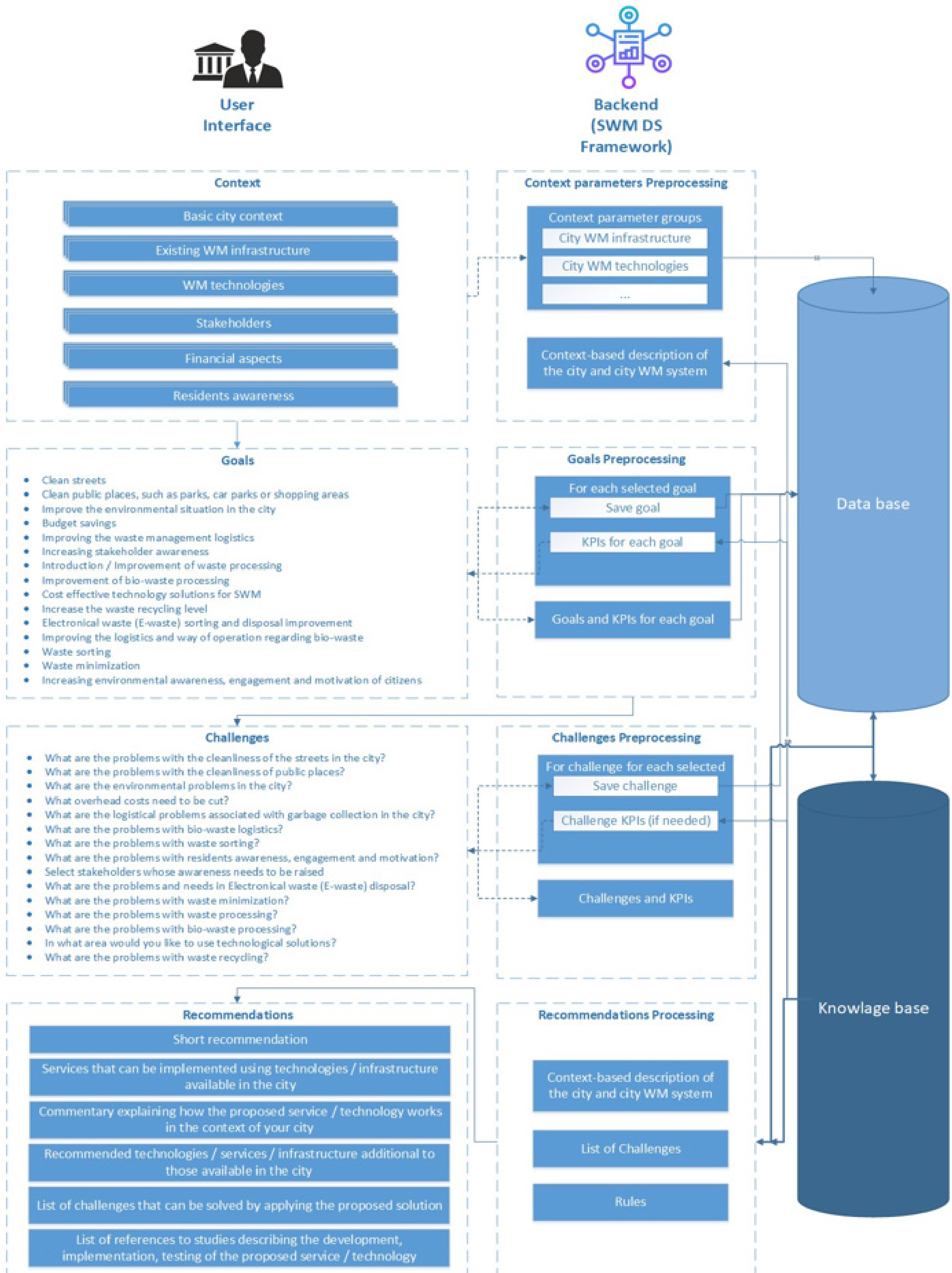
technologies and infrastructure available in the city, as well as recommended technologies, services, and infrastructure in addition to those available in the city. Section stakeholders and resident awareness influence some recommendations, such as goals related to resident awareness, knowledge, and motivation. Financial aspects will affect the evaluation of the cost of the proposed solutions when we have enough information in the knowledge base.

Next, the user needs to set goals for developing and improving the city's WM system. The goals currently include clean streets, clean public places (such as parks, car parks, and shopping areas, improving the environmental situation in the city), budget savings, improved WM logistics, increased stakeholder awareness, implemented and improved waste processing, improved bio-waste processing, cost-effective technology solutions for SWM, increased waste recycling level, e-waste sorting and disposal improvement, improved logistics and way of operation regarding bio-waste, waste sorting, waste minimization, increased environmental awareness, and engaged and motivated citizens. Figure 5 presents an example set of city context parameters text version from the expert testing of the DSF, and Figure 6 presents an example of a text version of a set of goals and goal-based challenges from the expert testing of the DSF.

Each goal has a set of KPIs that give a quantitative basis to evaluate the effectiveness of the recommended application(s). For example, the KPI for the goal of waste sorting is the amount of each type of waste per month (in kg, including mixed waste, bio-waste, plastic, carton, paper, glass, metal, hazardous waste, and fabric). We also added *Your KPI* for each goal, allowing users to add their own evaluation criteria and making the framework more flexible. Each KPI has two types of indicators: current indicators (now) and target indicators (online Appendix B).

The framework asks a clarifying question for each selected goal to identify challenges. For example, for the goal of improving the environmental situation in the city, the clarifying question is, "What are the environmental problems in the city?" For the goal of budget savings, the clarifying question is, "What overhead costs need to be cut?" The complete set of goals and clarifying questions is presented in Figure 3, and the complete set of challenges is in online Appendix B. Some

Figure 4. Framework reasoning engine and context-driven decision-making



challenges also include KPIs, which help the user evaluate the effectiveness of applying the received recommendations more accurately.

Figure 5. Example of a set of city context parameters (text version)

```
---------------------------------------------
Goals
-----
What goals do you want to achieve by modernizing the waste management system in the
city?
--------------------------------------------------------------------------------
------
Clean streets: Yes
Clean streets KPI
-----------------
Current status and KPIs:
Current status and KPIs
-----------------------
1
-
Number of citizens' complaints per month: {Empty}
Number of citizens' complaints per month: {Empty}
2
-
The number of pieces of garbage per 10 square meters: {Empty}
The number of pieces of garbage per 10 square meters: {Empty}
3
-
Your KPI
--------
Your KPI name: {Empty}
Your KPI value: {Empty}

Your KPI value: {Empty}

---------------------------------------------
Challenges
----------
What are the problems with the cleanliness of the streets in the city?
---------------------------------------------------------------------
Not enough trash cans: No
Streets not cleaned often enough by janitors: No
Low level of environmental awareness among residents: Yes
Insufficiently frequent of garbage trucks movement: No
Poor cleanliness of the area around waste containers: No
Overflow of waste containers: Yes
Birds scattering garbage: Yes
---------------------------------------------
```

The last step of the framework is the *recommendations* based on the city context parameters and challenges (see Figure 4). Based on the selected context parameters and challenges, the DSF reasoning engine builds a model describing the city and its WM system. If the user does not specify some contextual parameters and KPIs, this may affect the accuracy of recommendations and subsequent performance evaluation. However, the algorithm allows for providing recommendations on an incomplete set of context parameters (see Figures 7–8). Each challenge has multiple predetermined possible solutions, sorted by level of effectiveness and frequency of use (see Figure 7). Each solution has numerous context parameters associated with this solution (see Figure 8). The algorithm compares the context parameter groups for each solution with the context parameter groups selected by the user. With the comparison, the user interface displays proper solutions with the necessary infrastructure, services, and other conditions for the user. Then, the algorithm continues to display those solutions for which one or more context parameters are missing, providing a recommendation to supplement, for example, the existing infrastructure with the necessary components.

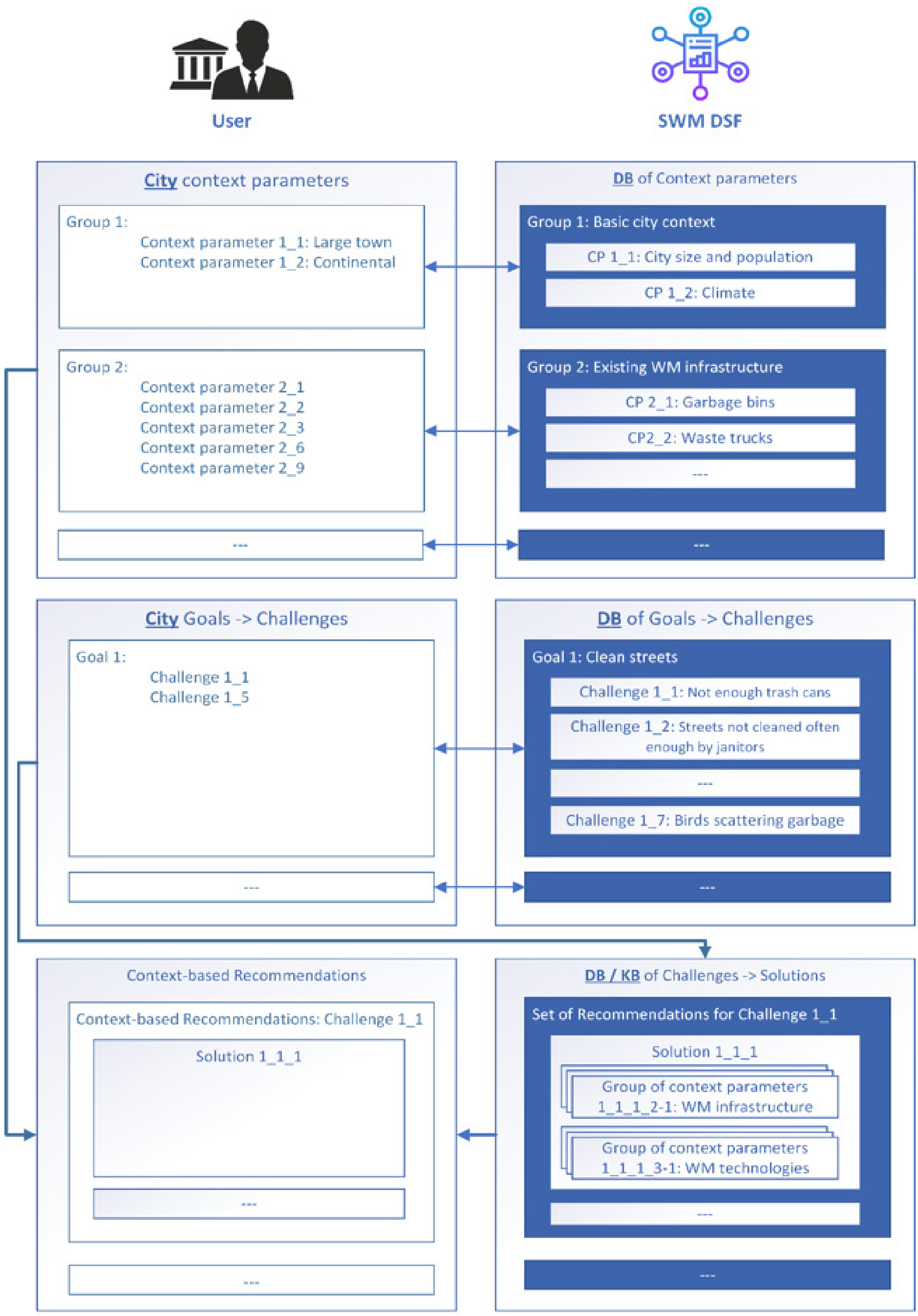
Figure 6. Example of a set of goals and goal-based challenges (text version)

```
---------------------------------------------
Goals
-----
What goals do you want to achieve by modernizing the waste management system in the
city?
------------------------------------------------------------------------------------
------
Clean streets: Yes
Clean streets KPI
-----------------
Current status and KPIs:
Current status and KPIs
-----------------------
1
-
Number of citizens' complaints per month: {Empty}
Number of citizens' complaints per month: {Empty}
2
-
The number of pieces of garbage per 10 square meters: {Empty}
The number of pieces of garbage per 10 square meters: {Empty}
3
-
Your KPI
--------
Your KPI name: {Empty}
Your KPI value: {Empty}

Your KPI value: {Empty}

---------------------------------------------
Challenges
----------
What are the problems with the cleanliness of the streets in the city?
---------------------------------------------------------------------
Not enough trash cans: No
Streets not cleaned often enough by janitors: No
Low level of environmental awareness among residents: Yes
Insufficiently frequent of garbage trucks movement: No
Poor cleanliness of the area around waste containers: No
Overflow of waste containers: Yes
Birds scattering garbage: Yes
---------------------------------------------
```

FRAMEWORK USER INTERFACE

The user interface (see Figure 9) in web Drupal-based DSF includes five steps—framework guide, context (see online Appendix A), goals (see online Appendix B), challenges (see online Appendix B), and recommendations—and follows previously described logic (see Figures 3–4). The content of each step is briefly described below from the user's point of view. The next section describes each user interface step in more detail. The *framework guide* describes the framework concept and goal, primary data for the framework operation, decision support, and basic steps for using the framework. After reading the framework guide, the user needs to fill in the *context parameters* that describe their city to the best of the user's knowledge. Users unsure about some context parameter or parameter group can simply skip any section. However, the accuracy of the recommendations depends on the completeness of the presented parameters of the city and the WM of the city system.

Figure 7. Context-driven recommendation algorithm



FRAMEWORK-BASED RECOMMENDATIONS

This subsection provides several examples of high-level recommendations that can be useful for WM companies and policymakers in a wide range of cities. We have focused on three common

Figure 8. Context-driven recommendations algorithm: Challenges, solutions, and context parameters

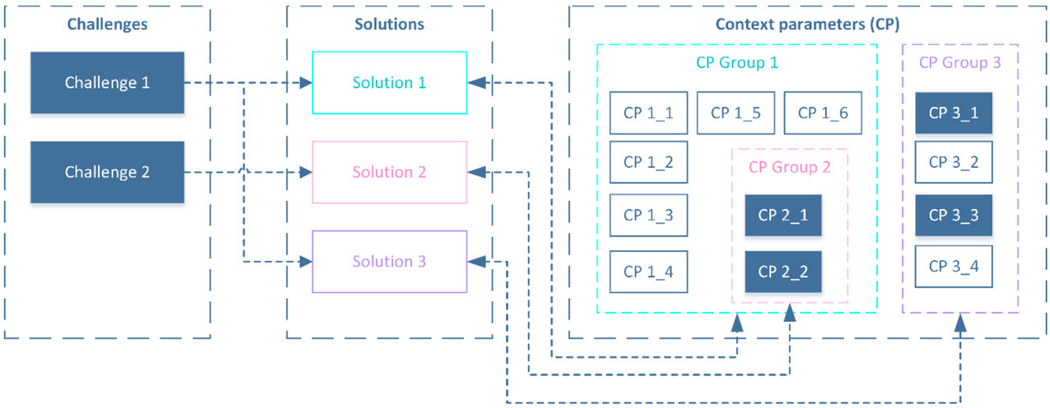
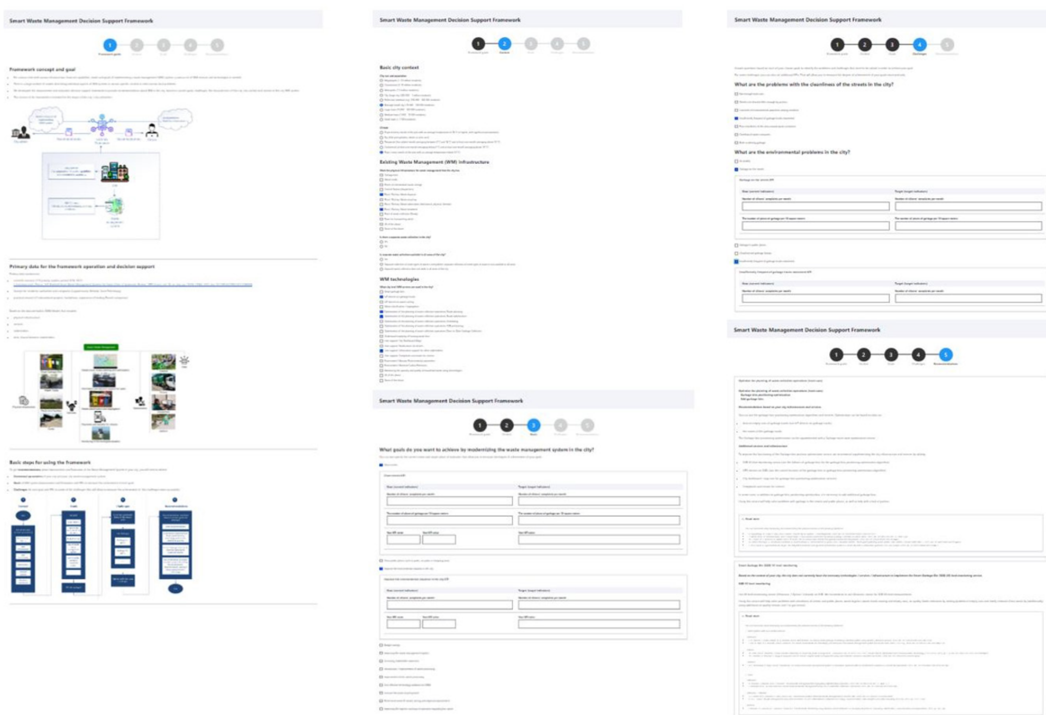


Figure 9. DSF user interface



directions: waste logistics, environmental problems related to WM, and citizen awareness and motivation to sort and minimize waste. To address waste logistics problems and environmental issues related to WM, the following services and technologies can be used: route planning and optimization, SGB fill-level monitoring, city dashboard (map), air quality measurements, and on-demand garbage bin emptying.

- *Route planning and optimization* (Shah et al., 2018) can involve automatic route planning (preliminary or real-time) based on the city dashboard (map), IoT devices on garbage trucks, GPS sensors on SGBs, and SGB fill-level data. The service will help solve problems with logistics (for example, regarding empty runs and waste disposal system efficiency), cleanliness of the city (with timely waste disposal), save the city budget (minimize driver work time, reduce the number of janitors, and reduce fuel costs), city ecology and air quality (lower emissions by solving the problem of empty runs and timely removal of bio-waste by using additional air quality sensors or a gas sensor).
- *SGB fill-level monitoring* can be done using ultrasonic, optical, or infrared on SGB. We recommend using an ultrasonic sensor for SGB fill-level measurements (Addabbo et al., 2019). Using this service will help solve problems with the cleanliness of streets and public places, waste logistics (waste trucks routing and empty runs), air quality (lower emissions by solving the problem of empty runs and timely removal of bio-waste by (additionally) using additional air quality sensors or gas sensor).
- *A city dashboard (map)* shows the city's WM infrastructure (Pardini et al., 2020). Drivers can use it to mark waste bins and waste collection routes.
- *Air quality measurements* can be done using gas sensors or air quality sensors on SGB for bio-waste (Devi et al., 2018). The service reduces problems with city air quality and logistics of bio-waste. Collected sensor data should be used for optimizing waste truck routes.
- *On-demand emptying* of garbage bins can help solve problems with logistics (fewer empty runs), air quality (less emissions), and cost savings (less gasoline, drivers working hours).

To solve the problems of citizen awareness and motivation to sort and minimize waste, the following can be considered: gamification to motivate citizens to sort waste, waste sorting guidelines, information for citizens about environmental problems and solutions, a city dashboard (map), publicity for environmental issues and sustainable WM practices, and increasing citizen awareness, followed by social motivation.

- *Gamification* can help solve problems with low citizen motivation to sort waste and incorrect waste sorting (Briones et al., 2018). SGB with weight sensors should be combined with gamification applications with rewards and social motivation. To improve the functioning of the service, we recommend supplementing the SGB set of sensors by adding a fill-level sensor, allowing the use of data from both the weight and fill-level sensors for the gamification application algorithms.
- *Guidelines for waste sorting* (Pardini et al., 2020) can be graphic or textual, posted at garbage collection points, or available on the website or mobile application.
- Informing city residents about environmental problems and ways to solve them (Pardini et al., 2020), publicity for environmental issues and sustainable WM practices (Ramzan et al., 2019), and increasing citizen awareness, followed by social motivation strategy (Xiao et al., 2017), will help solve problems with low citizen awareness and motivation, problems with citizen willingness to pay for new sustainable WM services and citizens participation in waste reduction, recycling, other sustainable WM practices, improve waste sorting and minimization.
- A *city dashboard (map)* can be used for citizens to mark on the map the nearest collection points for various types of waste (Pardini et al., 2020). Using this service will help solve problems with a lack of waste collection infrastructure or low citizen awareness of the placement of nearest waste collection points of some rare types of waste (for example, old clothes and batteries).

GUIDELINES FOR THE FRAMEWORK IMPLEMENTATION IN DIFFERENT TYPES OF CITIES

The SWM DSF incorporates good practices to address a wide range of WM-related problems. It is tailored to offer appropriate guidance for resolving WM challenges in cities of varying sizes, resource levels, and WM infrastructure capabilities. To implement the DSF in any specific city, the city context parameters should be set on DSF Step 2, *Content*. In the *basic city context* parameters, the required specifications include the *city size* and *climate*. In the *existing WM infrastructure* parameters, the selection of *infrastructure elements* (e.g., waste bins, waste trucks, and waste collection pipes) present in the city and the description of the situation regarding *separate waste collection* are necessary. Scalability is a key feature, as the framework tailors recommendations according to each city's context, including the budgetary and technological limitations of smaller cities.

The framework accounts for the reality that smaller cities may not have access to advanced IoT sensors and WM technologies. In these cases, the framework provides cost-effective alternatives, such as manual WM strategies, recommendations related to resident awareness, or budget-friendly, low-tech monitoring solutions. In the *WM technologies* parameters, the choices extend to IoT sensors for WM infrastructure and waste trucks, IoT actuators for waste trucks and waste bins, and the digital WM-related services used by the city. For instance, smaller cities can opt for affordable, phased deployments of IoT technologies, like simple GPS tracking on waste trucks, before scaling up to more advanced sensor networks. Recommendations are customized to each city's resource constraints, ensuring that cities with lower budgets can still benefit from WM improvements without adopting high-cost solutions from the outset. The example of setting these context parameters is presented in Figure 11. Additionally, the definition of *stakeholders, resident awareness,* and *financial aspects* is required. The full set of the context parameters is presented in the online Appendix A. Based on these parameters, the framework will generate a specific city model. After identifying city goals and challenges, the framework will provide recommendations based on the city model.

TESTING

First, the Excel framework was pre-tested at the university through a series of internal workshops, where it was thoroughly evaluated for its effectiveness, efficiency, and accuracy. Following this, the DSF web version underwent a comprehensive three-stage testing and evaluation process: by researchers at LUT University, by a panel of experts in the field of SWM and decision support systems, including professors from the leading universities of Finland and representatives of companies specializing in SWM, and by representatives of the city administration of two Finnish cities.

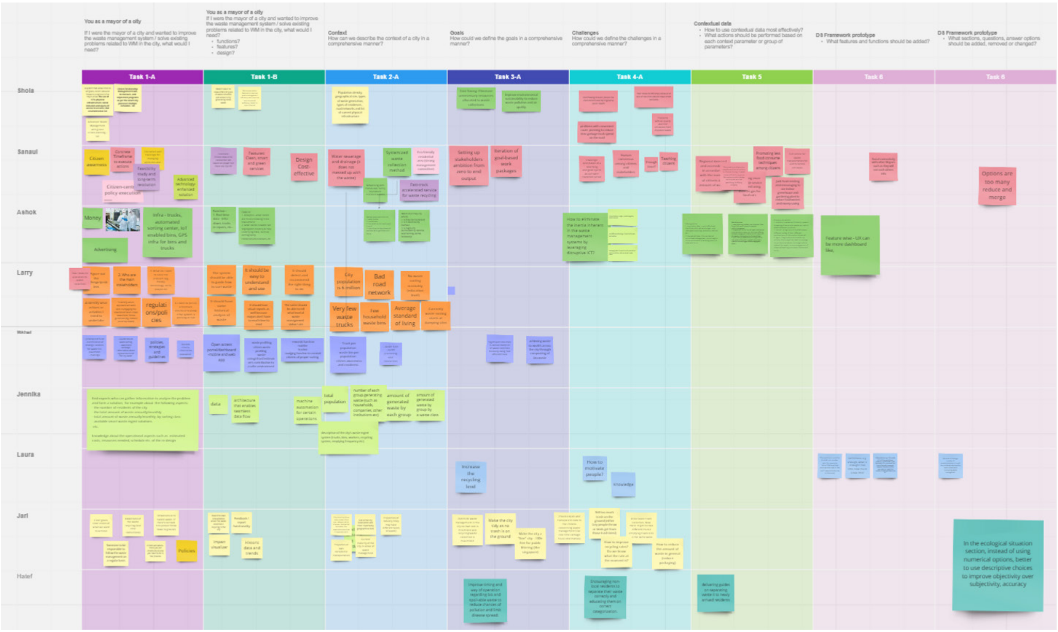
Internal Workshops

During the development process of the first version of the web-DSF, three internal workshops were conducted at the university to gather feedback on the Excel prototype. The participants were the members of the Department of Software Engineering (see Table 2). These internal workshops included technical work with data in Excel to check, refine, and verify the original data; discussions and brainstorming with the help of the Miro board (see Figure 10); and a set of creative tasks intended to represent the needs of end users (city authorities) when using the developed system. The internal workshops included three events, during which the tasks listed below were completed.

Task 1A: You, as the Mayor of a City

Regarding the question, "If I were the mayor of a city and wanted to improve the WM system / solve existing problems related to WM in the city, what would I need?", we received responses describing:

Figure 10. SWM DSF internal workshop micro board



- General needs in the field of WM and the city environment: "advanced WM with green urban planning," "advanced technology-enhanced solution"
- Necessary means to achieve the set goals: "citizen awareness," "money"
- Specific requirements for DPF: "figure out the challenge or problem," "Who are the main stakeholders?", "What do I need to solve the problem (money, technology, skills, people, etc.)?", "guidelines on waste sorting," "a system that allows cities to set goals, collect data and measure progress in five major areas: the use of ICTs, physical infrastructure, social inclusion and equity of access to services," "success criteria and metrics for evaluation"

Based on the analyses of the answers to this task, we supplemented the DSF concept in terms of describing contextual parameters, setting goals, and evaluating the effectiveness of the KPI system's recommendations.

Task 1B: You, As a Mayor of a City

Regarding the question, "If I were the mayor of a city and wanted to improve the WM system or solve existing problems related to WM in the city, what would I need (functions, features, design)?", we received:

- Some general descriptions: "recommendation features to improve WM efficiency and improve environmental wellbeing based on data collected," "open access portal/dashboard, mobile and web app"
- Specific functions and features: "guide how to sort waste," "feedback/report functionality"
- Usability-related answers: "it should be easy to understand and use"

These results allowed us better to identify future application user critical needs and expectations.

Task 2A: Context

Regarding the question, "How can we describe the context of a city in a comprehensive manner?", we received:

- Various sets of the context parameters describing the context of some specific city, for example: "city population is six million," "bad road network," "no waste sorting mentality (education level)," "very few waste trucks," "few household waste bins," "average standard of living," "currently waste sorting starts at dumping sites"
- Basic city context parameters, such as: "total population," "size of the city," "city structure (how many areas there are, categorization of areas: residential, business,)" "nature of primary city activity: is it a tourist city (e.g., Venice) / is it an industrial city (e.g., Suzhou) / is it an agro-city"
- City WM system context parameters, such as: "types of waste generation," "list of current physical infrastructure," "waste bin per population," "amount of generated waste by each group"

We used the results obtained to confirm the existing set of context parameters and group context parameters in the future system interface in a more user-friendly way. The second part of this task (Task 2B) was technical work on context parameters in the Excel version of the framework.

Task 3A: Goals

"How could we define the goals in a comprehensive manner?": During this task, we first discussed the possible goals of introducing or improving the city's WM system and then worked on the goals section in the Excel version of the framework (Task 3B). We have identified the following main areas of goal setting.

- Environmental-related goals: "improve environmental sustainability to reduce waste pollution and improve air quality," "significant reduction in the carbon footprint of waste collection trucks by using fuel-efficient trucks," "increase the level of recycling"
- Goals related to cost savings: "cost saving: eliminate unnecessary resources allocated to waste collection"
- Goals related to stakeholder motivation and awareness: "setting up stakeholders' ambition from zero to end output"
- Clean city-related goals: "make the city tidy with no trash on the ground"

Task 4A: Challenges

"How could we define the challenges in a comprehensive manner?": We asked participants to define the challenges of introducing or improving the city's WM system and worked on the challenges section in the Excel version of the framework (Task 4B). This task allowed us to clarify and discuss possible challenges for the goals identified in Task 3A.

Task 5: Contextual Data

"How to use contextual data most effectively? What actions should be performed based on each context parameter or group of parameters?": We discussed numerous options for using context parameters in decision-support systems and frameworks during this task.

Task 6: DSF Prototype

"What features and functions should be added? What sections, questions, and answer options should be added, removed, or changed?": The last task was to test the web application prototype, which must contain the complete set of context parameters and connections between context parameters. At this stage, the purpose of the review was to preliminarily assess system usability and identify critical flaws that should be corrected at an early stage of development. We received many comments regarding the prototype's usability, such as "options are too many, reduce and merge," and "the questions could be divided into smaller sets."

Internal Workshop Outcome

The feedback received during the workshops was analyzed using qualitative data analysis techniques, and the comments were categorized based on their relevance to the development process. When developing the first version of the web-DSF, we added a framework guide to provide more detailed explanations of the DSF concept and functions. Additionally, instructions and observations were added to each step of the framework to provide users with a better understanding of the process. The system of context parameters was simplified by removing unnecessary elements and grouping related parameters.

Testing by University Researchers

Testing by researchers at the university was done by the members of the Department of Software Engineering (see online Table 3). Among the testing participants were both internal workshop participants and PhD students who were previously unfamiliar with the framework. The main objective of this testing phase was to test the DSF usability. During the testing, participants had to use an early version of the framework (see Figure 4) to find solutions to WM problems in their home city, where they currently live, or any other city. They needed to specify the context of the city whose WM system they wanted to improve, set the context parameters of its WM system, goals, and challenges, and then evaluate the recommendations received (see Figure 7). They could also comment on every step of the framework using the feedback forms (see online Appendix C, Table C1). The following presents an analysis of the feedback on each of the framework's steps describes our findings and changes in the design and content of the framework based on the feedback analysis.

Framework Guide

We received:

- Generally positive feedback from most participants, including users unfamiliar with the framework: "It is completely clear" and "I believe these diagrams are comprehensive and clarify the purpose and framework. Therefore, it's good in its current state."
- I need more instructions from one user: "At the beginning, it was unclear what I should be doing here." and "A clear instruction, in a few sentences, of what is needed from the user such as myself"

Based on the feedback, we conclude that the framework guide is clear enough for most users. At one tester's request, we also expanded the instructions for using the framework.

Context

We received:

- A lot of usability-related feedback: "Some questions could benefit from explanation/example as not all is so clear for me (at least)," "too many details of WM services," "Assumption that city has SGB might need to be re-looked," "I would write Smart Garbage Bin each time (not SGB, people can get confused by acronyms)," "There can also be ambiguity on what is the difference between city streets and public places, so it might be good to add 'public places, such as parks, car parks or shopping areas,'" "It may be confusing that smart garbage bins appear under both infrastructure AND technologies—would it work to include it just in one of these categories?"

- Feedback indicating tester frustration due to the lack of knowledge about certain groups of contextual parameters (for example, regarding the presence of some elements of WM infrastructure in the city): "Everything is clear. However, due to my lack of knowledge about a few things, I could not answer."

We improved the section's usability by reworking and simplifying the context parameters system and correcting terminology.

Goals and Challenges

We received a lot of criticism of the KPI system: "overall this is the most confusing page where I am not sure what I should answer, even putting myself in the role of waste professional," "I personally feel more descriptive rating rather than stars can be easier to understand," "Is complaints a good waste management logistics KPI? I would use things like 'how many rides per week there are for waste management,'" "Waste sorting KPI is difficult, you ask each type, and there's only one number." Based on the feedback, we assessed the current KPI system as not meeting user needs and not allowing them to implement the framework's aim fully. Therefore, we abandoned the rating-based KPI system and developed a new one, a description of which can be seen in online Appendix B. The new KPI system version provided current and target indicators and the ability to create your own KPI for each goal.

Recommendations

We received:

- One report that some recommendations suggest using infrastructure not available in the city: "Some recommendations relate to smart garbage bins, but I am pretty sure I didn't select that the city had these (as I was answering hypothetically, I could be mistaken). This could be confusing. Maybe at some point, there needs to be some kind of dependencies between the recommendations, so that if recommending SGB-related actions, either SGBs are present, or a first recommendation is to install SGBs."
- Complaints about too many details and references to literature in the text of recommendations: "Too many reference and details, makes users confused," "Maybe adding a read more button and showing them in a pop-up window or maybe a summary of each reference"; "Recommendations are okay. I wonder if any city administrator has time/motivation to read the referenced articles."
- However, most of the feedback was positive: "I like the recommendations. It seems practical."; "Recommendations are pretty much clear."; "All recommendations are correct."

Based on the feedback on the recommendations provided by the DSF, we concluded that the context-sensitive part of the recommendation system needs to be significantly improved. The framework has been improved, and the new version provides a recommendation consisting of (1) recommendations on the services that can be implemented using technologies and infrastructure available in the city and (2) recommended technologies, services, and infrastructure additional to those available in the city. We redesigned the recommendations, making a solid text into a logical structure that describes the different aspects of the recommendation and adding a *Read More* button.

Feedback

The feedback was mostly positive but reflected some frustration due to the volume of contextual parameters, goals, and challenges, the KPI system: "the framework should be used with people with a stronger background in WM domain," "the framework seems easy to understand and clear," "overall, the framework is comprehensive with sound practical implications; an excellent effort," and:

> *This evaluation was probably slightly biased because I am already quite familiar with this work, so I may not have spotted things that would have been unclear to someone coming to these ideas for the first time. However, I think the overall structure and logic of the framework is good; it is just how the questions are sometimes presented that could confuse or mislead people.*

Outcome of Testing Stage 1

The usability testing with the specialists in software engineering, usability, human–computer interaction, and green ICT allowed us to make the web-DSF more user-friendly and efficient. Based on this evaluation and testing stage, we identified and fixed many usability-related shortcomings. During the second test, the system was rated as easy to use, and the system interface was quite user friendly.

Testing With Research Field Experts

Evaluation and testing with research field experts followed the same concept (see online Appendix C, Table C1). Still, they were conducted by experts in decision support systems, DSFs in green ICT, and SWM experts (see Table 4). The main objective of this testing phase was to test the DSF plausibility.

Context

We received some recommendations and corrected the terminology in the Basic City Context and WM Technologies sections. The experts concluded that the context parameters accurately and comprehensively describe the WM of the city system.

Goals and Challenges

The new KPI system received generally positive feedback from the experts, but we received and corrected comments regarding the lack of instructions for filling in KPI tables (for example, if the user does not have the necessary data): "Does every city have information, e.g., of complaints per month?", [need for the] "information to the user about what information is needed to fill this part properly."

Recommendations

We received a relatively high recommendation plausibility rating from test participants: "I like the recommendations, this seems useful" and some usability-related suggestions: "Those recommendations are linked with the challenges."

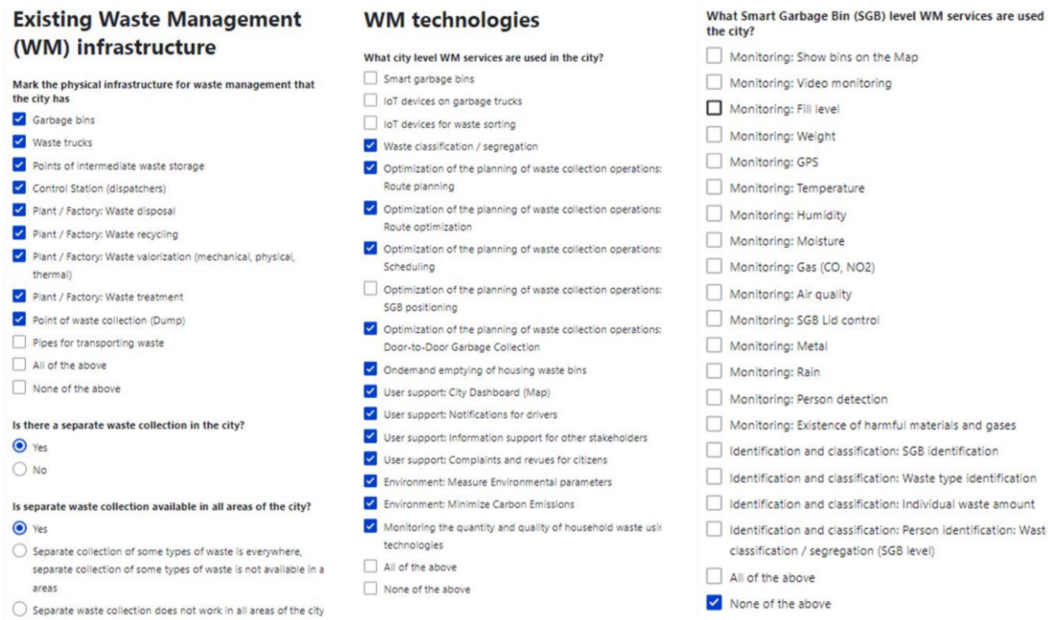
Outcome of Testing Stage 2

Based on the testing results, we made some changes to the terminology, added more instructions to the KPIs, and received materials for further research. We have also added to each recommendation a list of challenges that can be solved by following this recommendation. The experts have unequivocally evaluated DSF usability and plausibility. The recommendations provided by the framework are considered to logically correspond to given city context parameters, goals, and challenges.

Testing by the Representatives of the Authorities

The evaluation and testing by the authorities' representatives aimed to assess the framework's impacts. To achieve this, we held two sessions, including an introduction to the framework, testing the framework, discussion, and interviews (see online Appendix C, Table C2) with representatives of the authorities of two Finnish cities whose activities are related to the city's WM. Below, we will provide a description of the city, a testing and evaluation scenario, an administration representative's assessment of the framework, and recommendations and insights received for each session (for each city).

Figure 11. Lappeenranta: Main WM system context parameters



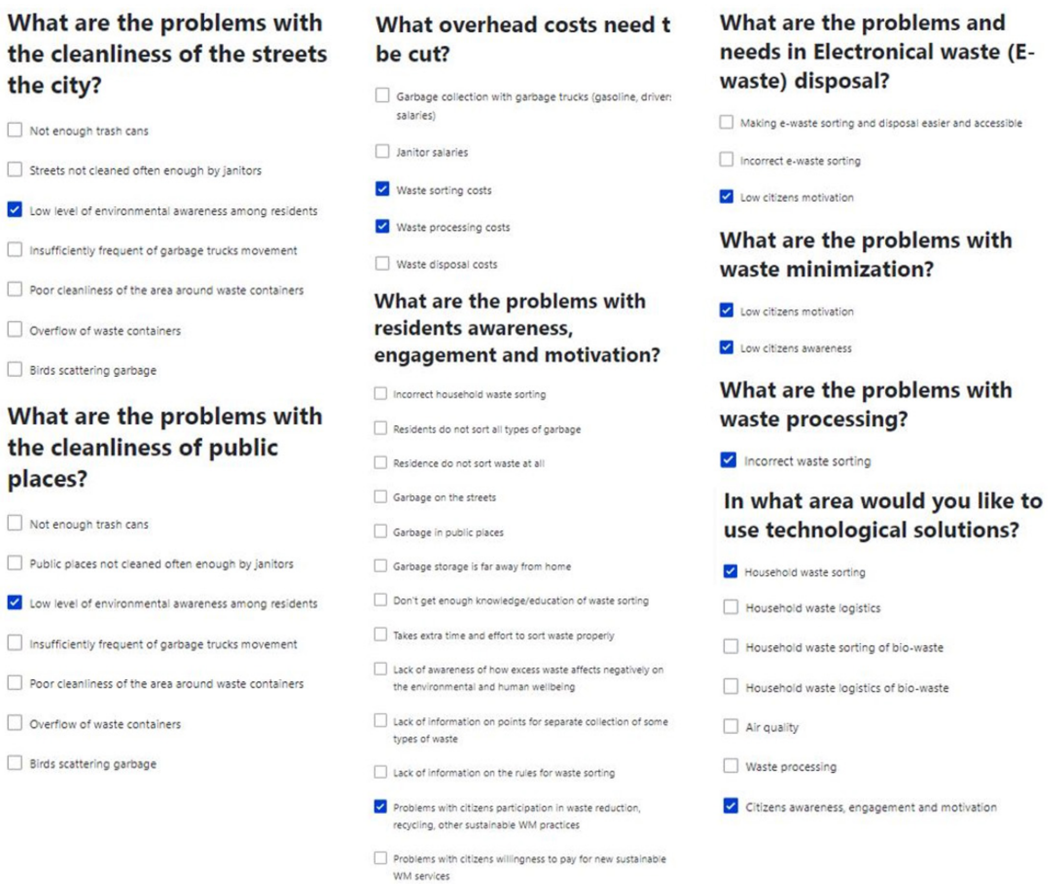
Session 1: Lappeenranta (Finland)

The profile of Lappeenranta (Finland): small city (area: 758 km^2, population: 73,415; Tilastokeskus, n.d.) with an excellent ecological situation, which is confirmed by the fact that Lappeenranta won the title of the European Green Leaf Award 2021 (Greenreality, 2021) in a competition organized by the European Commission; a developed WM and recycling infrastructure; and widespread sorting of at least eight different types of waste. Developed infrastructure refers to the presence of separate waste collection points in the yard of each house, as well as the availability of infrastructure for recycling and waste disposal. Finnish waste legislation is primarily based on EU legislation but, in some cases, includes stricter standards and limits than those applied in the EU as a whole (Finnish Ministry of the Environment, 2017).

The Lappeenranta representatives define Lappeenranta as a *small city* (10,000–100,000 residents) with a polar climate (every month of the year with an average temperature below 10 °C). However, this assessment of the representative of the Lappeenranta authorities is not accurate: Lappeenranta has a continental climate, with at least one month averaging below 0 °C and at least one month averaging above 10 °C. Figure 11 shows the main WM-related context parameters defined for Lappeenranta during the testing session. The city has a fairly extensive WM infrastructure and uses a large number of SWM technologies, but it does not have SGBs. Representatives of Lappeenranta decided to select all available goals for developing and improving the city's WM system, explaining this by the presence of all these goals in the city's WM development program. However, only a few items were selected at the stage of selecting challenges (the city's existing problems; see Figure 12). The Lappeenranta representatives concluded that the main city problem is citizen awareness and motivation.

To achieve the selected goals and solve identified problems, the DSF recommended informing residents about environmental problems and ways to solve them, publicity for environmental issues and sustainable WM practices, guidelines for waste sorting (Figure 13), stakeholder participation guidance, Increasing awareness in the field of e-waste sorting and ways to do it, information support for citizens about ways to minimize waste, gamification to motivate citizens to sort waste (Figure 13), and waste processing cost reduction.

Figure 12. Lappeenranta: Challenges

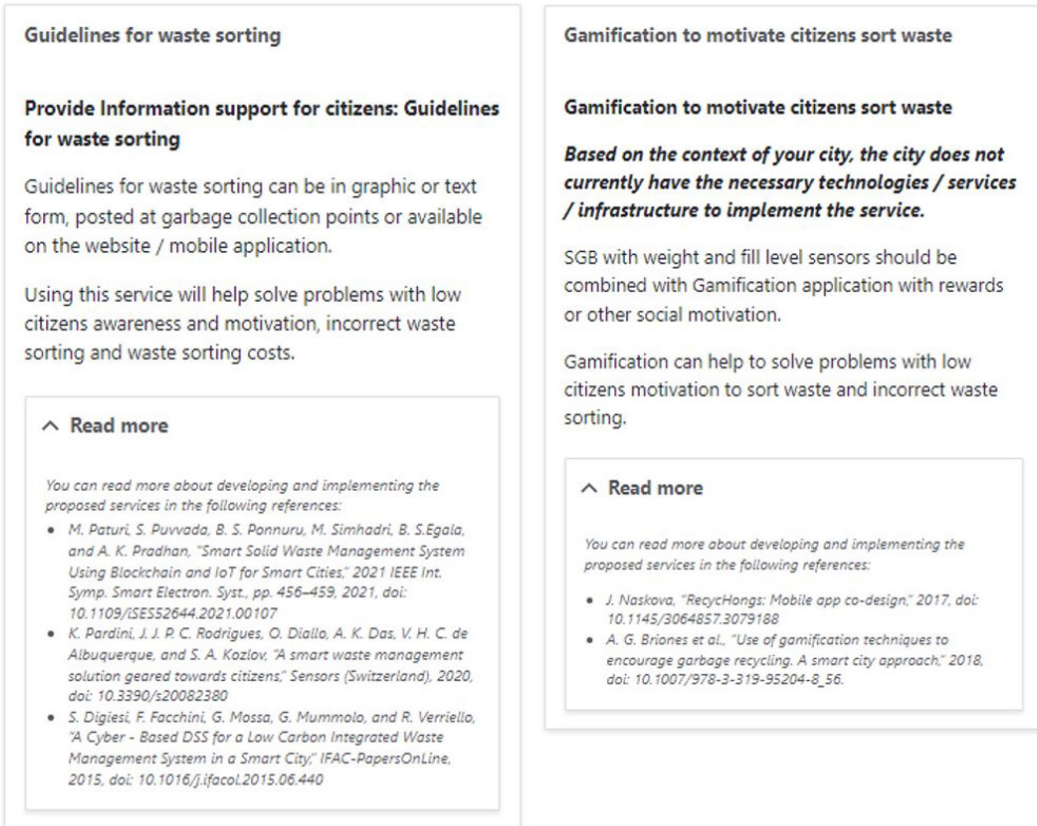


Outcome of Testing Stage 3 (Lappeenranta)

Representatives of Lappeenranta authorities assessed the framework as working correctly and being relatively comprehensive in terms of improving and developing the WM system of the city and solving problems in the field of WM. They also noted that the set of context parameters at the second step of the framework makes it possible to describe the WM system of the city of Lappeenranta rather comprehensively and accurately. It was concluded, that the SWM DSF could improve the WM system of the city by providing recommendations and guidelines on citizen motivation to sort waste through gamification. As a summary, the following recommendations have been noted for the next round of performance and framework utilization cases, specifically for the case city Lappeenranta:

- Add the challenge: *Sorting multiple types of waste in the kitchen*. The common problem of environmentally aware residents of Lappeenranta arises in response to a combination of two factors: (1) the ubiquitous ability to sort eight different types of waste (mixed, bio-waste, paper, cardboard, plastic packaging, plastic and metal bottles, glass, and hazardous waste) and (2) the small size of kitchens in standard layouts of many houses in the city.
- Add the challenge: *Lack of sorted waste of particular types for recycling in the city.* Due to the insufficient amount of properly sorted plastic packaging, this type of garbage has to be processed not in the city but sent for processing to a neighboring city.

Figure 13. Lappeenranta recommendations examples: Guidelines for waste sorting and gamification to motivate citizens to sort waste



- Add more detailed recommendations to increase resident motivation in cities where the authorities have long been working to solve this problem. All the options proposed by the framework to achieve this goal are already being applied in the city.

Representatives of Lappeenranta authorities also noted that "the model looks really good from the point of view of how wide of a coverage it has" and that "the base info entering might be laborsome, but if the tool is used once in every second or third year, compared to results, the cost of work could be considered acceptable." Despite the positive assessment of the framework's recommendations, Lappeenranta representatives concluded that they could not improve the situation in terms of WM in the city using the recommendations received since these recommendations describe the steps the city administration is already taking to achieve its goals. The exception is gamification, which motivates citizens to sort waste. However, the city does not currently have the necessary IoT technologies. However, representatives of the city noted that for the past 20 years, Lappeenranta has been solving environmental problems using modern approaches and technologies, has achieved outstanding results in the field of urban ecology, and is one of the greenest cities in the world. Based on this, we conclude the result of this part of the impacts testing and evaluation of the framework as successful since the system showed the accuracy and applicability of the recommendations, as well as the compliance of the recommendations with modern standards.

Session 2: Lahti (Finland)

The profile of Lahti (Finland): medium city (area: 517 km^2, population: 120,202) with an excellent ecological situation, the city became the environmental capital of Europe in 2021 (Yle, 2021). Lahti has long invested in environmental protection and the innovations that promote it. Lahti is known nationally for its achievements in water, environment, and climate protection. Developed infrastructure refers to the presence of separate waste collection points in the yard of each house, as well as the availability of infrastructure for recycling and waste disposal. The city uses innovative solutions in the field of WM, and it is possible to sort from eight types of waste everywhere in the city.

The Lahti WM company representatives define Lahti as a medium city (100,000–300,000 residents) with a continental climate (at least one month averaging below 0 °C and at least one month averaging above 10 °C). Lahti has an extensive WM infrastructure with plants and factories for waste disposal, recycling, valorization (mechanical, physical, and thermal), and treatment. Separate waste collection is available in all areas of the city. A large number of SWM technologies are used in the town. However, the city does not have SGBs (same as Lappeenranta). Representatives of Lahti selected three goals: Increase the waste recycling level, waste sorting, and waste minimization. All selected challenges were related to citizen motivation and engagement. To achieve the selected goals and solve identified problems, the DSF recommended guidelines for waste sorting, on-demand emptying of garbage bins, publicity for environmental issues and sustainable WM practices, increased citizen awareness, followed by social motivation, increased environmental awareness, gamification to motivate citizens to sort waste, information support for citizens, ways to minimize waste, and social motivation to reduce waste.

Outcome of Testing Stage 3 (Lahti)

Despite the slight differences in setting goals, the main problems in the field of WM in the two cities studied were somewhat similar and related to citizen motivation and awareness. It was concluded, that the SWM DSF could improve the WM system of the city by providing recommendations and guidelines on citizen motivation and awareness through gamification. Representatives of Lahti WM company assessed the framework as comprehensive, covering all the main areas of WM in the city in terms of describing the city's WM context and goals of improving its WM system.

The terminology in the Context / WM Infrastructure section was unclear for the participants because we used the terms known in the literature but not in accordance with the terms used in the company. In the Context / Financial Aspects section, we ask about the city's annual budget for tasks related to WM and the city budget for solving current WM-related problems. Still, in the case of Lahti, the WM is handled by the company, not the city. We were asked to add challenges, such as the quality of waste sorting and recycling rate. The next framework version will add clarifications to the terms in the Context / WM Infrastructure section and, more generally, formulate questions in the Context / Financial section.

DISCUSSION AND CONCLUSION

The study explored the development of an IoT-based SWM system for improving the WM processes and then developed and tested SWM system improvement and evaluation DSF to provide recommendations about WM implementation in cities based on the city goals, the characteristics of the city, and the current WM status in the city. The developed framework incorporates theoretical research of the literature on the topic, surveys conducted with the main WM system stakeholders, practical research conducted during international projects and hackathons, and practical knowledge obtained from interviews with the representatives of the world's greenest cities' authorities and companies responsible for WM. The proposed SWM DSF provides recommendations about WM in the city based on current tasks, the city's characteristics, and the city's context. We evaluated and tested the framework's plausibility, usability, and impact on two Finnish cities, and our results demonstrate that the developed framework can significantly improve WM processes and promote sustainable development by providing for each common WM-related city goal (and goal-related set of problems) the good practices, that are used in the greenest and most successful in SWM cities, solutions described in the literature, that were evaluated by the field experts, taking into account specific parameters of the city and cities WM system. The developed framework is based on the idea of constantly expanding and refining the sets of contextual parameters and relationships between them, refining existing goals, challenges, and recommendations and adding new ones. This is achieved by collecting data (from system users, experts, and representatives of various areas of WM), processing it, and expanding the knowledge base.

The Excel version of the framework was evaluated and improved during the series of workshops by specialists in computer science, green ICT, DS framework development and evaluation, and the SusAF framework. When developing the first version of the web-DSF, we considered comments on the prototype: we added a framework guide, simplified the system of context parameters, and added instructions and comments at each step of the framework. Then, the SWM DSF was tested and evaluated in three phases: (1) by researchers at a university (specialists in the areas of computer science, behavioral science, web development, DS frameworks development, green ICT, and WM), (2) by a panel of experts in the field of SWM and decision support systems, including professors from leading universities of Finland and representatives of companies specializing in SWM (specialists in the areas of user-centered software engineering, semantic web behavioral science, business and innovation management, DS frameworks development and evaluation), (3) by representatives of the city administration of two Finnish cities (Lappeenranta and Lahti—one of the most green cities on the planet, whose authorities use the most modern approaches to WM).

The framework's usability was confirmed during the evaluation and testing by area-specific researchers. The DSF plausibility was confirmed during the evaluation and testing with research field experts. We concluded that the results of the impact testing and evaluation of the framework were successful since the system showed the accuracy and applicability of the recommendations, as well as the compliance of the recommendations with modern standards during the testing of the DSF by representatives of the city administration of two Finnish cities.

This study contributes to the current literature on WM by providing a DSF that combines theoretical research of the literature on the topic, surveys with key stakeholders, practical research from international projects and hackathons, and practical knowledge from interviews with city authorities and companies responsible for WM in the world's greenest cities. The developed DSF provides guidance on achieving all major WM-related goals, applies to different types of cities with different contexts, and is not restricted to a single country or region. The DSF has an extensive structure of contextual parameters, goals, and challenges, making it possible to obtain relevant recommendations for a wide range of cities, from small technologically unequipped towns to megacities with a developed WM infrastructure that uses several modern technologies in WM.

The range of goals the framework allows one to achieve varies from improving WM logistics, waste sorting, and waste minimization to increasing environmental awareness and citizen engagement and motivation, introducing cost-effective technology solutions for SWM, and increasing the waste recycling level. It also includes several specific narrowly focused goals such as e-waste sorting, disposal improvement, and improving the logistics and way of operation regarding bio-waste. The framework provides an extensive and flexible KPI system that can help users numerically evaluate the effectiveness of applying the recommendations.

Regarding social ecology, the developed SWM DSF emphasizes the importance of community engagement, education, and fostering behavioral change. The framework includes strategies to actively involve citizens in WM processes, integrating public education campaigns and motivational systems such as gamification. These approaches aim to raise environmental awareness and encourage responsible waste behavior, embedding sustainability in the community. By providing tailored recommendations for cities to implement socially driven initiatives, the framework promotes collaboration between local authorities, WM companies, and residents. For the follow-up research and advancing the work on the social-ecological front (Dorninger et al., 2024), we see the importance of looking deeper into potential hidden forces affecting social-ecological systems (Gonzalez-Redin et al., 2024) to add extra depth of value, within the recommendations frameworks like these gives to the users.

From a policy perspective, local governments and policymakers are encouraged to adopt the SWM DSF as a guiding tool for sustainable WM strategies. The framework provides actionable insights for city administrators to design targeted policy initiatives, including public education programs, incentives for waste reduction, and regulations for waste sorting and recycling. Policymakers are also urged to consider integrating advanced digital solutions into WM infrastructure, ensuring long-term sustainability.

At the moment, the known limitation of the study includes a limited number of cities participating in the original study and named updates for the usability front. Related to the future development efforts, while testing the framework with representatives of the authorities of Lappeenranta and Lahti, we identified numerous areas for further work on the framework. For example, the option to add more detailed recommendations to increase resident motivation for green cities with a developed WM infrastructure and the widespread use of modern technologies in the field of WM. There is potential to cross-study commercial companies' green growth (Tereshchenko et al., 2023), environmental impact, and resource utilization success stories (Bose et al., 2023) to increase the effectiveness of the model in city operations from a financial feasibility point of view. Also, we will supplement the terminology and functionality of the framework so that it can be used not only by representatives of the city authorities but also by representatives of companies responsible for WM in the city.

In the future, the framework is planned to be updated with a *citizen* role in the framework, which will be adjusted for city residents to solve local WM-related problems, for example, by participating in environmental monitoring (Palacin et al., 2019; Berti Suman et al., 2023) and sustainability-related digital citizen science activities (Palacin et al., 2020; Shruti et al., 2023), with proper data quality metrics considerations (Vaddepalli et al.,2023). Based on our research, we have identified the need for the subject area in frameworks based on an extensive knowledge base, including academic literature knowledge, expert knowledge, and practical knowledge (obtained from repeated testing and improvement of the framework in diverse cities and municipalities) to generate more wide scope frameworks and globally generalizable decision support systems.

On top of the named practical development points, we have identified short- and medium-term needs to enhance the tool based on modern fast-phased digitalization of services and assets (Mat Nawi et al., in press), including options for fleet-based asset management (Giomaria et al., 2023), like vehicles in management company fleets (Metso et al., 2023). This is especially important now, when many traditional companies are transforming from asset companies to knowledge companies (Kortelainen et al., 2019), changing the nature of waste consumers and industries produced in municipalities and cities WM areas. When developing WM-related decision support tools, new promises of artificial intelligence (Ghoreishi & Happonen, 2020) and the role of Industry 4.0 (Happonen & Minashkina, 2020; Nobre et al., 2023) need to be added to future development directions. At the same time, cities need to include the potential role of gamification, e.g., in waste segregation (Sandhi & Rosenlund, 2024) and also citizen activation (Santti et al., 2020; Palacin et al., 2020), into the WM systems they run or purchase from third-party WM companies.

The SWM DSF contribution to sustainable development extends beyond improving operational efficiency in WM. It provides long-term environmental benefits by guiding cities toward reducing waste generation and enhancing recycling practices, thus promoting circular economy principles. The framework's adaptability ensures that it caters to cities of varying economic and infrastructural capabilities, fostering social equity in access to sustainable WM solutions. The DSF supports the Sustainable Development Goals (SDGs; United Nations, n.d.), particularly in relation to responsible consumption and production (SDG 12), climate action (SDG 13), and sustainable cities and communities (SDG 11). By integrating technological innovations with a deep understanding of local contexts, the SWM DSF empowers cities to achieve environmental sustainability while addressing the economic and social dimensions of WM.

Our future work will encompass expanding the contextual parameters system, goals, and challenges of the DSF. Additionally, we plan to develop a GUI for experts to input data directly into the framework. We will also create DSF recommendations tailored specifically for city residents. As such, our next step will involve testing the framework across a broader range of cities with varying levels of WM infrastructure and technologies, including a focus on platform economies for data sharing (Metso & Happonen, 2023) and views to available data quality (Vaddepalli et al., 2023), to enhance the value of insights and help the model provides, for its users. This testing will include quantitative metrics such as environmental impact assessments, alongside evaluations from key stakeholders and potential additions in specific focus groups like tourists, immigrants (Xu, 2024), seasonal workers (Wani et al., 2024), and second homeowners.

CONFLICTS OF INTEREST

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

PROCESS DATES

11, 2024
Received: April 16, 2024, Revision: October 1, 2024, Accepted: October 31, 2024

CORRESPONDING AUTHOR

Correspondence should be addressed to Inna Sosunova; inna.sosunova@lut.fi

ACKNOWLEDGMENTS

This work was supported by the AWARE project under Grant KS1913 from the European Neighborhood Instrument Cross-Border Cooperation (ENI CBC), Co-funded by the European Union. This work was also supported by the Erasmus Mundus Joint Master Degree program SE4GD-619839, and the work was finalized with the support of project Createch Wake Up Etelä-Karjala!, co-funded by the European Union.

REFERENCES

Addabbo, T., Fort, A., Mecocci, A., Mugnaini, M., Parrino, S., Pozzebon, A., & Vignoli, V. (2019). A LoRa-based IoT sensor node for waste management based on a customized ultrasonic transceiver. *Proceedings of the 2019 IEEE Sensors Applications Symposium*. DOI: 10.1109/SAS.2019.8705980

Ahmed, F., Hasan, S., Rana, M. S., & Sharmin, N. (2023). A conceptual framework for zero waste management in Bangladesh. *International Journal of Environmental Science and Technology*, *20*(2), 1887–1904. DOI: 10.1007/s13762-022-04127-6

Al-Masri, E., Diabate, I., Jain, R., Lam, M. H., & Reddy Nathala, S. (2019). Recycle.io: An IoT-enabled framework for urban waste management. *Proceedings of the 2018 IEEE International Conference on Big Data*. DOI: 10.1109/BigData.2018.8622117

Anagnostopoulos, T., Zaslavsky, A., Georgiou, S., & Khoruzhnikov, S. (2015). High capacity trucks serving as mobile depots for waste collection in IoT-enabled smart cities. In Balandin, S., Andreev, S., & Koucheryavy, Y. (Eds.), Lecture Notes in Computer Science: *Vol. 9247*. *Internet of Things, Smart Spaces, and Next Generation Networks and Systems. ruSMART NEW2AN 2015 2015*. Springer., DOI: 10.1007/978-3-319-23126-6_8

Antmann, E. D., Shi, X., Celik, N., & Dai, Y. (2013). Continuous-discrete simulation-based decision making framework for solid waste management and recycling programs. *Computers & Industrial Engineering*, *65*(3), 438–454. DOI: 10.1016/j.cie.2013.03.010

Arkorful, V. E., Shuliang, Z., & Lugu, B. K. (2022). Investigating household waste separation behavior: The salience of an integrated norm activation model and the theory of planned behavior. *Journal of Environmental Planning and Management*, *66*(10), 2195–2221. DOI: 10.1080/09640568.2022.2063112

Arun Gnanaraj, A., & Gnana Jayanthi, J. (2017). An application framework for IoTs enabled smart agriculture waste recycle management system. *Proceedings of the Second World Congress on Computing and Communication Technologies*. DOI: 10.1109/WCCCT.2016.11

Auvinen, H., Santti, U., & Happonen, A. (2020). Technologies for reducing emissions and costs in combined heat and power production. *E3S Web of Conferences, 158*, 1–6. DOI: 10.1051/e3sconf/202015803006

Bao, Z., & Lu, W. (2021). A decision-support framework for planning construction waste recycling: A case study of Shenzhen, China. *Journal of Cleaner Production*, *309*(127449), 127449. Advance online publication. DOI: 10.1016/j.jclepro.2021.127449

Berti Suman, A., Peca, M., Greyl, L., Greco, L., & Carsetti, P. (2023). The “citizen sensing paradigm” to foster urban transitions: Lessons from civic environmental monitoring in Rome. *European Journal of Risk Regulation*, *14*(3), 526–548. DOI: 10.1017/err.2022.28

Bevish Jinila, Y., Shahzad Alam, M., & Dayal Singh, P. (2019). Cloud-based scheme for household garbage collection in urban areas. *Advances in Intelligent Systems and Computing*, *750*, 539–546. DOI: 10.1007/978-981-13-1882-5_47

Bhargavi, N. K., & Anantharama, V. (2020). Repercussions of COVID-19 pandemic on municipal solid waste management: Challenges and opportunities. *The Science of the Total Environment*, *743*, 140693. DOI: 10.1016/j.scitotenv.2020.140693 PMID: 32663690

bIoTope. (2018). http://www.biotope-project.eu

Bose, E., & Biswas, S. B. (2023). Green human resource management: Few selected corporate success stories. *AIMA E-Journal, 15*(1).

Briones, A. G., Chamoso, P., Rivas, A., Rodríguez, S., De La Prieta, F., Prieto, J., & Corchado, J. M. (2018). Use of gamification techniques to encourage garbage recycling: A smart city approach. *Communications in Computer and Information Science*, *887*, 674–685. DOI: 10.1007/978-3-319-95204-8_56

Chen, X., Kurdve, M., Johansson, B., & Despeiss, M. (2023). Enabling the twin transitions: Digital technologies support environmental sustainability through lean principles. *Sustainable Production and Consumption*, *28*, 13–27. DOI: 10.1016/j.spc.2023.03.020

Chowdhury, N. R., Paul, S. K., Sarker, T., & Shi, Y. (2023). Implementing smart waste management system for a sustainable circular economy in the textile industry. *International Journal of Production Economics*, *262*(108876), 108876. Advance online publication. DOI: 10.1016/j.ijpe.2023.108876

Cooney, R., de Sousa, D. B., Fernández-Ríos, A., Mellett, S., Rowan, N., Morse, A. P., Hayes, M., Laso, J., Regueiro, L., Wan, A. H., & Clifford, E. (2023). A circular economy framework for seafood waste valorisation to meet challenges and opportunities for intensive production and sustainability. *Journal of Cleaner Production*, *392*(136283), 136283. Advance online publication. DOI: 10.1016/j.jclepro.2023.136283

CroBoDDIT project. (2021). https://forumvirium.fi/croboddit-disruptiivisten-teknologioiden-kehittamista-urbaaneissa-infrastruktuureissa-alueellisten-yritysten-osaamista-hyodyntaen/

Devi, P., Ravindra, W. S., & Sai Prakash, S. K. L. V. (2018). An IoT enabled smart waste management system in concern with Indian smart cities. *Proceedings of the 2nd International Conference on Trends in Electronics and Informatics, ICOEI.* 64-69. DOI: 10.1109/ICOEI.2018.8553764

Digiesi, S., Facchini, F., Mossa, G., Mummolo, G., & Verriello, R. (2015). A cyber-based DSS for a low carbon integrated waste management system in a smart city. *15th IFAC Symposium onInformation Control Problems inManufacturing: INCOM 2015*48 (3), 2356-2361. DOI: 10.1016/j.ifacol.2015.06.440

Dorninger, C., Menéndez, L. P., & Caniglia, G. (2024). Social-ecological niche construction for sustainability: Understanding destructive processes and exploring regenerative potentials. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *379*(1893), 20220431. DOI: 10.1098/rstb.2022.0431 PMID: 37952625

Elsaid, S., & Aghezzaf, E. H. (2015). A framework for sustainable waste management: Challenges and opportunities. *Management Research Review*, *38*(10), 1086–1097. DOI: 10.1108/MRR-11-2014-0264

Farooq, M., Cheng, J., Khan, N. U., Saufi, R. A., Kanwal, N., & Bazkiaei, H. A. (2022). Sustainable waste management companies with innovative smart solutions: A systematic review and conceptual model. *Sustainability (Basel)*, *14*(20), 13146. DOI: 10.3390/su142013146

Finnish Ministry of the Environment. (2017). *Environmental protection legislation: Waste legislation*. https://ym.fi/en/waste-legislation

Ghoreishi, M., & Happonen, A. (2022). The case of fabric and textile industry: The emerging role of digitalization, Internet-of-Things and Industry 4.0 for circularity. *Lecture Notes in Networks and Systems*, *216*, 189–200. DOI: 10.1007/978-981-16-1781-2_18

Giomaria, C., Magni, C. A., & Baschieri, D. (2023). Greening the fleet: Financial modeling vehicle replacement in waste management. *SSRN*. DOI: 10.2139/ssrn.4645735

Gonzalez-Redin, J., Gordon, I. J., Polhill, J. G., Dawson, T. P., & Hill, R. (2024). Navigating sustainability: Revealing hidden forces. *Social–Ecological Systems. Sustainability (Basel)*, *16*(1132), 1132. Advance online publication. DOI: 10.3390/su16031132

Greenreality. (2021). *Lappeenranta: Green Leaf*. https://www.greenreality.fi/en/greenreality-lappeenranta/green-leaf

Happonen, A., Metso, L., Hasheela-Mufeti, V., & Ali, I. (2024). Electric vehicle and batteries pre-emptive maintenance service support: Costs, sustainability and material recycling perspectives. *The Fourth International Conference on Electrical, Computer, Communications and Mechatronics Engineering*, 1–7.

Happonen, A., Metso, L., Hasheela-Mufeti, V., & Garcia, M. (2023). Electric Vehicles Servicing Digital Support Platform. Pre-emptive Maintenance with Vehicular Data and Cost Information, in Transforming Engineering Systems for Sustainability (TESS-2023), pp. 1-5

Happonen, A., & Minashkina, D. (2020). State of the art preliminary literature review: Sustainability and waste reporting capabilities in management systems. *E3S Web of Conferences*. DOI: 10.1051/e3sconf/202021103014

Happonen, A., Osta, I. L., Potdar, A., & Alcaraz, J. L. G. (2021). Financially feasible and sustainable: Reviewing academic literature on sustainability related investment studies. *Financially Feasible and Sustainable - Reviewing Academic Literature on Sustainability Related Investment Studies.* 1–43. DOI: 10.9734/bpi/mono/978-93-5547-032-4

He, Sandoval-Reyes, M., Scott, I., Semeano, R., Ferrão, P., Matthews, S., & Small, M. J. (2022). Global knowledge base for municipal solid waste management: Framework development and application in waste generation prediction. *Journal of Cleaner Production*, *377*(134501), 134501. Advance online publication. DOI: 10.1016/j.jclepro.2022.134501

International Hackathon in Disruptive Information Solutions. (2021). https://croboddit.devpost.com/

Jadli, A., & Hain, M. (2020). Toward a deep smart waste management system based on pattern recognition and transfer learning. *Proceedings of the Third International Conference on Advanced Communication Technologies and Networking*, 1–5. IEEE. DOI: 10.1109/CommNet49926.2020.9199615

Jain, M., Kumar, D., Chaudhary, J., Kumar, S., Sharma, S., & Verma, A. S. (2023). Review on e-waste management and its impact on the environment and society. *Waste Management Bulletin*, *1*(3), 34–44. DOI: 10.1016/j.wmb.2023.06.004

Jones, R. E., Renouf, M. A., Speight, R. E., Blinco, J. L., & O'Hara, I. M. (2022). SeqFLoW: A systematic approach to identify and select food waste valorisation opportunities. *Resources, Conservation and Recycling*, *189*(106732), 106732. Advance online publication. DOI: 10.1016/j.resconrec.2022.106732

Kaya, K., Ak, E., Yaslan, Y., & Oktug, S. F. (2021). Waste-to-energy framework: An intelligent energy recycling management. *Sustainable Computing: Informatics and Systems*, *30*(100548), 100548. Advance online publication. DOI: 10.1016/j.suscom.2021.100548

Khan, S., Anjum, R., Raza, S. T., Bazai, N. A., & Ihtisham, M. (2022). Technologies for municipal solid waste management: Current status, challenges, and future perspectives. *Chemosphere*, *288*(1), 132403. Advance online publication. DOI: 10.1016/j.chemosphere.2021.132403 PMID: 34624349

Khan, S. A. R., Tabish, M., & Yu, Z. (2023). Mapping and visualizing of research output on waste management and green technology: A bibliometric review of literature. *Waste Management & Research*, *41*(7), 1203–1218. DOI: 10.1177/0734242X221149329 PMID: 37052320

Kilpeläinen, M., & Happonen, A. (2021). Awareness adds to knowledge. Stage of the art waste processing facilities and industrial waste treatment development. *Current Approaches in Science and Technology Research*, *4*, 125–148. Advance online publication. DOI: 10.9734/bpi/castr/v4/9636D

Lozano, Á., Caridad, J., De Paz, J. F., González, G. V., & Bajo, J. (2018). Smart waste collection system with low consumption LoRaWAN nodes and route optimization. *Sensors (Basel)*, *18*(5), 1465. DOI: 10.3390/s18051465 PMID: 29738472

Maddalene, T., Youngblood, K., Abas, A., Browder, K., Cecchini, E., Finder, S., Gaidhani, S., Handayani, W., Hoang, N. X., Jaiswal, K., Martin, E., Menon, S., O'Brien, Q., Roy, P., Septiarani, B., Trung, N. H., Voltmer, C., Werner, M., Wong, R., & Jambeck, J. R. (2023). Circularity in cities: A comparative tool to inform prevention of plastic pollution. *Resources, Conservation and Recycling*, *198*, 107156. DOI: 10.1016/j.resconrec.2023.107156

Mainardis, M., Hickey, M., & Dereli, R. K. (2024). Lifting craft breweries sustainability through spent grain valorisation and renewable energy integration: A critical review in the circular economy framework. *Journal of Cleaner Production*, *447*(141527), 141527. Advance online publication. DOI: 10.1016/j.jclepro.2024.141527

Mat Nawi, M. N., Fauzi, M. A., Ting, I. W. K., Wider, W., & Amaka, G. B. (2024, March 04). (in press). Green information technology and green information systems: Science mapping of present and future trends. *Kybernetes*. Advance online publication. DOI: 10.1108/K-10-2023-2139

Metso, L., & Happonen, A. (2023). Data sharing concept for electric car services: Fleet level optimization and emission reduction based on monitored data In: Juuso, E., Galar, D. (eds) Proceedings of the 5th International Conference on Maintenance, Condition Monitoring and Diagnostics 2021, (3–14). Springer. DOI: 10.1007/978-981-99-1988-8_1

Minashkina, D., & Happonen, A. (2022). Analysis of the past seven years of waste-related doctoral dissertations: A digitalization and consumer e-waste studies mystery. *Energies*, *15*(18), 6526. Advance online publication. DOI: 10.3390/en15186526

Minashkina, D., & Happonen, A. (2023). Warehouse management systems for social and environmental sustainability: A systematic literature review and bibliometric analysis. *Logistics (Basel)*, *7*(3), 40. Advance online publication. DOI: 10.3390/logistics7030040

Mondal, S., Singh, S., & Gupta, H. (2023). Green entrepreneurship and digitalization enabling the circular economy through sustainable waste management: An exploratory study of emerging economy. *Journal of Cleaner Production*, *422*, 138433. Advance online publication. DOI: 10.1016/j.jclepro.2023.138433

Naskova, J. (2017). RecycHongs: Mobile app co-design. *Proceedings of the 2017 ACM Conference on Designing Interactive Systems*. DOI: 10.1145/3064857.3079188

Nobre, G. C., & Tavares, E. (2023). The role of Industry 4.0 technologies in the transition to a circular economy: A practice perspective. *Sustainability: Science*. *Sustainability*, *19*(1), 2289260. Advance online publication. DOI: 10.1080/15487733.2023.2289260

Palacin, V., Gilbert, S., Orchard, S., Eaton, A., Ferrario, M. A., & Happonen, A. (2020). Drivers of participation in digital citizen science: Case studies on Järviwiki and Safecast. *Citizen Science: Theory and Practice*, *5*(1), 22. Advance online publication. DOI: 10.5334/cstp.290

Palacin, V., Ginnane, S., Ferrario, M. A., Happonen, A., Wolff, A., Piutunen, S., & Kupiainen, N. (2019). SENSEI: Harnessing community wisdom for local environmental monitoring in Finland. *Proceedings of the CHI Conference on Human Factors in Computing Systems*, 1–8. DOI: 10.1145/3290607.3299047

Pamučar, D., Behzad, M., Božanić, D., & Behzad, M. (2022). Designing a fuzzy decision support framework for assessing solid waste management in the South European region. *Environmental Science and Pollution Research International*, *29*(28), 42862–42882. Advance online publication. DOI: 10.1007/s11356-022-18891-y PMID: 35094278

Pardini, K., Rodrigues, J. J. P. C., Diallo, O., Das, A. K., de Albuquerque, V. H. C., & Kozlov, S. A. (2020). *A smart waste management solution geared towards citizens*. Sensors., DOI: 10.3390/s20082380

Porras, J., Venters, C. C., Penzenstadler, B., Duboc, L., Betz, S., Seyff, N., Heshmatisafa, S., & Oyedeji, S. (2021). How could we have known? Anticipating sustainability effects of a software product. In Wang, X., Martini, A., Nguyen-Duc, A., & Stray, V. (Eds.), *Software Business. ICSOB 2021. Lecture Notes in Business Information Processing* (*Vol. 434*). Springer., DOI: 10.1007/978-3-030-91983-2_2

Ramzan, S., Liu, C. G., Munir, H., & Xu, Y. (2019). Assessing young consumers' awareness and participation in sustainable e-waste management practices: A survey study in Northwest China. *Environmental Science and Pollution Research International*, *26*(19), 20003–20013. DOI: 10.1007/s11356-019-05310-y PMID: 31102225

Rybnytska, O., Burstein, F., Rybin, A. V., & Zaslavsky, A. (2018). Decision support for optimizing waste management. *Journal of Decision Systems, 27*(sup1), *68–78.* DOI: 10.1080/12460125.2018.1464312

Sandhi, A., & Rosenlund, J. (2024). Municipal solid waste management in Scandinavia and key factors for improved waste segregation: A review. *Cleaner Waste Systems*, *8*(100144), 100144. Advance online publication. DOI: 10.1016/j.clwas.2024.100144

Santti, U., Happonen, A., & Auvinen, H. (2020). Digitalization boosted recycling: Gamification as an inspiration for young adults to do enhanced waste sorting. *AIP Conference Proceedings*, *2233*(1), 1–12. DOI: 10.1063/5.0001547

Saranya, K. C., Sujan, V., Abivishaq, B., & Nithish Kanna, K. (2020). Smart bin with automated metal segregation and optimal distribution of the bins. In Subramanian, B., Chen, S. S., & Reddy, K. (Eds.), *Emerging Technologies for Agriculture and Environment. Lecture Notes on Multidisciplinary Industrial Engineering*. Springer., DOI: 10.1007/978-981-13-7968-0_9

Sarkkinen, M., Kujala, K., & Gehör, S. (2019). Decision support framework for solid waste management based on sustainability criteria: A case study of tailings pond cover systems. *Journal of Cleaner Production*, *236*(117583), 117583. Advance online publication. DOI: 10.1016/j.jclepro.2019.07.058

Shah, P. J., Anagnostopoulos, T., Zaslaysky, A., & Behdad, S. (2018). A stochastic optimization framework for planning of waste collection and value recovery operations in smart and sustainable cities. *Waste Management (New York, N.Y.)*, *78*, 104–114. DOI: 10.1016/j.wasman.2018.05.019 PMID: 32559893

Shin, S. K., Um, N., Kim, Y. J., Cho, N. H., & Jeon, T. W. (2020). New policy framework with plastic waste control plan for effective plastic waste management. *Sustainability (Basel)*, *12*(15), 6049. DOI: 10.3390/su12156049

Shruti, V. C., Kutralam-Muniasamy, G., Pérez-Guevara, F., & Roy, P. D. (2023). An assessment of higher-value recyclable wastes in Mexico City households using a novel waste collector citizen science approach. *The Science of the Total Environment*, *863*, 161024. DOI: 10.1016/j.scitotenv.2022.161024 PMID: 36549527

Sosunova, I., & Porras, J. (2022). IoT-Enabled smart waste management systems for smart cities: A systematic review. *IEEE Access : Practical Innovations, Open Solutions*, *10*(July), 73326–73363. DOI: 10.1109/ACCESS.2022.3188308

Sosunova, I., Porras, J., Niskasaari, P., & Rybin, A. (2023). Smart waste management survey: Comparison of needs and challenges in three different sized northern cities. *Proceedings of the 11th International Conference on Communities and Technologies*. Association for Computing Machinery. DOI: 10.1145/3593743.3593789

Subbulakshmi, K. (2019). Smart recyle trash management systems for smart city using IoT. *Journal of Mechanics of Continua and Mathematical Sciences. Special Issue*, *1*(2). Advance online publication. DOI: 10.26782/jmcms.spl.2019.08.00050

Swapnil, A., Metso, Oruganti, K., & Happonen, A. (2024). Driving the future: Utilizing software foundations to improve vehicles functionalities. *Proceedings of the Fourth International Conference on Electrical, Computer, Communications and Mechatronics Engineering*, 1–7.

Tereshchenko, E., Happonen, A., Porras, J., & Vaithilingam, C. A. (2023). Green growth, waste management, and environmental impact reduction success cases from small and medium enterprises context: A systematic mapping study. *IEEE Access : Practical Innovations, Open Solutions*, *11*, 56900–56920. DOI: 10.1109/ACCESS.2023.3271972

Thyberg, K. L., & Tonjes, D. J. (2015). A management framework for municipal solid waste systems and its application to food waste prevention. *Systems*, *3*(3), 133–151. DOI: 10.3390/systems3030133

Tilastokeskus. (n.d.). *11lj: Preliminary population structure by area, 2024M01*-2024M09**. https://statfin.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__vamuu/statfin_vamuu_pxt_11lj.px/

United Nations. (n.d.). *The 17 goals*. https://sdgs.un.org/goals

Vaddepalli, K., Palacin, V., Porras, J., & Happonen, A. (2023). Taxonomy of data quality metrics in digital citizen science. In: Nagar, A.K., Singh Jat, D., Mishra, D.K., Joshi, A. (eds) Intelligent Sustainable Systems. Lecture Notes in Networks and Systems, vol 578. Springer, Singapore DOI: 10.1007/978-981-19-7660-5_34

Vergara, S. E., & Tchobanoglous, G. (2012). Municipal solid waste and the environment: A global perspective. *Annual Review of Environment and Resources*, *37*(1), 277–309. DOI: 10.1146/annurev-environ-050511-122532

Verge, A., & Kerry Rowe, R. (2013). A framework for a decision support system for municipal solid waste landfill design. *Waste Management & Research*, *31*(12), 1217–1227. DOI: 10.1177/0734242X13507310 PMID: 24163376

Wani, N. R., Rather, R. A., Farooq, A., Padder, S. A., Baba, T. R., Sharma, S., Mubarak, N. M., Khan, A. H., Singh, P., & Ara, S. (2024). New insights in food security and environmental sustainability through waste food management. *Environmental Science and Pollution Research International*, *31*(12), 17835–17857. DOI: 10.1007/s11356-023-26462-y PMID: 36988800

Xiao, L., Zhang, G., Zhu, Y., & Lin, T. (2017). Promoting public participation in household waste management: A survey based method and case study in Xiamen city, China. *Journal of Cleaner Production*, *144*, 313–322. DOI: 10.1016/j.jclepro.2017.01.022

Xu, D. (2024). Tracking the adoption of sustainable trash disposal practices: Evidence from Benin's waste management amid urbanization. *Urban Governance*, *4*(3), 198–209. DOI: 10.1016/j.ugj.2024.07.003

Yle. (2021). *Lahti is the European Environmental Capital for 2021: Received the title as the first Finnish city*. https://yle.fi/a/3-10842352

Zaikova, A., Deviatkin, I., Havukainen, J., Horttanainen, M., Astrup, T. F., Saunila, M., & Happonen, A. (2022). Factors influencing household waste separation behavior: Cases of Russia and Finland. *Recycling*, *7*(52), 1–15. DOI: 10.3390/recycling7040052

Zorpas, A. A. (2020). Strategy development in the framework of waste management. *The Science of the Total Environment*, *716*(137088), 137088. Advance online publication. DOI: 10.1016/j.scitotenv.2020.137088 PMID: 32059326

APPENDIX

Links to online appendix resources:

- Online Appendix A: https://zenodo.org/records/10978214/files/Appendix%20A%20-%20Context%20parameters%20of%20the%20city%20and%20WM%20system.pdf?download=1
- Online Appendix B: https://zenodo.org/records/10978214/files/Appendix%20B%20-%20The%20goals%20challenges%20and%20its%20KPIs.pdf?download=1
- Online Appendix C: https://zenodo.org/records/12582189/files/Appendix%20C%20-%20Evaluation%20and%20testing%20questionnaires.pdf?download=1

Inna Sosunova is a researcher at the LUT School of Engineering Science within Lappeenranta University of Technology, Finland, boasting a recently conferred Doctor of Science in Technology degree (2023) from LUT University. With a career spanning 15 years in software engineering, she has garnered a lot of expertise in the domain. Having previously worked as a programmer at St. Petersburg State University, an Engineer at the Faculty of Information and Communication Technologies at ITMO University, and a Leading Engineer at the Software and Network Systems Laboratory of the National Center of Quantum Internet, ITMO University. During her tenure at ITMO University, she actively contributed to various projects, showcasing her versatility in decision support systems, IoT-enabled waste management systems, smart transport, and quantum cryptography. In last years, while working at LUT, Inna has diligently directed her research focus towards the engineering of Decision Support Systems (DSSs), Green ICT, IoT-enabled waste management, Context-driven systems, and Knowledge representation. She also has experience of participation as a mentor in hackathons, organizing hackathons and workshops for students, conducting interviews with representatives of Finnish companies and city administration. Inna Sosunova developed context-driven decision support systems (DSSs) in 4 international projects (bIoTope project; CroBoDDIT; AWARE project; Createch progect). The developed DSSs aimed to help with decision making, choose and use of modern technologies (IoT, AI, etc.) for various stakeholders of waste management process (city administration, city residents, waste truck drivers, janitors, dispatchers) and representatives of the small and medium sized business in Finland. ORCID: 0000-0003-0021-1054, Scopus Author ID: 56989679100, ResearcherID: L-5376-2016

Associate Professor at LUT and Adjunct Prof. at Taylors university and a project manager/principal investigator at LUT School of Engineering Science in Lappeenranta University of Technology, Finland. Assoc. Prof. Ari Happonen is a native-born University-Industry collaborator specializing in Digitalization capabilities, Hackathons & Code Camps, ICT for Sustainability, and modern waste reduction methodologies. Dr. Happonen has a Master’s degree (2005) from Lappeenranta University of Technology from Information Technology with minor in industry engineering. His research includes practical and efficient industrial-related applied collaborative activities in B2B and B2C contexts, both nationally and internationally. He contributes to software engineering, ICT & sustainability, Artificial intelligence and creative technologies for greater good, hackathons & education-related research areas. During his career, he has authored over 150 scientific publications in various topics of software engineering & digitalization and sustainability & education development. Dr. Happonen has given guidance for over 170 theses so far. He also actively participates in education and teaching development efforts with 20+ years of experience, also recently working as head of the bachelor program in Software Engineering at LUT School of Engineering Sciences, in which time he was one of the key persons for overseeing units' successful ASIIN accreditation process. He works as an intermediary in multiple research projects between universities, innovative front-line companies & governmental and municipal offices aiming to promote SDGs. Assoc. Prof. Happonen is the current representative for LUT Software Engineering unit in the LUT School of Engineering Science

Annika Wolff is an assistant professor whose research is in the newly emerging field of human-data interaction, at the intersection between complex data, machine and human learning. Her research focuses on engaging people with data, such as from smart cities, and in supporting non-experts in designing products and services that use data. She has expertise in using inquiry-based methods and co-creation, in developing applications of data science and in the use of tangibles, creativity and games to support learning. She has previously led work in developing and piloting new methods for teaching data literacy skills in UK primary and secondary schools and in understanding how open data can be utilized in education. She has many years of experience working within UK and European funded projects, combining applications of data science to human understanding. She has published in a number of international journals and is an active member of research communities related to community-based innovation and HCI.

Jari Porras D.Sc (Tech) is a Professor of Software Engineering (especially Distributed Systems) at the Lappeenranta-Lahti University of Technology LUT. Prof. Porras received the DSc. (Tech.) degree from the Lappeenranta University of Technology, Finland in 1998 about modeling and simulation of communication networks in a distributed computing environment. He's a visiting professor at Aalto University, Finland, and at the University of Huddersfield, UK. He has supervised and examined 500+ Master’s Thesis works and 27 Dissertations, as well as acted as an external evaluator for 28 doctoral thesis works since the start of his professorship in 2000. He has conducted research on parallel and distributed computing, wireless and mobile systems and services, as well as sustainable ICT. In the last years, he has focused his research on human and sustainability aspects of software engineering. He is actively working in international networks and organizations.