Thesis for The Degree of Doctor of Philosophy

Decoding Urban Metabolism´s black box

Advancements in Urban Analytics to support circular material flows

Jonathan Cohen

Department of Architecture and Civil Engineering
Chalmers University of Technology
Gothenburg, Sweden, 2024

Decoding Urban Metabolism´s black box
Advancements in Urban Analytics to support
circular material flows

JONATHAN COHEN

ISBN 978-91-8103-058-7
Doktorsavhandlingar vid Chalmers tekniska högskola,
Ny serie nr 5516.
ISSN 0346-718X

Department of Architecture and Civil Engineering
Division of Urban Design and Planning
Spatial Morphology Group
Chalmers University of Technology
SE-412 96 Göteborg,
Sweden
Phone: +46(0)31 772 5908

Cover: A black box with a city inside. The original image was created with ImageFX and edited to match my vision of the cover.

Printed by Chalmers Digitaltryck,
Gothenburg, Sweden 2024.

"The finitude of space and time within the local configuration causes delays, distortions or extinction of processes. Seen in this perspective the world seems like a garden where a thousand seeds give rise to only a hundred flowers."

Hägerstrand (1976)[p.333]
Geoforum

Decoding Urban Metabolism´s black box

Advancements in Urban Analytics to support circular material flows

JONATHAN COHEN
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

The overexploitation of natural resources is causing life on Earth to operate beyond its safe limits. To overcome this challenge, shifting away from the current linear economy (take-make-dispose) is urgent. Despite international efforts to address this challenge, less than 10% of materials are being reused at the end of their life, and global resource consumption is expected to double by 2050. As a result, it is recognised that our economic systems are wasteful, and resources must be used more efficiently.

Most global wealth consumption and production occurs in urban areas. Therefore, it is essential to employ adequate quantification methods to study resource throughput in these systems. Urban Metabolism (UM) offers a framework to examine how resources flow in and out of cities at different geographical scales. However, it needs to provide more details to describe the complexities that generate those flows of resources. As these flows are caused by specific processes that occur at a particular time and location by specific actors, these processes deserve to be investigated to improve the system's resource efficiency.

This thesis addresses the need to deliver resource-efficient city regions, recognising the need for adequate tools and methods for exposing urban processes and their interactions. Urban Analytics (UA) can contribute to revealing urban processes and their interactions by employing computational techniques such as data collection, processing, visualisation and modelling. The overarching aim of this work is to advance the development of digital models to support urban metabolism by demonstrating: **(I) How can UA methods contribute to the analysis of urban material flows?** and exploring various applications to understand and **(II) How can the Urban Metabolism framework be enriched to support urban strategies to close material loops?** This last inquiry also considers how spatial, temporal, and behavioural factors influence the metabolism of urban areas.

This thesis takes an explorative approach to show the importance of (i) **knowledge management** to organise information about waste and resources, (ii) **geographic information** to integrate spatial characteristics into urban and regional analysis and (iii) **simulations** to describe urban processes and evaluate potential outcomes of different planning scenarios.

The first research question is addressed by first, **proposing a general framework to manage knowledge about resources and waste** and second by **employing UA to incorporate spatial, temporal and behavioural aspects**. Adequate knowledge management and data standards about city resources are crucial because they allow information sharing across urban systems, enabling a more holistic understanding of material flows. Moreover, it contributes to identifying information gaps and enables data processes to be reproduced and generalised. The general framework was validated by developing various applications. These applications required the use of UA and contributed to demonstrating the role that UA can play in enhancing UM.

The second research question is answered by exploring models incorporating the

spatial, temporal, and behavioural elements in three strategies that promote circular material flows in city regions. A **simulation of residential waste sorting at the neighbourhood scale** informs how different urban scenarios influence residents' waste sorting behaviour. Then, a **city scale simulation of the construction and demolition sector** discusses different planning scenarios and their consequences for material circularity. The thesis highlights the importance of considering location when analysing **industrial symbiosis for potential waste exchanges between firms at the regional scale**. By considering distances between firms, a methodology was developed to identify possible partnerships, resulting in fewer potential exchanges.

To conclude, this thesis highlights the importance of data models and simulation techniques in advancing the field of UM. The models presented here serve as preliminary steps to demonstrate the importance of using UA to incorporate spatial, temporal and behavioural aspects when studying the metabolism of urban areas.

Keywords

Circular Economy; Spatial Planning; Urban Metabolism; Waste Management; Industrial Symbiosis; Construction and Demolition; Urban Mining; Digitalisation; Data model; Simulation; Agent-based model; Decision Support System.

List of Publications

Appended publications

This thesis is based on the following publications:

[**Paper I**] **J. Cohen**, J. Gil, *An entity-relationship model of the flow of waste and resources in city-regions: Improving knowledge management for the circular economy*
Resources, Conservation & Recycling Advances 12. 2021

[**Paper II**] J.Patricio, Y. Kalmykova, L. Rosado, **J. Cohen**, A. Westin, J. Gil, *Method for identifying industrial symbiosis opportunities*
Resources, Conservation & Recycling 185. 2022.

[**Paper III**] **J. Cohen**, J. Gil, L.Rosado, *Exploring urban scenarios with an agent-based model to assess residential waste sorting*
Submited to Waste Management. 2024

[**Paper IV**] **J. Cohen**, J. Gil & L.Rosado, *Understanding residential waste sorting behaviour with situational factors: a data-driven approach*
Submited to Waste Management & Research. 2024

[**Paper V**] **J. Cohen**, J. Gil, L.Rosado & M. Lanau, *A Spatio-Temporal Simulation of the Construction and Demolition sector. Methodological Advances to quantify embodied carbon of buidlings*
Draft with main results. 2024

Other publications

The following publications were published during my PhD studies or are currently in submission/under revision. However, they are not appended to this thesis due to their contents partially overlapping the main objectives of the present work.

[**a**] **J. Cohen**, J. Gil, *Mapping the spatial distribution of the effects of urban traffic congestion: a methodological exploration using web-based services*
IOP Conference Series: Earth and Environmental Science 588(3) (2020)

[**b**] **J. Cohen**, J. Gil & L. Rosado, *ODD: Residents planned behaviour of waste sorting to explore urban situations (Version 1.2.0)*
CoMSES Computational Model Library - Under review

[**c**] **J. Cohen**, L. Rosado & J. Gil, *How is the construction sector addressing the Circular Economy? Lessons from current practices and perceptions in Argentina*
IOP Conference Series: Earth and Environmental Science, Volume 1078 (2022)

[**d**] G. Dokter, **J. Cohen**, S. Hagejärd, O. Rexfelt & L. Thuvander, *Mapping the practice of circular design: A survey study with industrial designers and architects in the Netherlands and Sweden*
Journal of Design Research - Accepted

Author's contribution

The Contributor Role Taxonomy (CRediT) is used to indicate the role of Jonathan Cohen in each of the papers listed above. More information about the taxonomy can be seen in Allen, O'Connell and Kiermer (2019).

In Paper 1, Jonathan Cohen was responsible for Conceptualization, Methodology, Software, Validation, Investigation, Writing - Original Draft, Writing - Review & Editing, and Visualization.

In Paper 2, Jonathan Cohen was responsible for the spatial application related to wood waste, which encompassed Conceptualization, Software, Validation, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing and Visualization.

In Paper 3, Jonathan Cohen was responsible for Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing and Visualization.

In Paper 4, Jonathan Cohen was responsible for Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing and Visualization.

In Paper 4, Jonathan Cohen was responsible for Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing and Visualization.

In Paper 5, Jonathan Cohen was responsible for Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Acknowledgement

Five years have passed since I started this journey of completing this PhD, and little did I know that it would be one of the most rewarding and challenging chapters of my life. Here, I want to detach myself from the technicalities and details of the work and briefly pay a humble tribute to those who have inspired and motivated me to pursue and finish this goal. Only because of your support have I made it this far.

First, I would like to express great gratitude towards Jorge, who has guided me through the ups and downs of this process. Thanks for your patience, generosity and trust. I have been fortunate to have you as my supervisor. Secondly, thanks to Leonardo, who has been constantly consulted about all kinds of nuances regarding the metabolism of cities. I'm pleased that you accepted the invitation to join the supervision team. This work reached this point with your valuable input. Thanks to both for always being available to talk and join our supervision meetings with such energy.

This first round of acknowledgements would be incomplete without including Meta and Lars, who, from a distance, have safeguarded and significantly contributed to shaping my PhD. Your voices have encouraged me to pursue my research ambitions within a realistic boundary throughout the various seminars, checkpoints and informal conversations. Hopefully, I have collected and incorporated your suggestions graciously. If, after these years, I have become a better professional and researcher, it is most likely thanks to you all. Moreover, I want to thank my colleagues and friends at SMOG and ACE for supporting me during this process. Although your input has been invaluable in clarifying my thoughts, I'm mostly thankful for keeping a safe and warm work environment.

To my new friends and those scattered around the globe (mainly at home), thank you for your friendship. Thanks for being there when it mattered the most! Besides the distance, thanks for staying close to me.

Viejitos, gracias por estar presente todas las semanas durante estos años. Estoy donde me encuentro gracias a su esfuerzo y todas las herramientas que me supieron dar. Gracias por mostrarme el valor del esfuerzo y dedicación, dando el ejemplo. Hermanitos y familia gracias por darme animos para terminar esta etapa.

Last but certainly not least, thank you, Stina. Thanks for sharing your joy and smiles and for your unconditional love. Thanks for bringing the feeling of family closer. I'm very grateful we crossed paths.

Acronyms

ABM Agent-based Model. 41, 44, 47, 54, 75, 77

C&D Construction and Demolition. xvi, 33, 34, 41, 54, 55, 62, 65, 75

CE Circular Economy. xv, xvii, 4–6, 12, 15–25, 34, 73, 76, 77

CO$_2$ Carbon Dioxide. 78

CO$_2$e Carbon Dioxide Equivalents. xvi, xvii, 42, 44, 65, 68

DPSIR Driver-Pressure-State-Impact-Response Framework (DPSIR). 8

DSS Decision Support System. 67, 77

EPD Energy Performance Declaration. 43

ERM Entity-Relationship Model. 37, 49, 54

EU European Union. 5

FTI Förpacknings- och Tidningsinsamlingen. 45, 46

GFA Gross Floor Area. 42

GIS Geographic Information System. 39

IE Industrial Ecology. 26

IoT Internet of Things. 28, 52, 55

IS Industrial Symbiosis. 33

KPI Key Performance Indicator. 67

LCA Life Cycle Assessment. 77

MFA Material Flow Analysis. 6, 68, 77

ODD Overview, Design concepts, and Details. 47

SDGs Sustainable Development Goals. 4

SWM Solid Waste Management. 33

TPB Theory of Planned Behaviour. 62

UA Urban Analytics. 6, 7, 11, 12, 15, 33–35, 71, 72, 74

UM Urban Metabolism. xiv, 5–13, 15, 25–29, 71–73

WM Waste Management. 5, 12, 75

Contents

Paper I - An entity-relationship model of the flow of waste and resources in city-regions: Improving knowledge management for the circular economy

Paper II - Method for identifying industrial symbiosis opportunities

Paper III - Exploring urban scenarios with an agent-based model to assess residential waste sorting

Paper IV - Understanding residential waste sorting behaviour with situational factors: a data-driven approach

Paper V - A Spatio-Temporal Simulation of the Construction and Demolition sector. Methodological Advances to quantify embodied carbon of buildings

List of Figures

List of Tables

Part I

Extended summary

Chapter 1

Introduction

1.1 Addressing environmental challenges

Half a century ago, in 1972, a dramatic report titled *Limits to growth* about the planet's future was presented to the Club of Rome. The report's prognosis communicated a clear message: "If the present growth trends in world population, industrialisation, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years" (Meadows et al., 1972)[p.23].

The report is considered a significant landmark because it collected and summarised insights related to environmental problems associated with the consequences of economic growth. The report represents long and continuous efforts from the scientific community to raise concerns and provide evidence about the potential effects of persisting in producing and consuming without checking the status of the environment. The evidence presented in the report played a pivotal role in initiating a global dialogue about the need to balance economic development with environmental protection and to develop strategies for sustainable resource management and equitable distribution of wealth.

Although the publication of the report inspired subsequent research and activism aimed at finding solutions to the growing environmental challenges facing the planet, it is concerning that the use of material resources has increased by approximately 12-fold since 1970 to 2017 (OECD, 2019). In fact, as of 2022, global consumption has reached an equivalent of 1.7 planet Earths (Global Footprint Network, 2023). Despite subsequent efforts and warnings to revert this situation, humankind's ecological footprint has increased by 190% (Collins et al., 2020) and global demand for resources is expected to double by 2050 (Krausmann et al., 2018; OECD, 2019). As a result of over-exploiting natural resources and polluting the environment, life on Earth is operating beyond its safe limits (Persson et al., 2022; Rockström et al., 2009; Steffen et al., 2015; Wang-Erlandsson et al., 2022).

Without further action to resolve this situation, the environment will likely continue to deteriorate, and negative climate impacts will accelerate. Addressing this problem is critical because it has profound implications for a variety of dimensions that range from food and water security to human health and even peace and global stability (Perera, Nik & Chen, 2020; Romanello et al., 2021; Schmidt, 2022; Vicedo-Cabrera, Scovronick & Sera, 2021; Zhao et al., 2022).

Mobilised to confront the pressing challenges of our time and forge a path toward a global sustainable future, world leaders made a historic commitment in 2015 by endorsing the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). This marked a significant turning point in human history as leaders recognised the situation's urgency and committed to allocating resources and efforts toward achieving 17 SDGs. These goals encompass many objectives, from fostering a sustainable environment to ensuring access to fundamental human rights such as health, food, and education.

Humanity's overarching challenge lies in balancing the pursuit of higher living standards for all with the imperative to restore and safeguard our planet's health and resilience. This dual challenge highlights the interconnectedness of social, economic, and environmental sustainability and calls for holistic and integrated approaches. The tension and synergies across the various SDGs are complex, and understanding their linkages is crucial to unlocking their potential and ensuring progress (European Commission. Statistical Office of the European Union., 2019, 2022).

As expected, there is a strong relationship between how we live (SDG 11: Sustainable cities and communities) and how and what we consume (SDG 12: Responsible consumption and production) with the rest of the SDGs (Lucertini & Musco, 2020). Delivering Sustainable Cities and Communities is a critical Goal that catalyses to achieve other Goals (European Commission. Statistical Office of the European Union., 2019).

Cities are fundamental pieces of infrastructure, engines of growth and responsible for providing diverse goods and services to residents. By 2050, cities will host up to 70% of the global population (United Nations Human Settlements Programme, 2020). Therefore, adequate management of urban areas is critical to delivering health, education, and wealth to its residents.

At the same time, urbanity contributes to delivering well-being; urban areas are hotspots of resource consumption and resulting waste. They are globally responsible for producing 70% of the wealth, 70% of the waste, and 70% of the greenhouse gases (United Nations Conference of Housing and Sustainable Urban Development, 2016). Paradoxically, while the material needs to deliver urbanity have grown constantly, reused materials have remained relatively low, below 10% (Circle Economy, 2020; Haas et al., 2015, 2020a). This situation offers an opportunity to use resources more efficiently and reduce extraction by transforming and recovering what is being wasted. Adequate management of cities and the activities producing and consuming resources within them will be determined in delivering sustainability (European Commission, 2018; Graute, 2016; OECD, 2020).

In this context, the idea of Circular Economy (CE) has been gaining traction among academics, policymakers, and industry (European Parliament, 2020; Ghisellini, Cialani & Ulgiati, 2016; OECD, 2020). The CE is perceived as a relevant set of strategies for delivering economic growth while meeting environmental targets (European Commission, 2020). At its core, contrary to the current linear economy (”take-make-dispose”), the CE aims to (one) take as little as possible from nature, (two) maintain rather than make new products, and (three) minimise waste by reusing materials for their highest possible value (Bocken, Bakker & de Pauw, 2015). Academics (Gura et al., 2023; Martin Calisto Friant & Salomone, 2023) and practitioners (Arup, 2023; Ellen MacArthur Foundation, 2018; Sweco, 2023) recognise the importance of better understanding how to implement CE ideas in cities.

Dedicated to accelerating this transition, the European Union (EU) CE Plan is one of the main building blocks of the EU Green Deal. This plan sets ambitious targets for five themes to be met by 2025. For instance, for Waste Management (WM), 55% of municipal waste and 65% of packaging waste must be prepared for reuse or recycled (European Commission, 2020). Because of the relevance of cities and the current traction of CE, exploring how these strategies can be integrated into the city has the potential to lead to environmental benefits (ESPON, 2019). Spatial planning could contribute to establishing long-term sustainable frameworks and cohesion within cities and their network that compose regions. Spatial planning is a crucial instrument that fosters the integration between various actors and sectors by facilitating their organisation in the territory (United Nations, 2008).

Spatial planning means influencing future spatial distribution of activities to create a more rational territorial organisation of land use and linkages between them. To plan is to balance the demands for development with the need to protect the environment while achieving social and economic objectives (United Nations, 2008; Wegener, 1998). This complex activity requires engaging with multiple interacting sub-systems that create a complex and intricate reality where proposing solutions is not straightforward. Usually, the problems planners face lack an adequate definition; it is difficult to determine when policy roles are achieved, and solutions cannot be tested beforehand. These characteristics are described as wicked Problems by Rittel and Webber (1973). Taming such problems has been a concern for planners and policymakers- for a long time, and different approaches have been proposed to deal with these problems better.

The development of cities and their activities require the consumption of resources to flow into the city. As these resources are used or transformed, other materials flow out as waste and pollution or are dissipated as heat. Kennedy and Hoornweg (2012a) reminds us that “Understanding energy and material flows through cities lies at the heart of developing sustainable cities.”.

If abstracted, an analogy can be drawn between the process that generates the inflow and outflow of resources in cities and the metabolism of a living organism. As its name indicates, the field of Urban Metabolism (UM) is known for using this analogy to strive for urban environments that mimic efficient biological processes. It would be more appropriate to relate the concept of cities with an ecosystem. In the field of UM, natural ecosystems (Golubiewski, 2012; Kennedy, Pincetl & Bunje, 2011a) are seen as perfect because they are generally self-sufficient. There is no waste because, once used, resources are recycled and used in various other natural processes.

The concepts of UM and CE strive for similar objectives despite being developed independently (Lucertini & Musco, 2020). In both cases, the focus is to deliver sustainability by improving resource management. On one hand, the concept of CE aims to regenerate the environment by offering a concrete set of strategies to guide practitioners and consumers. Often, the focus of the CE is not set on the location and drivers of material flows but rather on how to minimise the environmental impacts. CE provides a supportive economic system and guides practitioners towards better practices.

On the other hand, UM engages with these flows and provides methods of accountability to track the stock of materials, which flow through the cities (Haas et al., 2020b; Lucertini & Musco, 2020). Usually, UM uses an accountability method known as Material Flow Analysis (MFA) to study the material flowing in and out of the city. UM can offer an adequate framework to quantify how resources are used and how to improve their use. Articulated adequately, the concepts of UM and CE provide a comprehensive understanding of how resources flow and what actions can be placed to improve material use (Cui, 2022; Gao et al., 2020; Haas et al., 2020b; Lucertini & Musco, 2020; Mayer et al., 2019)

Despite the name of the field suggesting a focus on urbanity, the field of UM has been criticised for mainly focusing on material flows and adopting a flat simplification of the urban processes. Overlooking questions about where and how these materials move (in space), what are the drivers of these flows (behaviours and actors) or how the material flows over time (Athanassiadis, Crawford & Bouillard, 2015; Céspedes Restrepo & Morales-Pinzón, 2018; Dijst, 2013; Dijst et al., 2018; Newman, 1999a; Pincetl, Bunje & Holmes, 2012; Rosado, Niza & Ferrão, 2014; Zhang, Yang & Yu, 2015). For local authorities to capitalise on the insights derived from UM analysis, it is critical to identify where the resources are in the territory and what actors are responsible for their production and consumption. Also, policymakers could benefit from having as much updated information as possible instead of receiving information years after implementing changes or policies. Eventually, temporal information and evaluation of scenarios will be essential to manage resources in cities (Lucertini & Musco, 2020).

The study of UM is challenging and context-dependent. It is information-intensive and requires knowledge across various urban domains. To date, only 122 case studies of MFA in urban areas have been carried out (Guibrunet & Sánchez Jiménez, 2023), demonstrating the gap in addressing environmental sustainability with UM (Kennedy, Pincetl & Bunje, 2011b).

Urban Analytics (UA), positioned as a sub-field within the evolving domain of geo-data science, offers a methodological approach for comprehending cities through computational techniques (Andrea Caragliu & Nijkamp, 2011; Batty, 2011; Singleton & Arribas-Bel, 2021). According to Batty (2019), “UA is a core set of tools employed to deal with problems of big data, simulations, and geo-demographics.”

The field of UA has played a crucial role in developing, deploying and using new data sources to deliver better human settlements by providing more detailed insights about various urban dynamics. For instance, logistics and mobility are some of the fields of application that have benefited the most from using these new data sources and techniques. To some extent, the rapid growth in these fields is related to data availability and the ubiquity of technology that enables activity tracking. Although there are clear benefits to using more precise information to manage urban systems, its development and deployment to other domains have been asymmetric. When it comes to managing resources or quantifying, the application of UA is arguably at the early stages. The use of new technologies to capture, process and analyse data to produce insights represents an excellent opportunity to transition towards the CE (Athanassiadis, 2020; European Commission. Directorate General for Research and Innovation. et al., 2022; Hedberg & Sipka, 2020; World Economic Forum, 2015; Zhang, Yang & Yu, 2015).

Consequently, UA can help enrich the framework of UM by introducing (one) techniques to manage and analyse spatiotemporal information and (two) simulations and models of urban processes.

1.2 Problem definition

The research field of UM started as an accounting method to consider overall material inputs, stocks and outputs of an urban system in a given moment. Traditionally, these studies overlooked the various urban dynamics such as the residents' lifestyles, urban form, technologies or institutions (Athanassiadis, Crawford & Bouillard, 2015; Newman, 1999a; Zhang, Yang & Yu, 2015). Figure 1.1 shows a typical representation of how material flows of an urban area are analysed and represented when performing a metabolic study. In this figure, the city is abstracted to a single element to show that the city is responsible for transforming materials.

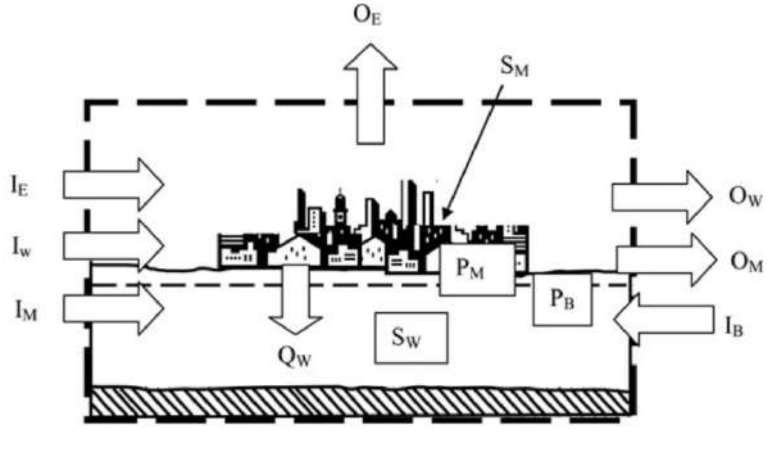


Figure 1.1: Material flow diagram of a city. Source: Kennedy and Hoornweg (2012b)

The figure presents the results of calculating various materials flowing in and out of the city. UM, studies can be used to optimise flows and to reflect upon multiple ways material flows can be affected to attain particular objectives: reducing natural extraction or minimising pollution. However, because the focus of UM is set on the flows, these studies can not inform about how changes in material flows affect the city or how changes in the city affect material flows (Lucertini & Musco, 2020). Moreover, it is impossible to understand how material flow changes affect specific urban actors such as industries or residents. Because these processes were hidden, UM has been associated with a black-box framework.

Navigating the complexities of urban life requires methodologies that complement and interact with UM (Zhang, Yang & Yu, 2015). It is crucial to note that UM contributions are invaluable in accounting for material and energy flows within cities. The efficacy of UM is unquestionable. UM studies can be used to optimise flows and to think of various ways flows can be affected to attain particular objectives: reducing natural extraction or minimising pollution.

To address this gap Fischer-Kowalski (1998), Fischer-Kowalski and Hüttler (1998) and Newman (1999b) advocated the importance of extending the UM framework with social aspects and looking at the dynamics of settlements. Together with frameworks aimed to explore drivers in material flows and changes in the environment, such as the Driver-Pressure-State-Impact-Response Framework (DPSIR) can improve the description of urban systems and better inform policies (Dijst et al., 2018; Rapport & Friend, 1979; Tscherning et al., 2012a).

After an extensive review, Papangelou, Bahers and Aissani (2023) categorise and provide evidence of how various drivers influence the metabolism of cities. For example, in lower-income and more vulnerable neighbourhoods, the housing stock is often older and less energy-efficient than newer homes (Porse et al., 2016). As the age of the buildings increases, more energy per square meter is required. Therefore, a policy that aims to upgrade the building stock to improve its efficiency requires dealing with the complexities of the socio-economic fabric.

This example illustrates how socio-economic factors (b) relate to the urban form (a) and determine the metabolism of a place (c). As resources are used and waste and pollution are generated, the status of the environment (e) changes over time (d). The abovementioned process can be traced in Figure 1.2. The diagram can also be used to explore other examples. Still, in all cases, it helps to reflect the role that spatial, temporal and social (economic-institutional-behavioural) aspects play in determining the status of our environment.

Since its initial conceptualisation, several authors contributed to opening the UM black box by introducing spatial (Kennedy, Pincetl & Bunje, 2011a; Patricio, Kalmykova & Rosado, 2020; Porse et al., 2016) and social (Huang et al., 2018; Rosado, Kalmykova & Patrício, 2016) and temporal aspects (Huang et al., 2018; Kalmykova, Sadagopan & Rosado, 2018a; Kennedy, Cuddihy & Engel-Yan, 2007; Kolkwitz, Luotonen & Huuhka, 2023). Moreover, another stream of contributions enabled the granularity of the macro material flows to be gained by accounting for different products and their environmental impacts across their life cycles (Gontia et al., 2018; Lanau & Liu, 2020; Lavers Westin et al., 2019; Patricio et al., 2017; Rosado, Kalmykova & Patrício, 2016).

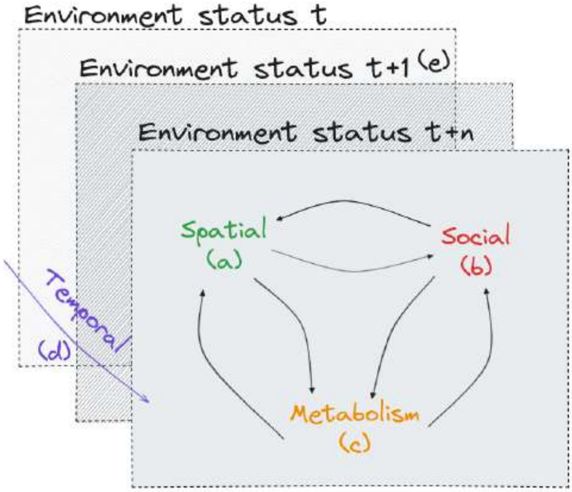


Figure 1.2: Relationship across multiple urban dimensions.

However, much research is needed to continue finding evidence of the interplay of these urban factors. The relationship between the *tangible* and the *intangible* dimension remains unsolved (Céspedes Restrepo & Morales-Pinzón, 2018)[p.223].

The laking of adequate (A) information, (B) metrics, and (C) tools and methods to track environmental progress represent significant challenges in the field of UM (Kalmykova & Rosado, 2015; Kennedy & Hoornweg, 2012c; Papangelou, Bahers & Aissani, 2023; Rosado, Niza & Ferrão, 2014; Zhang, Yang & Yu, 2015). These challenges relate to the digitalisation process and represent interrelated obstacles to the metabolic study of urban areas. Figure 1.3 outlines the main challenges addressed in this thesis.

Overcoming these challenges is critical to continuing to open the ***UM black box*** and revealing the relationship between the spatial, temporal, and behavioural aspects that determine city metabolism.

Adequate and sufficient information (A) is one of the most critical aspects. Without a comprehensive understanding of the processes governing material flows in city regions, decision-makers lack the essential insights to inform sustainable urban development. A solid information foundation is needed to improve the ability to set meaningful targets, evaluate the impact of interventions, and develop models to make informed decisions.

Metrics are pivotal in tracking progress (B), assessing system efficiency, and identifying areas for improvement. However, defining meaningful metrics becomes a formidable challenge without a solid information base and accurate tools. The need for well-defined metrics limits their effectiveness in providing insights and guiding decision-making processes. This is reflected in having poor

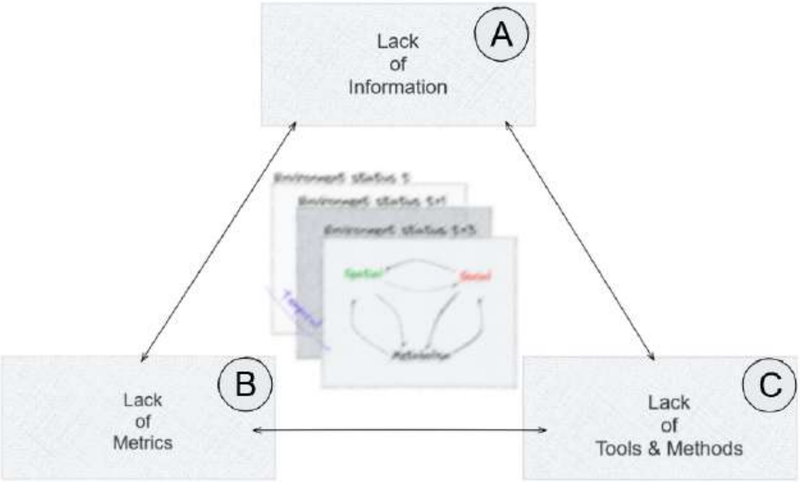


Figure 1.3: Digitalization Obstacles Loop

guides about relevant information, and with no metrics, it is challenging to think of using models.

Finally, the challenge of developing and deploying digital tools and methods (C) is directly connected to the information deficit. These tools, crucial for data collection, processing, and analysis, rely on a robust information foundation. Conversely, the absence of accurate tools hinders the extraction of valuable insights from available data, creating a feedback loop that perpetuates the information gap.

The interplay between these elements results in a systemic challenge where deficiencies reinforce each other. This can lead to a cycle of suboptimal decision-making, ineffective interventions, and an overall lack of progress in understanding and managing material flows in city regions. Progress in these obstacles will enrich the UM framework by integrating more details to identify stakeholders and their drivers in space and time.

Addressing this multifaceted challenge necessitates a holistic approach. Initiatives to enhance information gathering must go hand-in-hand with developing advanced digital tools and establishing meaningful metrics. Closing gaps in one of these aspects can positively impact the others, creating a more robust and interconnected system that facilitates a better understanding of the metabolic processes in cities.

1.3 Thesis purpose and research questions

This thesis aims to advance the development of digital models to enrich the framework of UM. Ultimately, in the long run, by incorporating the spatial, temporal and behavioural dimensions into this field of research, it would be possible to design policies that promote circularity and environmental regeneration. This research addresses the challenges addressed in the previous section by proposing digital tools and models that enable the exploration of how interventions in complex urban systems will determine material flow changes. First, a general framework was developed to organise knowledge and information about waste and resources in cities. Secondly, a set of applications focused on disentangling how space, behaviour and time affect material flows. Figure 1.4 presents the main dimensions to explore.

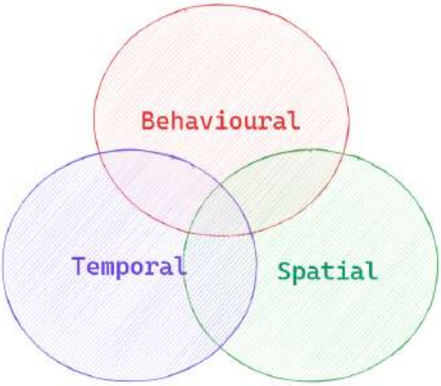


Figure 1.4: Dimensions to be explored: Space-Time-Behaviour

To achieve this aim, this thesis pursues the following objectives:

1. To model information about waste and resources in city regions
2. To enrich UM framework by proposing models that include space, time or behavioural aspects
3. To explore methods to quantify material flow and support closing material loops
4. Expand the areas of application of UA

This dissertation is structured around the following two main research questions to achieve the stated aims successfully.

- **RQ1: How can Urban Analytics methods contribute to the analysis of urban material flows?**
- **RQ2: How can the Urban Metabolism framework be enriched to support urban strategies to close material loops?**

The pursuit of RQ1 contributes to model information about resources and expands the areas of application of UA. Because of its broad nature, answers to this question are addressed in two forms throughout the thesis. RQ1 is first discussed on a conceptual level by developing a general framework for city waste and resources. This framework is presented as a core development that enables the exploration of various applications with UA. The framework was crafted to include spatial, temporal and behavioural aspects in future analysis. Secondly, answers to RQ1 are also found while further exploring the set of applications used to validate the general framework. In this case, the question is addressed practically, as using various methods of UA enriches the description of material flows.

The second question has practical implications and relates directly to some of the limitations identified in the UM framework. Answers from RQ1 enabled the development of a set of applications to enrich the framework. To answer RQ2 these applications show how spatial, temporal and behavioural aspects could be used to quantify material flows. Also, these explorations expand the areas of application of UA and explore methods of UA to close material loops. Because this thesis focuses on showing how spatial, temporal and behavioural aspects can be introduced, RQ2 is three-folded and can be divided into three sub-questions, each referring to one of the specific dimensions to be explored.

- How can spatial aspects enrich material flow analysis?
- How can temporal aspects enrich material flow analysis?
- How can behavioural aspects enrich material flow analysis?

1.4 Audience and relevance

This dissertation makes a direct contribution to the field of UM by exploring how advancements in UA can help manage information and integrate the spatial, temporal, and behavioural dimensions of the UM framework. The project uses tools from UA to reveal urban dynamics and complement the analysis of the metabolism of cities. The models presented in this project serve as proof of concept and demonstrate how they can be further developed to inform decision-making aimed at closing material loops and reducing the environmental impact of urban areas.

The outcomes of this thesis and the models developed during this project are expected to provide valuable support to urban planners and practitioners in the field of WM or CE. These tools and models are not standalone solutions but require continuous input and feedback from various experts to ensure their effectiveness. This thesis is a collaborative resource, inviting practitioners to contribute to advancing the digitalisation of waste and resources in city regions.

While this thesis primarily presents methodological advances to enrich UM, this project, initially driven by urgent environmental and sustainable development challenges, is expected to make a lasting positive impact on delivering sustainable settlements (SDG11) by promoting responsible consumption and production practices (SDG12). The long-term benefits of this research are aimed at fostering a more sustainable and resilient urban environment.

1.5 Disposition of the dissertation

The dissertation's outline consists of six chapters. In Chapter I, the introduction chapter, the reader is introduced to the research topic, and the research questions are presented. Chapter II provides a literature review of this project's main concepts and theories, laying the foundation for the subsequent chapters. Chapter III presents the methodology used in this project, detailing the specific techniques used in pursuing the different articles produced during this PhD. Chapter IV presents the main findings, and in Chapter V, these results are discussed and analysed, reflecting on how the individual studies pursued during this project contribute to answering the research questions. Lastly, the final chapter presents concrete answers to the research questions. This chapter discusses limitations faced during this project and makes propositions for further enriching the modelling framework of UM are discussed.

Chapter 2

Theoretical background

In response to the rising environmental and material scarcity problems, various policies have been developed to address the need to reduce waste and improve resource efficiency. During the last decades, two overlapping concepts have increased visibility and attention from policymakers, academia, and the private sector. Both Circular Economy (CE) and Urban Metabolism (UM) focus on transitioning from the current linear economy of 'extract-use-dispose' to a more circular economic system where resources and products are better utilised (Lucertini & Musco, 2020).

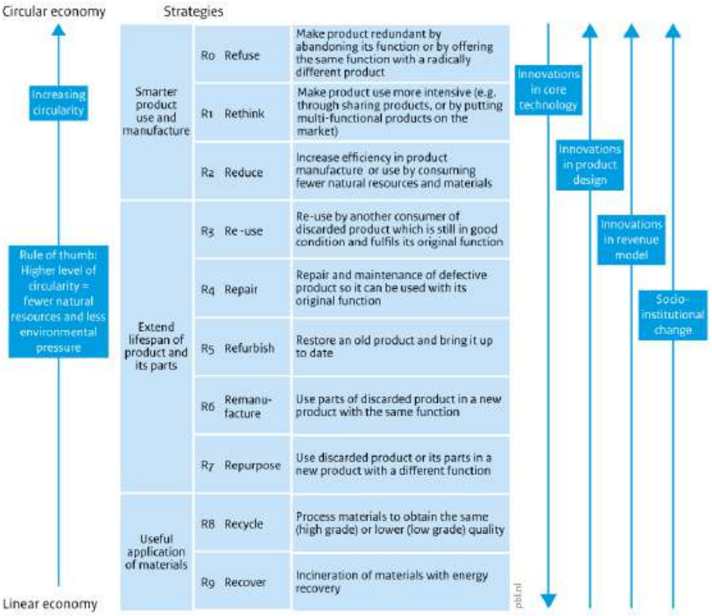
At the same time, the field of Urban Analytics (UA) offers a distinct and indispensable methodology for translating these policies into tangible actions and assessing their effects (ESPON, 2020; European Commission. Directorate General for Research and Innovation. et al., 2022; Gupta et al., 2019a; Kennedy & Hoornweg, 2012c; Li & Kwan, 2018; Morphet & Morphet, 2019; Tseng et al., 2018; Zhang, Yang & Yu, 2015).

The remainder of this chapter introduces each of these three main concepts. First, the idea of CE is introduced, and the focus is set on efforts to measure and promote advances in cities and regions. Then UM is presented as a framework to support the reuse of materials in cities by quantifying how materials flow in cities. Finally, advancements in UM using UA to study material flows.

2.1 Circular Economy

During the past decades, CE has gained traction among academics, policymakers, and businesses, especially since the EU presented the CE Action Plan in 2015. Under the CE, the current linear economy is mainly responsible for the problems previously mentioned and proposes a radical system change to a CE (Geissdoerfer et al., 2017). The CE offers concrete strategies to regenerate the environmental damage caused by our current linear economic systems while continuing to generate wealth and social benefits. The CE is an economic system that enables the *decoupling* of economic prosperity from environmental degradation (Fischer-Kowalski, 2011).

The concept of CE is not new and, to some extent, familiar (Sikdar, 2019). “Economics of the Coming Spaceship Earth” by Boulding (1966) introduced the metaphor of the *Cowboy and the Spaceman economy* to address a fundamental critique of the current economic system. While the Cowboy’s Economy measures growth “by the amount of the throughput from the factors of production”, Spacemen Economy views “throughput as something to be minimised, and the focus is maintaining the total stock”. Because of this radical position,CE is sometimes perceived as a new paradigm (Geissdoerfer et al., 2017; Nielsen et al., 2004) aligned with the Rs hierarchy of waste management popularised during the 1990s. The Rs hierarchy, or the three Rs, refers to an economy that seeks the reduction of material needs, reuse of products and recycling (European Commission, 2023). Eventually, the hierarchical framework of the three Rs was expanded to nine Rs (Potting et al., 2017) and ten Rs (Reike, Vermeulen & Witjes, 2018). This initial conceptualisation prioritises actions and strategies to minimise waste and reduce environmental degradation. Often, CE are aligned with these Rs strategies. Figure 2.1 presents the expanded waste hierarchy framework about the level of circularity. Under this framework, the “Rs” strategies are usually grouped into three categories: narrowing resource loss (R0 to R2), slowing material loops (R3 to R7), and closing loops (R8 and R9). Each of the Rs is associated with specific strategies dependent on the application sector. The strategies range from refusing (R0), rethinking (R1), and reducing (R2) waste to reusing (R3), repairing (R4), refurbishing (R5), remanufacturing (R6), repurposing (R7), recycling (R8), and recovering materials(R9).



Strategies			
Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3	Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recover	Incineration of materials with energy recovery

Figure 2.1: CE strategies. Source: Potting et al. (2017)

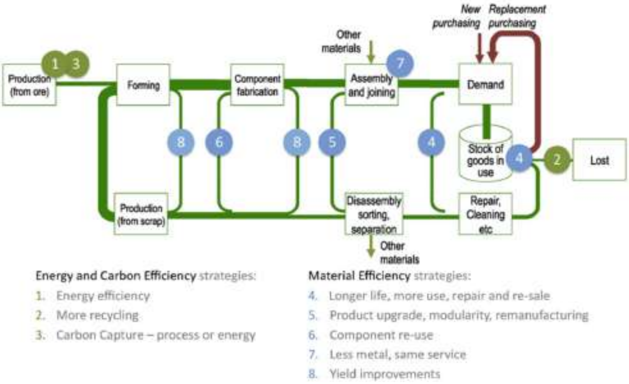
Among the various actors responsible for mainstreaming and tractioning the idea of CE, the Ellen McArthur Foundation has had a clear role in leading and forging the discussion about what CE implies and how it can be instrumented (Antikainen, Lazarevic & Seppälä, 2018; Johansson & Henriksson, 2020). Initially, the audience of such ideas were businesses looking to become more resource-efficient and environmentally sound. The concept of CE is often communicated with clear and simple visuals. For instance, the popularised Butterfly diagram distinguishes between biological and technical loops, each focusing on different aspects (Foundation, 2015a, 2015b). On the one hand, the biological loop promotes environmental protection and regeneration by recycling renewable resources that can safely be returned to the environment; this side focuses on products consumed, such as food.

On the other hand, the technical loop focuses on non-renewable and critical materials, such as metals or plastics. The framework is known as ReSOLVE because of the initial letters of the promoted strategies. It introduces three principles: 1- preserve and enhance natural capital, 2- optimise resource yields, and 3- foster system effectiveness and translate them into six business actions that promote REgenerating, Sharing, Optimising, Looping, Virtualizing, and Changing Foundation (2015a).

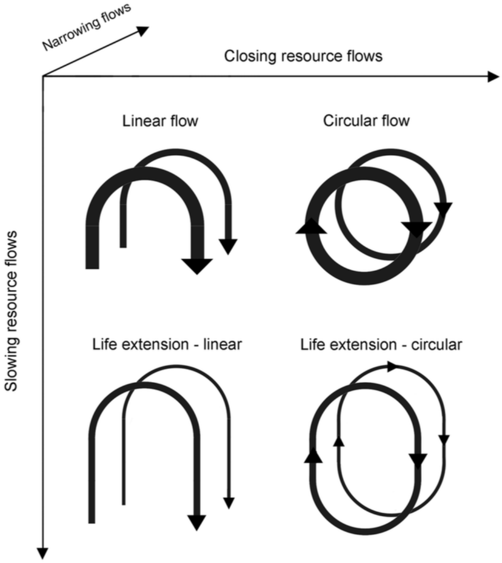
Although a circular resource flow is at the definitions' core, other authors emphasise various aspects (Murray, Skene & Haynes, 2017). For example, Allwood et al. (2011) focuses on closing loose ends of the linear economy and making material use more efficient. Figure 2.2(a) presents the R strategies and how they can be placed at different supply chain and product life cycle stages. It clearly shows the placement of various actions and the interrelationships between the supply chain. According to Bocken, Bakker and de Pauw (2015), all these strategies can fall within a three-axis framework. The main CE strategies extend the life of products, narrow material cycles and close loops. This conceptualisation explicitly shows the desirability of the actions in a simple but effective diagram presented in Figure 2.2(b). Others, like Geiser (2001), focus on the nature and characteristics of the products and materials. Under this view, it is critical to keep track of two dimensions: toxicity and persistency.

Because of its multiple definitions and uses, the CE is often considered an umbrella concept (Blomsma & Brennan, 2017). The field of CE is growing fast; in 2017, (Kirchherr, Reike & Hekkert, 2017) collected over 100 definitions of CE and provided for the first time a working definition that could hold a variety of perspectives. Since then, the number of definitions has almost doubled, and in 2023, their review of definitions was updated Kirchherr et al. (2023). The new definition showed a focus shift from main businesses and introduced an economic system that aims to regenerate the environment. These changes are reflected in their updated definition:

"a regenerative economic system which necessitates a paradigm shift to replace the 'end of life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities.". Kirchherr et al. (2023, p. 7)



(a) Framework of CE according to Allwood et al. (2011)



(b) Framework of CE according to Bocken, Bakker and de Pauw (2015)

Figure 2.2: Comparison of frameworks for CE

In opposition, Figge, Thorpe and Gutberlet (2023) view such definition as broad and argue that the definition of CE must contribute to delineating the concept from related ones. As a result, their definition contains four necessary and sufficient characteristics. First, CE must introduce closed resource loops. Two, CE must include the optimisation of resource flows. Three, CE is a multi-level concept and four, a caveat: the perfect resource circularity is highly unlikely to occur due to the law of thermodynamics and human errors. Even though, to date, there is no commonly agreed-upon definition of CE, it has been endorsed and mobilises a significant amount of resources (Kirchherr et al., 2023).

The discourse surrounding the definition of the CE continues to evolve, with multiple proposals emerging to measure its impact. Extensive reviews offer valuable insights and classifications regarding the CE, shedding light on its practical translation and de facto definition. Examination of the indicators used to evaluate circularity reveals a notable shift within the CE framework from emphasising regeneration and footprint reduction to prioritising material circularity (Corona et al., 2019; De Pascale et al., 2021; Geng et al., 2012; Mies & Gold, 2021; Parchomenko et al., 2019). The list of indicators used to assess CE often overlaps with various areas of sustainable development (Superti et al., 2021).

These reviews and analyses of indicators that track circularity align with the European Union's conceptualisation of CE. The EU defines CE as a production and consumption model centred on reusing, repairing, refurbishing, and recycling materials and products to minimise waste and promote resource efficiency. In practice, a CE minimises waste through reusing, repairing, refurbishing, and recycling existing materials and products. The EU's CE Action Plan outlines measures across five priority sectors: plastics, food waste, critical raw materials, construction and demolition, and biomass and bio-based products (European Commission, 2020).

High-level strategies such as Refuse or Rethink are absent from this definition, suggesting a focus primarily on material management rather than broader behavioural shifts. The extensive reviews provided by De Pascale et al. (2021), Moraga et al. (2019) and Parchomenko et al. (2019) effectively demonstrate the range of indicators used to address circularity. More than 60 indicators are being used to assess different aspects of the CE. Given the diversity of domains targeted by the CE, it is reasonable that a set of indicators are used for this purpose (Moraga et al., 2019) and new metrics should contribute to guide policies by indicating direct links of CE actions and environmental improvement (Corona et al., 2019).

Alongside environmental considerations, the CE EU plan also aims to reduce material dependency and secure critical resources for the EU (Domenech & Bahn-Walkowiak, 2019; Foster & Saleh, 2021; Mayer et al., 2019; Oakdene Hollins, 2017). The Action Plan proposes various measures, including legislative actions, communication strategies, implementation and enforcement efforts, guidance and best practices dissemination, development of indicators and standards, support mechanisms, and financing instruments, all aimed at fostering a more CE within the EU. Moreover, the progress of CE is not homogeneous, with some regions leading while others are lagging (Mazur-Wierzbicka, 2021; Silvestri, Spigarelli & Tassinari, 2020). The transition towards this vision can be accelerated by deploying better infrastructure, policies, and technologies that foster resource efficiency (Mhatre et al., 2021)

In summary, the discourse on the CE encompasses ongoing debates about its definition and measurement. While the EU's framework emphasises material circularity and resource efficiency, it falls short of addressing broader behavioural changes. The CE Action Plan outlines a comprehensive set of measures across multiple sectors and areas to promote circular practices and address challenges related to waste management and resource dependency within the EU.

As the CE is often presented as a means to sustainable development, the alignment between the three dimensions of sustainability and the reviewed indicators is analysed, which showed that the majority of indicators focus on economic aspects, with environmental and mainly social elements included to a lesser extent (Kristensen & Mosgaard, 2020; Mies & Gold, 2021; Moreau et al., 2017). This biased approach to a CE that favours economic aspects over environmental and social impacts can lead to sub-optimisations when companies apply a CE and may lead to a narrower approach to sustainability than what has previously been the case. Mies and Gold (2021) addressed this gap and identified a set of social factors to be included in the discourse of CE. For future research, it can be interesting to explore if the same bias exists on the meso and macro levels and analyse how a more coherent approach can be standardised on a micro level.

The discussion around the definition of CE is both relevant and critical. Without a clear and unified definition, it is practically impossible to understand the reach of the CE, and more importantly, it hinders the possibility of tracking its progress. Despite the multiplicity of definitions, transitioning to a CE is perceived as desirable and a way of delivering several of the SDGs simultaneously (Rodriguez-Anton et al., 2019; Schroeder, 2018; Velenturf & Purnell, 2021).

Advancing CE and closing material loops have to be perceived as a means to regenerate the environment and deliver better living standards. Blum, Haupt and Bening (2020) suggest that policymakers should aim to deliver a Sustainable CE, a more specific CE. The transition towards this subtype of CE can be achieved only if four conditions are present. First, if the amount of material circulated at its highest possible quality increases. Two, when more economic value is created, and three, if less environmental harm is created. Fourth, when better social conditions are delivered, the concept of CE has been defined as an umbrella concept that concentrates on various aspects of sustainability (Blomsma & Brennan, 2017; Geissdoerfer et al., 2017; Kirchherr et al., 2023; Korhonen et al., 2018). These arguments also reflect the position of various critical studies on the contribution of CE to sustainability, especially discussions about the need to reinforce the social gains of CE and whether this approach delivers strong or weak environmental sustainability (Bond et al., 2011; Velenturf & Purnell, 2021).

The difficulty in establishing common ground across academia, practitioners, and policymakers is rooted in two main characteristics of the concept. First, a systems approach is needed to understand how material extraction, transformation, and disposal of products affect our environment. The field of CE is interdisciplinary (Murray, Skene & Haynes, 2017; Ritzén & Sandström, 2017) and transdisciplinary (Walmsley et al., 2019), needing experts from finance, chemists, logistics, designers or lawyers, and so forth to collaborate with practitioners and governmental agencies. Second, the concept engages with physical objects which last in time and move over space. Following products along a supply chain also implies that the idea presents relationships across multiple scales and actors.

The ideas behind the CE have been critically reviewed. Some critics point out that the CE needs to address established knowledge about whether loops' complete closing is achievable. Closing loops create dissipation and entropy, which means a loss of energy (Figge, Thorpe & Gutberlet, 2023). Consequently, thinking of an economic system without new materials is practically impossible. Moreover, questions about definitions and measurements must be addressed for the CE to emerge as a prevailing paradigm.

Recent research in environmental science has revealed that the decoupling strategies that propose that economic growth can still be achieved while maintaining environmental sustainability may not be sufficient to meet the current climate targets. In recent years, the concept of degrowth has been gaining attention. Several indicators used to evaluate progress on CE neglect metrics of overall consumption and R strategies aimed to refuse and reduce consumption by narrowing material flows. Degrowth research advocates for narrowing material loops (Refuse, Rethink and Reduce), and it is expected that future definitions CE will incorporate recent evidence (Parrique et al., 2019; Vadén et al., 2020). Moreover, Bauwens, Hekkert and Kirchherr (2020) discuss different variations of how the future CE would look. The study presents a framework of four quadrants composed of the intersection between the degree of innovation (low-high) and the governance style (centralised-decentralised). This schema offers stakeholders alternatives to discuss policies and actions towards the transition towards CE. For example, this schema shows that a single R strategy can be delivered with high or low technologies.

Territorial implementation of Circular Economy

Since 2019, research and policy on CE have continued to grow, and its multiple benefits have been identified. The narrative of CE has emerged at the city level. Although the leading five city labels identified in the literature review performed by De Jong et al. (2015) and Wang, Ho and Fu (2019) are sustainable, smart, digital, eco and green cities, the concept of Circular City is growing. It will reach a conceptual maturity sometime before 2040. Besides academic publications, CE has become a recurrent term in policy and planning documents in various cities across the globe, such as Amsterdam, London, Umeå, Munich, Utrecht, Gothenburg, Scotland, Sicily, Stockholm or Copenhagen (Coskun et al., 2022; ESPON, 2020; Gravagnuolo, Angrisano & Fusco Girard, 2019; Prendeville, Cherim & Bocken, 2018; Williams, 2023).

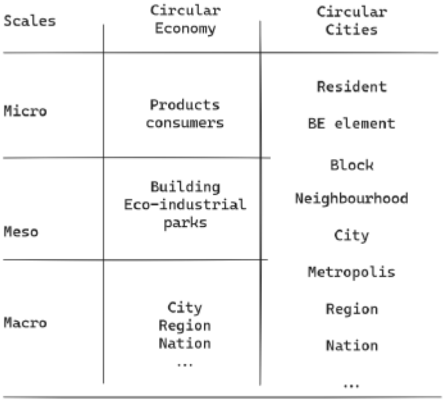
Several contributions have studied specific territories adopting CE strategist and compared them using various frameworks. For instance, Prendeville, Cherim and Bocken (2018) propose to study city circularity by considering top-down approaches. As a result, the strategies of six cities were evaluated using the dichotomy of top-down and bottom-up in the context of the ReSOLVE framework. The resulting analysis indicated the CE concept was intertwined with ideas of smart cities and general sustainability practices and that policymakers were having difficulties grasping how CE can be a guiding principle for managing cities. After evaluating CE policies in Amsterdam, Glasgow and Copenhagen, Martin Calisto Friant and Salomone (2023) conclude that the strategies often focus on resources and technological advances. Similar conclusions were synthesised by other authors who studied progress in the Netherlands,

In the context of China, in 2013, 40 cities were subject to the CE pilot program. Wang et al. (2018) and Wu et al. (2022) study their progress from 2015 to 2017 and conclude that overall, CE, as measured by a composite index, circularity increased significantly. Again, the metrics used to assess circularity use a narrow and, to some extent, simplistic understanding of the CE. Most of the indicators focus on material use efficiency; there is no direct link to environmental variables, and it isn't easy to track progress on circularity goals.

Campbell-Johnston et al. (2019) study how the strategies of CE are implemented in practice in three cities of the Netherlands. They interview policymakers, analyse white documents, and conclude that the critical municipal instruments to deliver CE include public procurement, zoning laws, capacity building and knowledge exchange. Their study also revealed that these practices mainly affect purchases and the construction and demolition sector. Overall, the officers faced difficulty determining how CE can be translated into a policy tool to affect value chains and reduce material consumption. In a similar context Savini (2019) and Zeller et al. (2019) identify waste management and households' central role in delivering circularity at the local scale.

As previously stated, the fixation on material efficiency can deliver weak sustainability because of the lack of social components. For example, some cities from developed countries are perceived and self-perceived by their residents with low environmental footprints, but due to imports, the footprint is on the rise Bolger and Doyon (2019). Despite previous blunders on how CE is being translated or measured, the policies set by cities play an essential role in the transition. The authors highlight the importance of adopting holistic and system thinking approaches Bassi et al., 2021a that enable one to understand the bigger picture of the problem. The CE is seen as an aspect of urban sustainability, and it offers a rich set of metrics to measure resource efficiency (Superti et al., 2021). Moreover, without a link to environmental measurements, assessing whether material circularity contributes to regenerating the environment is impossible. Such measurements in isolation do not contribute to informing policymakers and urban planners to determine how the various interventions are contributing to delivering any of the sustainable goals (Kalmykova, Sadagopan & Rosado, 2018b; Papageorgiou et al., 2021).

Despite these challenges, several cities have implemented CE differently. These reviews show the use of CE in planning documents and address the need for policymakers to understand better the full scope of the CE. The



Scales	Circular Economy	Circular Cities
Micro	Products consumers	Resident BE element
Meso	Building Eco-industrial parks	Block Neighbourhood City
Macro	City Region Nation ...	Metropolis Region Nation ...

Table 2.1: Comparison of scales of operation of CE for businesses and the territory

translation of CE to urban policies is not straightforward, and these early CE developments in cities have faced several limitations while working with the ReSOLVE framework. For example, the CE's scale of operation does not work in urban and regional planning. The macro level scales usually contain Cities, Regions, Nations and beyond (Kirchherr, Reike & Hekkert, 2017), but from the point of view of territorial organisations, these are significantly different scales. Therefore, territorial strategies can be operated at a continuum of interdependent geographical scales as shown in Table 2.1.

Seven aspects can be found among the leading proponents of Circular Cities (Bassi et al., 2021a; Paiho et al., 2020; Verga & Khan, 2022; Williams, 2023). First, this framework was developed to address businesses and markets and does not consider one of the most valuable resources in cities: land. At the core of urban planning is adequate land management and the organisation of the desired activities in specific locations. Therefore, Circular Cites and Urban Circularity must incorporate this dimension, such as urban farming and parks. A second limitation is that cities are not the same as firms or sectors. Cities are usually seen as complex urban systems with various actors interacting and having their motivations. Third, cities and their material flows depend on multiple scales, often exceeding the city scale. This means that the material demand, waste production and pollution impact various scales. Acknowledging these scales is crucial to localise material flows. Next, CE often focuses on the production side, but consumers and their behaviour play a pivotal role in determining the influx of resources and how much waste is generated. Finally, infrastructure and its adaptation are crucial to integrate urban activities and, at the same time, increase the system's resiliency. The more flexible the infrastructure is, the less resources will be wasted.

The implementation of CE in cities is intended to address these challenges. Williams (2023) uses the ReSOLVE principles and suggests seven circular actions. Three core actions: 1- Looping, 2- regenerating, and 3- adapting,

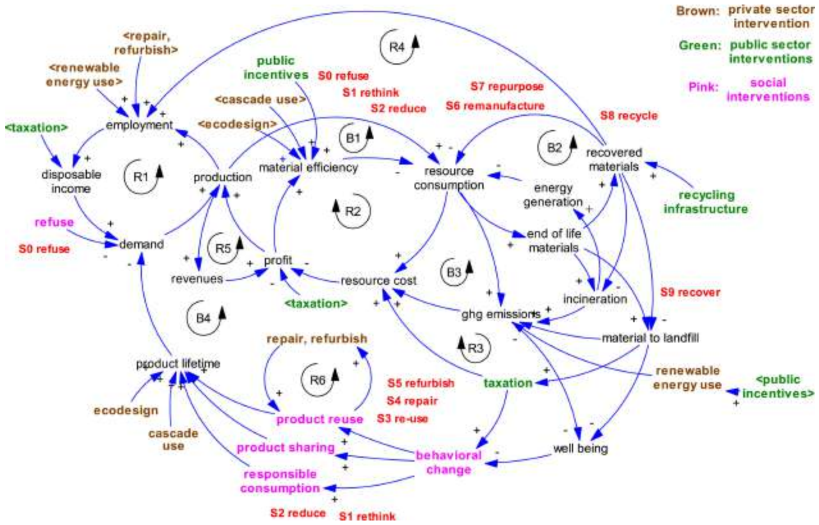


Figure 2.3: Causal loop diagram of CE strategies. Source: Bassi et al. (2021b)

underpin the resource cycling processes. Implementing these actions guides more efficient use of resources while regenerating the environment. On top of these main actions, the other four supporting actions reinforce the more efficient use of materials. These actions are characterised by localising, substituting, sharing, and optimising loops. This definition overlaps with the articulation developed during the ESPON CIRCTER project aimed to study the territorial implication of the CE, delivering two main academic outputs (ESPON, 2020). The first research classified different CE definitions and determined the spatial characteristics relevant to delivering CE (Carlos Tapia & Bassi, 2021). In this case, agglomeration economies and land productivity are the core identified factors. These two factors determine the overall material efficiency of the city and cluster of cities within a region. Hard factors, such as technological innovation and infrastructure, and soft factors, such as governance and knowledge-related factors, catalyse these two factors. Secondly, (Bassi et al., 2021b) presents CE as a complex challenge that requires a system thinking approach and uses Casual Loop Diagrams to track progress on CE. Figure 2.3 presents the framework for analysing specific areas' circularity. The model describes the various interactions across and actions that determine and affect the level of circularity.

Verga and Khan (2022), refers to Urban Circularity, and it proposes a broader definition. In their conceptualisation, cities pursue circularity-driven ambitions. This purpose allows policymakers to question how the planning of the territory can contribute to reducing environmental damage and better managing finite resources. This definition is similar to the one ascribed by (Fusco Girard & Nocca, 2019; Paiho et al., 2020; Prendeville, Cherim & Bocken, 2018), which defines a circular city that pursues circular actions with the help of the various city stakeholders (citizens, business, policies, NGOs and academia).

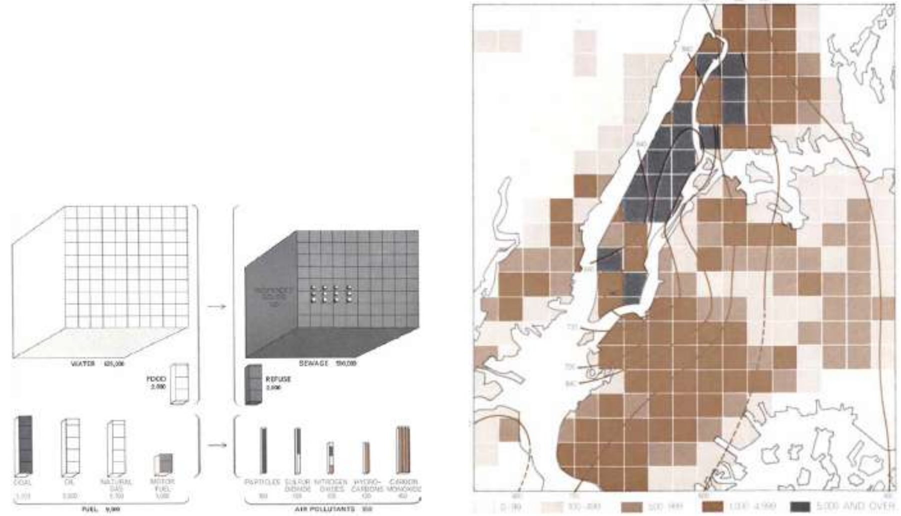
Finally, in 2022, the European Commission. Directorate General for Research and Innovation. (2022) presented a methodology to implement CE at a local and regional scale. The report collects and synthesises the ongoing research on circular cities and connects it with relevant policies. The report identifies seven key sectors crucial for CE: electronics, batteries, packaging, plastics, textiles, construction, and food. The document proposes a three-step process to develop and deploy circular solutions. The process starts by mapping the resources and establishing a baseline, defining policies, implementing them and monitoring their progress. As pointed out by other researchers, a critical point in managing resources is to study the material demand of the city that generates various material flows. One of the leading frameworks to study these materials flows is known as UM and has been identified as a critical analysis tool to determine the baseline of flows and understand how to transition to urban circularity (Brglez, Perc & Lukman, 2023; European Commission. Directorate General for Research and Innovation., 2022; Kalmykova, Rosado & Lisovskaja, 2015; Lucertini & Musco, 2022; Rosado, Kalmykova & Patrício, 2016)

Among the various proposed solutions to the current environmental problems, the concept of CE is perceived as a successful framework capable of delivering socio-economic development by restoring the environment. In recent years, the concept of CE has been helpful as a policy instrument that encompasses many aspects of mainly material sustainability. For instance, the CE Plan is a crucial aspect of the European Green Deal, responsible for setting a roadmap for carbon neutrality in Europe by 2050. Conceptually and at its core, CE calls for a paradigm shift in our current linear economic systems. Yet, this exploration of the literature has shown that many definitions and metrics focus on material circularity, and the systemic change of CE is challenging to capture and overlook. Although this PhD project does not extend, evaluate, or develop any further knowledge regarding the CE, the concept cannot be disentangled from waste prevention, management, and other strategies offered to minimise the amount of waste and pollution. Moreover, CE provides an adequate conceptual framework that concentrates arguments and motivates resource circularity. It offers specific strategies that will play a fundamental role in this research. The successful implementation of a sustainable CE in urban areas will depend on our comprehension of how materials, energy and information flow in the territory and the drivers that determine them. At the moment, information availability about the CE is still reported at macro-meso geographical scales, making developing and deploying territorial strategies difficult. The review also identified the importance of looking at UM as a necessary framework to study and develop insights to close material loops and transition towards more resource-efficient societies where less waste and less environmental damage are created.

2.2 Urban Metabolism

The growth, development and activities occurring in cities demand vast resources. Waste and pollution are generated as these resources are used and transformed to provision products and services. UM is a research area within Industrial Ecology (IE), and in both cases, metaphors are used to describe the complex processes that mimic nature (Ferrão & Fernández, 2013). The term focuses on the supply chains and production processes, emphasising how these activities affect the environment. Since cities and regions share similarities with ecosystems regarding their multi-scalar nature and complexity, efforts have been made to create self-sufficient systems that conserve mass through various processes. This approach seeks to mimic natural ecosystems within a defined boundary, leading to sustainable strategies for industrial activities. Since natural ecosystems are in material balance, the intention is to deliver cities that closely mimic these material balances. By keeping material balance and reducing environmental damage, urban systems are believed to become more resilient, healthier and ultimately more sustainable (Steward T.A. Pickett & Felson, 2014).

The first study of the UM of a city is often referred to as the work of Wolman (1965) work. This pioneering work introduced a model of a hypothetical population of one million inhabitants that pollutes its environment. Figure 2.4 presents parts of the analysis showing his conceptualisation of that hypothetical city's material inputs and outputs. On the left side, one can see the water, food, and fuels; on the right, he presents the outputs of such a system. This hypothetical example helps him illustrate the problem with the metabolism of cities. Towards the end of his analysis, he presents a map of the pollution in New York to show the most affected places in the city.



(a) Conceptualisation of materials flows of a city of one million residents.

(b) Map of New York City, showing the concentration of sulphur dioxide and particulate matter.

Figure 2.4: First Urban Metabolism Study. Source: Wolman (1965)

Similarly, the work of Howard Odum focused on energy flows instead of materials. His work is also perceived as groundbreaking in his efforts to formalise complex energy flow in ecology using circuit diagrams (Brown, 2004; Ramage & Shipp, 2020). Part of the novelty of his work was rooted in the abstraction and the vision of using notations used for electricity to illustrate energy flows in cities.

Since these initial developments, the field of UM has continued to be developed. As the possibility of gathering statistical information about cities and regions grew, it enabled the possibility of synthesising the information in Sankey-like diagrams as the one presented in Figure 2.5, to show the material metabolism of Brussels (Lachmund, 2017). These models and representations simplified the complexities and specificities of the city to communicate the flow of materials in cities.

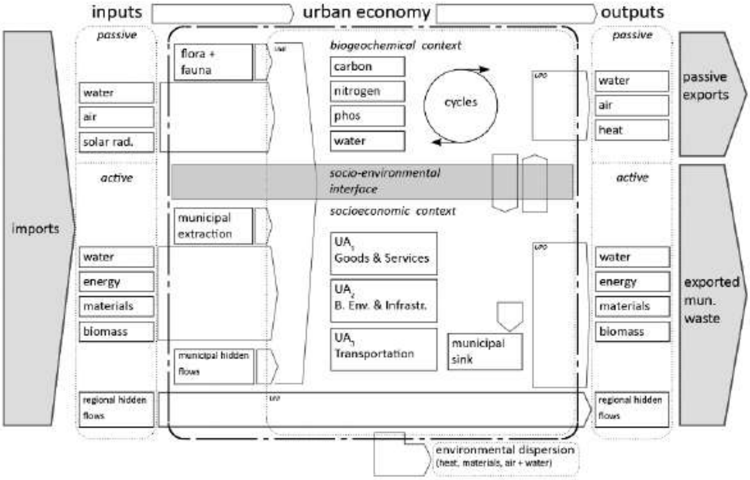


Figure 2.5: Updated Urban Metabolism framework (Ferrão & Fernández, 2013)

Kennedy and Hoornweg (2012c) defines UM as the "sum of the total technical and socio-economic processes that occur in cities resulting in the growth production of energy and waste elimination. The study of the metabolism of cities has borrowed tools from industrial ecology, such as material flow analysis and life cycle assessments, to assess the metabolism of cities. UM is a crucial tool to understand how cities transform materials". During this metabolic process, cities take material inputs and energy and transform those inputs to deliver mobility, health, recreation and other urban activities. This process also creates waste, pollution and energy dissipation through heat. Consequently, understanding cities' material and energy flow is critical to assessing their sustainability if we want to act upon environmental sustainability.

Developing a metabolic study of cities is complicated and requires much information and understanding of the context (Kennedy & Hoornweg, 2012c). This has hindered the production of such studies and resulted in drawbacks, including the knowledge of how urban processes relate to material demand and waste generation. As a result, efforts have been put on one side to mainstream the concept of UM as a framework, developing guidelines and structuring the steps to create such studies. Besides its usefulness, UM needs to be more than a data collection and resource accounting exercise Kennedy, Cuddihy and Engel-Yan, 2007; Weisz and Steinberger, 2010, “there needs to be a standardised, comprehensive UM framework, and some degree of agreement on which parameters, out of the many possible, should ideally be included in basic level reporting” Kennedy, Pincetl and Bunje (2011b).

Besides the challenges of pursuing UM studies, the framework has various limitations that make its application and usability difficult. UM is often considered a black box due to its complex and dynamic nature (Athanassiadis, Crawford & Bouillard, 2015). A methodological black box refers to a process or methodology where the inner workings or underlying mechanisms are not fully understood or transparent to the observer or user. It implies that while the inputs and outputs of the process may be known, the detailed processes occurring within the “black box” are unclear or not easily accessible.

The study of material flows in cities and regions encompasses a wide range of activities in the territory over a while. The accounting of these materials is complex, and the method does not offer the study of the drivers and consequences of these materials’ flows. Due to this complexity, fully understanding and modelling UM can be challenging. Many aspects of UM are not directly observable and may involve numerous interconnected feedback loops, nonlinear relationships, and uncertainties (Kalmykova & Rosado, 2015; Kennedy, Pincetl & Bunje, 2011b; Kennedy, Cuddihy & Engel-Yan, 2007; Song et al., 2018).

Several authors have enriched the UM framework in many ways. Although the list of studies and projects is extensive, various projects have advanced in developing data standards and data models to establish a common ground (Sileryte et al., 2022; Sileryte, Wandl & Timmeren, 2023). Conceptually, the work Newman (1999b) proposes an extended model capable of incorporating various aspects of urban life into the model and some others like hidden material flows Barles (2009) in space and time Kennedy, Cuddihy and Engel-Yan (2007), Lavers Westin et al. (2019) and Rosado, Kalmykova and Patrício (2016). In the search for more holistic models, Smeets, Weterings et al. (1999) presented a framework to study the interaction and casual relationship between humans and the environment. The framework identifies *drivers*, such as economic activity, and puts *pressure* on an environmental system that changes its *state*. Later, various Environmental Agencies expanded and adopted this model as a core tool to assess environmental changes (Tscherning et al., 2012b).

Some other studies have profited from new data sources and Internet of Things (IoT) devices to exploit new data sources and significant volumes of information to deliver real-time information about how resources flow in cities (Shahrokni, Levihn & Brandt, 2014). New data sources have been used to improve techniques to potentially share waste material across industries or even determine the number of materials (Patricio et al., 2017; Patricio, Kalmykova & Rosado, 2020) and footprint of the built environment (Gontia et al., 2018; Kolkwitz, Luotonen & Huuhka, 2023; Lanau & Liu, 2020). Finally, another set of studies has focused on explaining the relationships and interdependence of various actors. These studies use new simulation techniques and are capable of exploring what-if scenarios to assess policy or situational changes (Davis, Nikolic & Dijkema, 2008; Hicks, 2022; Koide et al., 2023; Lan & Yao, 2019; Micolier et al., 2019; Raimbault et al., 2020).

2.3 Urban Analytics

Urban analytics has many definitions and is a term that has permeated the daily lives of those who work with quantitative urban challenges such as transportation, pollution, and segregation, among others. According to Batty (2019), "Urban Analytics is a core set of tools employed to deal with problems of big data, simulations, and geo-demographics." To some extent, it deals with techniques of capturing, handling and making meaningful insights into complex problems with the aid of computing. Urban Analytics is also related to a more excellent pursuit of city science. According to Batty, this is the quest of premises to help us improve, correct, and organise how we live in urban areas. Urban analytics and informatics have experienced a remarkable surge in the past decade, fueled by the proliferation of lower-cost sensors, advanced data servers, ubiquitous technology, and the widespread adoption of object-oriented programming. The growth and development of urban analytics are closely tied to the presence of robust systems and sensors. This symbiotic relationship has sparked a revolution in urban analytics, driven by the ubiquity of technologies like GPS, LiDAR, digital twins, and climate sensors. These innovations have facilitated the capture of unprecedented information, empowering planners to enhance transportation systems, study heatwaves, analyse canopy coverage, investigate segregation, and much more.

In recent years, advancements in urban analytics techniques have significantly contributed to our understanding of UM dynamics. These techniques encompass a wide range of methodologies, including simulations, data modelling, geographic information systems (GIS), decision support systems (DSS), and extensive data analysis (D'Amico et al., 2022).

Chapter 3

Research design and methods

3.1 Research design

The work has been organised into two parts to respond to the research questions and meet the objectives stated in Chapter 1. A general framework was developed in the first part, and a set of applications was further developed in the second part. Figure 3.1 maps these two parts, the research questions addressed and the resulting articles from each component.

Although the first part of the thesis mainly addressed RQ1, answers to this question can also be found in the second part. RQ2 was addressed in the second part of the research project.

The starting point of this research can be identified during the development of Paper a. This article is not included in the dissertation because it focuses on developing methods for transport and mobility in cities. Still, it inspired me to reflect upon the methods, data, and tools available for city resources and waste management. Without going into details about the study, it takes advantage of standardised data on transport to propose a reproducible approach to studying traffic congestion in cities. The approach advances transport research in various aspects. First, the method uses standardised open-source data. This feature makes this process accessible to others, allowing future improvements in the methods.

Moreover, the same method can be applied to different cities because the information is standardised. Eventually, as long as the information is available, the same study can be performed for various periods, allowing the study of the evolution of congestion in cities. The central technology that enables this sort of study and that, to some extent, has revolutionised the field of transportation is data availability in a standardised form. The learnings from this study steer the dissertation with purpose and direction.

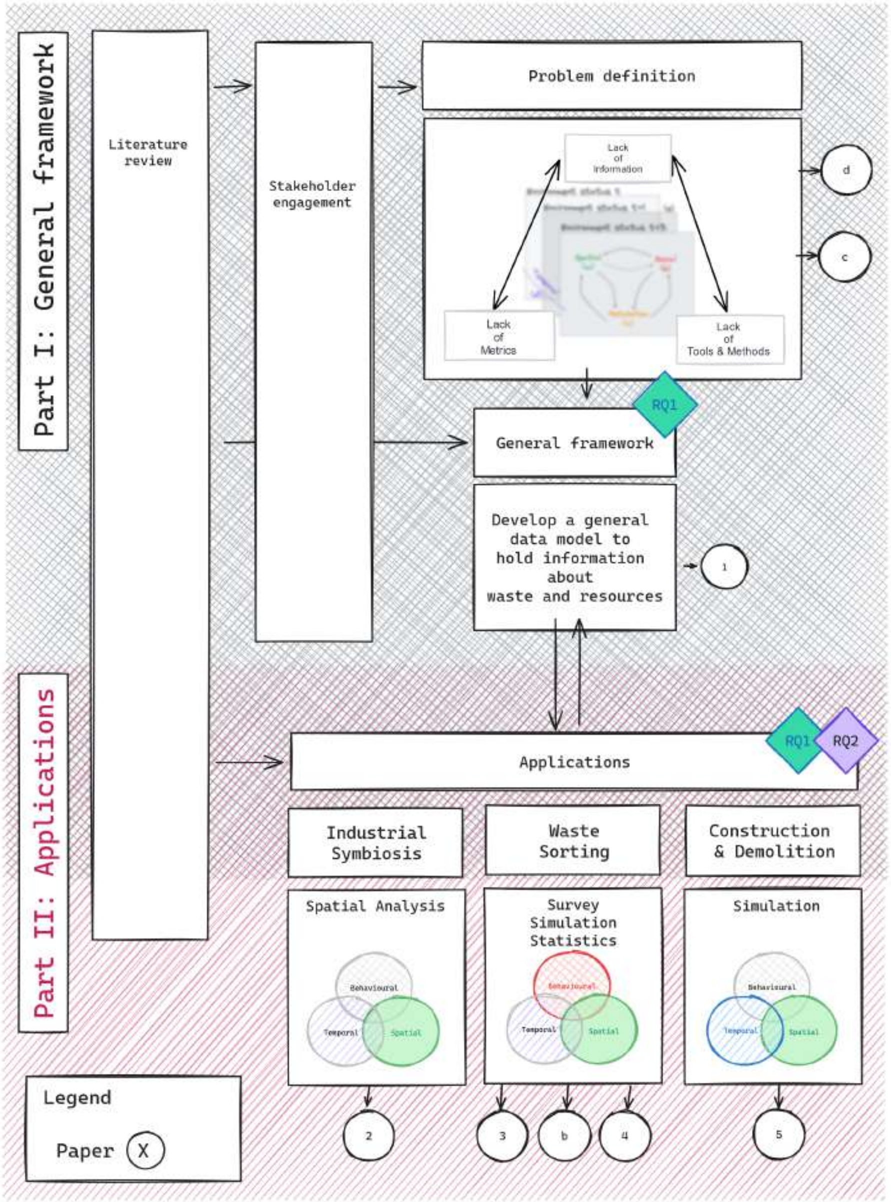


Figure 3.1: Research process followed during the Ph.D. project. Each of the papers developed during the project is indicated with numbers and letters if they were not included in the thesis

The first step of the research involved conducting a broad literature search about previous efforts to standardise information to manage waste and resources in cities or digital tools and methods to evaluate environmental progress in cities. Soon after this initial stage, the problem defined in Chapter 1 started to rise, and the need to engage with practitioners became evident. It was necessary to understand how local authorities, the private sector and other stakeholders working to meet environmental targets were utilising digital tools and managing knowledge. During this initial period, several actors were contacted, and after a set of meetings, the main problem addressed by this project was defined. The next step was to develop a data model to hold this information.

After developing a general framework to handle information about city resources, interview inputs were used to create a set of applications to validate the general framework. The applications demonstrate how the framework can be utilised in situations like Solid Waste Management, the Construction and Demolition (C&D) sector or Industrial Symbiosis (IS). The main results of this research are reflected in Paper 1, and outcomes of the different applications are reflected in the other various papers as shown in Figure 3.1

The purpose of the second part was three-fold. First, the development of various applications contributed to validating the general framework by providing examples of how the framework can be applied. Second, the applications were further explored using UA and contributed to demonstrating such techniques' potential. Finally, these applications contribute to highlighting the various dimensions to be explored and bring answers to RQ2

The methodological details followed in each study are detailed in each of the papers, and a general description of the methods is introduced below.

Research approaches

This research adopts three distinct approaches: exploratory, transdisciplinary, and deductive. Firstly, it primarily aligns with exploratory research, as the questions that are pursued are open-ended and lack definitive answers. Furthermore, the research objectives aim not to validate hypotheses but to demonstrate the potential of UA tools or methods in enhancing the understanding of city material flows. In essence, this research explores a relatively new or less-explored research domain. Following Silva et al. (2014, Ch. 2) exploratory research *"focuses on relatively unknown or little understood phenomena to generate more specific research questions for subsequent descriptive or explanatory studies"*.

Secondly, this dissertation fits the description of transdisciplinary. Polk (2014) and Renn (2021) proposes three arguments to understand when it is suitable to follow a transdisciplinary approach. **(One)** The research benefited non-academic stakeholders because non-academics were contacted at different study stages to comprehend the challenge better and discuss potential solutions. **(Two)** related to system thinking, the topic is broad and demands mastering a vast range of competencies. In this case, it required comprehension of urban analytics, specific urban domains such as waste management or construction and demolition and topics within industrial ecology. **(Three)** Finally, academics and practitioners research to find an equilibrium between social relevance and academic rigour. Also, transdisciplinary research has an orientation toward the common good and focuses on specific, complex, societally relevant, real-world situations or problems (Lawrence et al., 2022). This approach motivates academics to leave the ivory tower's comfort and produce appropriate results for their communities (Lang et al., 2012; Sauvé, Bernard & Sloan, 2016). Moreover, the transdisciplinary approach is most suitable for addressing questions and issues characterised by uncertainty and complexity. So its link to spatial planning issues and problems is potentially very significant (Silva et al., 2014)[p.5].

This research also falls under an inductive approach because it departs from facts to provide answers to the main research questions (Miller & Brewer, 2003). Certainly, normative statements or theories are worth examining in a deductive approach. Still, lack of information or improper match between data specifications and research questions impose barriers to developing knowledge under this approach. For example, to know if the amount of resources shared by industries increases as the distance between them decreases, we need information about those exchanges.

Research scope

The scope of this research is delimited by intersecting strategies to close material loops and relevant geographical scales for urban and regional planning. The strategy that delimits this research originated in the R´s strategies, which CE is based upon. UA define the methodological scope addressed during this research. The inclusion of case studies adds granularity to these research boundaries. These delineations are visually represented in Figure 3.2.

From the Circular Economy perspective, the dissertation exclusively engages with materials and their associated emissions, deliberately excluding considerations of water or energy. Despite the broader recognition of the CE as a paradigm with potential social and economic benefits, this research uniquely focuses on material circularity, leaving aside political, economic, or social concerns. Moreover, given that less than 10% of the resources are being reused, this work focuses on closing material loops relevant to urban and regional planning. It focuses on (i) Industrial Symbiosis, (ii) Urban Mining, and (iii) Residential Waste Management.

These areas were selected based on the literature review and round interviews that helped validate the general framework and answer RQ1. First, Industrial Symbiosis was chosen because it is an essential and recurrent strategy focusing on closing material loops by exchanging by-products across firms. This case was also a result of data availability, and the wood sector was selected because this sector was used to validate the methodology developed in Paper 2. The second application explores urban mining in the C&D sector. Again, this case study was selected due to the insights and challenges shared during the round of interviews aimed at developing the data model. Finally, the application for Residential Waste contributed to exploring how the data model can be implemented at a smaller geographical scale while integrating a rich behavioural dimension. Overall, further exploring the applications was organic and resulted

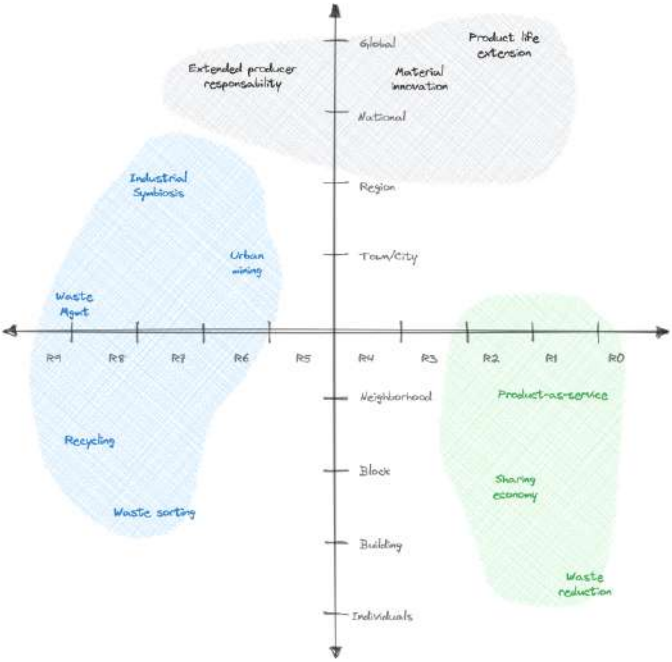


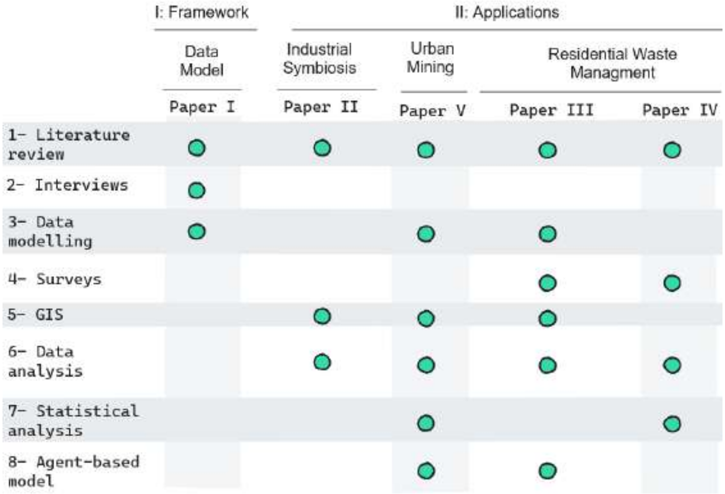
Figure 3.2: scope of the dissertation in terms of CE and spatial scales

in the combination of data availability, researchers' fields of expertise, and personal contacts that facilitated the interviews. These applications are not exhaustive but illustrative, and more instantiations and explorations can be further developed.

From the UA perspective, the dissertation centres on the role of digitalisation, explicitly concentrating on knowledge management, metric development, and simulations. The main focus of the dissertation is a set of problems of quantification.

3.2 Methods

Specific methods were used in each study pursued during this research to meet the objectives and provide answers to the research questions previously stated. Most of these methods employ UA to pursue the research objectives. Table 3.1 summarises the various techniques used during the project. The methods used throughout this thesis are briefly introduced as they were applied in different applications.



	I: Framework	II: Applications			
	Data Model	Industrial Symbiosis	Urban Mining	Residential Waste Managment	
	Paper I	Paper II	Paper V	Paper III	Paper IV
1- Literature review	●	●	●	●	●
2- Interviews	●				
3- Data modelling	●		●	●	
4- Surveys				●	●
5- GIS		●	●	●	
6- Data analysis		●	●	●	●
7- Statistical analysis			●		●
8- Agent-based model			●	●	

Table 3.1: Tools and methods used in the various articles

3.2.1 General framework

The steps followed to develop the general framework were adapted from previous methods for building information systems in Storey (1991), and can be decomposed into four main activities: (i) Desk literature survey, (ii) Engagement with stakeholders, (iii) Development of the data model, and (iv) Validation using case studies. Activities (i) and (ii) helped understand the system, identify the problems and case studies, and set the solution's scope in light of related efforts. With the support of these activities, the model was designed and developed in activity (iii). Activity (iv) consisted of evaluating the main output of this research.

The stakeholder engagement phase used semi-structured interviews and workshops with different stakeholders to complement and validate knowledge gained from the literature survey. Interviews are standard research methods to collect data and systematically gather participant information. Semi-structured interviews are a type of interview method that combines elements of both structured and unstructured interviews. In semi-structured interviews, the researcher has a predetermined set of questions or topics to cover but allows flexibility in the order and wording of questions and encourages open-ended responses from participants. This approach enables the researcher to explore specific issues in depth while allowing for spontaneous conversation and new themes or insights to emerge during the interview. Semi-structured interviews are beneficial when exploring complex or sensitive topics where participants' perspectives and experiences are valuable (Dolczewski, 2022).

Although there is no single method to develop a data model, using interviews to extract stakeholder understanding is common practice when creating digital solutions (Gupta et al., 2019b). The interviews provided first-hand information on how practitioners are managing waste materials and how the digitalisation process of information can enhance their practices. Table 3.2 provides information on stakeholders and interview stages.

		Interviews & Workshops			
Stakeholder group	N	SI	SII	SIII	Total
Representatives of waste management units (public sector)	7	7	5	3	15
Tech developers	6	2	4	3	9
Domain experts (non-public)	4	-	4	3	7
Total interviews		**9**	**13**	**9**	**30**

Table 3.2: Interviews with stakeholders

Three groups of stakeholders were consulted at different stages: (i) public sector staff from municipal waste management or environmental departments; (ii) tech developers; (iii) domain experts from the fields of UM, CE and data management. Although all these stakeholders work in different areas to improve environmental quality or minimise waste, their focus and understanding of the system vary and, thus, are complementary.

Three types of interviews were performed. Initial contact was established during the first round of interviews (SI). Semi-structured interviews were used to understand better the actors' challenges and how the system operated. The second interaction was a workshop (SII), where the first version of the data model was presented to verify if any system components were missing. This workshop helped map the different actors and their roles in the system. Finally, the last interviews (SIII) validated the model applied to the specific use cases of each stakeholder and explored how KM could be used in their practice.

The development of the data model started by producing a conceptual model that was then formalised using a framework known in computer science as Entity-Relationship Model (ERM), which is used to provide a detailed representation of the system components as *entities*, explicitly defines their *relations*, and represents the set of characteristics that describes those entities as *attributes*. Figure 3.3 shows two *entities* related to each other. The diamond shape in the middle indicates the relationship's cardinality, where there can be many (n) of Entity A related to one (1) Entity B.

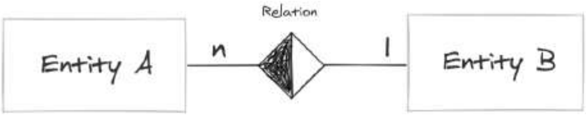


Figure 3.3: ERM - notation Rein85

For instance, a waste bin is an entity, and colour is one of its possible attributes. The waste bin can be owned by a firm (another entity). Thus *ownership* defines the relationship between the firm and a waste bin, of which a firm can own many.

The development of the ERM is a crucial step towards a database architecture. Entities, attributes and relationships can be translated into different types of database management systems, such as hierarchical, graph, or relational. In this case, we used a relational database schema to demonstrate how the ERM can be implemented. A relationship is a formal link between two entities or, in this case, tables. Usually, an ID attribute is used to connect information between them.

Thanks to the interviews and knowledge gained during the first study, selecting a specific set of applications to reflect upon RQ2 was possible. These applications were chosen to highlight the three dimensions that this dissertation contributes to explore: Spatial, Temporal and Behavioral. All these applications are based on the fundamental research developed in Paper 1. Therefore, for every application, reviewing the previously developed models was necessary.

3.2.2 Applications

The second part of this thesis focused on further developing the applications used to validate the general framework and showcasing how data analysis and simulations can be used to explore the spatial, temporal, and behavioural aspects of material flows.

Although it is expected that the findings or methods of this PhD project will be replicable and generalisable in various contexts, specific contexts were used to test and validate the findings. All the applications were developed for the Swedish context within the western region (Västra Götaland). On the most extensive scale, the whole area was considered when exploring the case of industrial symbiosis. Then, at the city scale, Gothenburg was used to analyse material flows and the environmental impacts of the construction and demolition case. Finally, in the case of Solid Waste Management, the geographical scale was reduced at the neighbourhood level, and two locations within the city of Gothenburg were selected and further explored.

Industrial Symbiosis in Western Sweden

To explore potential material exchanges across industries This example analyses residual sawdust, shavings, cuttings, wood, particle board, and veneer (LoW 30105). The linear distances between potential donors and receivers were calculated based on the geographical location of the companies. This section demonstrates how spatial proximity can be used to identify realistic IS opportunities by applying different filters to the Matches database, A total of 2,520 companies located in the region were analysed. Figure 3.4 The following map shows the explored area with the location of all the wood industries researched. These industries have been categorised depending on whether they are potentially producing or consuming materials classified as LoW 30105.

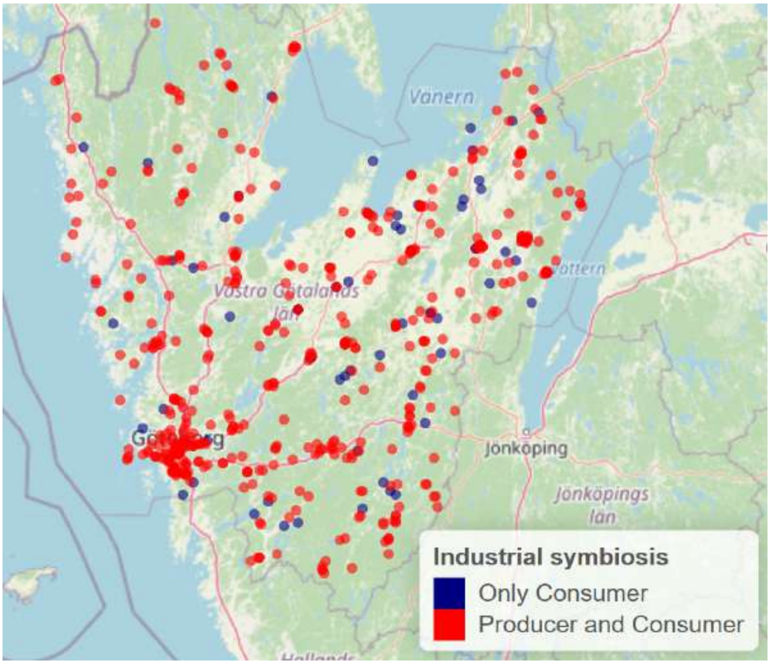


Figure 3.4: Map of the location of wood-related industries

Methods

This application mainly focused on exploiting the location of industries to identify which industrial exchanges can occur in a specific region. The tools used for this application mostly were data management and Geographic Information System (GIS). While commonly used for map creation, the true power of GIS lies in its ability to collect, manage, analyse, and display geographic information for various purposes beyond cartography. GIS facilitates the connection between physically drawn features and their associated attributes, providing valuable insights into geographic features' shape, size, location, and characteristics. This information aids in understanding the condition of material flows, waste, logistics, etc. The primary purpose of this application was to reflect on the spatial dimension, and the main outputs of this activity are reflected in Paper 2.

Construction and Demolition in Gothenburg

The city of Gothenburg is located in the western region of Sweden, with a growing population of above 600 thousand residents. By the year 2035, it is expected that approximately 150 thousand more residents will live in the city. The increase in population pressures the production of adequate and sustainable new housing units. Figure 3.5 presents the future vision for the city and the areas that will be further developed.

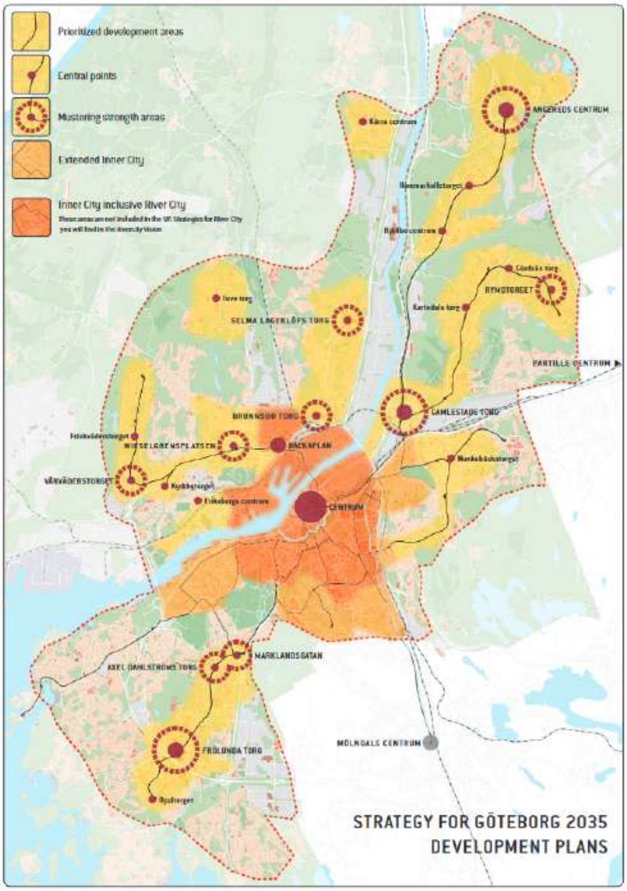


Figure 3.5: Vision of future Gothenburg 2035

By 2035, to host the population, the city should enable the development of 45-55 thousand more homes, which means that around 2.5–4 thousand homes are needed (Planning and Building Committee, 2014). The city has aggressive goals regarding carbon neutrality, which means that (City of Gothenburg, 2021). The program focuses on three axes: nature, climate and people. Within the climate objectives, the program aims to reduce the CO2e per person per year from 4.2 tons to 1.1. To meet this target, the primary energy consumption needs to decrease to 12MWh per person. This will imply increasing the energy efficiency of residential buildings.

According to the Lantmäteriet (Swedish National Land Survey) database, there are 6689 multi-family buildings and 49,556 single-family units. The information about residential buildings also contained information about the construction year (or significant renovation) and the primary material of the building, such as wooden, concrete or brick residences. Using the Material Intensity Coeffcieint (MIC) developed by Gontia et al. (2018), it was possible to enrich the database of the buildings with various materials per building. Figure 3.6 shows the Municipality of Gothenburg, a population grid, and the residential buildings according to their typology.

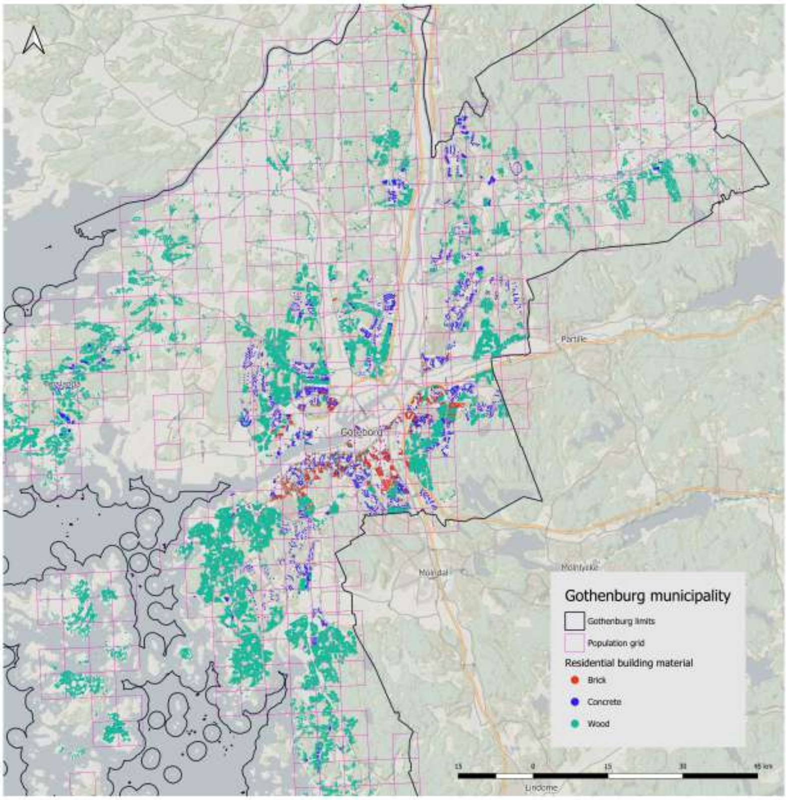


Figure 3.6: Residential buildings and main materials (brick, concrete and wood)

Methods

The application focuses on temporal and spatial dimensions of the C&D. This application uses Agent-based Model (ABM) and data analysis to study construction and demolition material flows.

ABM are computer models comprising agents or variables capable of taking on finite states. The state of each agent is determined by a set of rules governing its interactions with other agents, and these rules can be either deterministic or stochastic. ABMs are increasingly employed in multidisciplinary research that tries to incorporate a holistic situation perspective. They offer an intuitive formulation and can be explored via a graphical interface, making them accessible to researchers from diverse disciplines. The concept of complexity in ABMs arises from these agents' various interactions and behaviours. This promotes interdisciplinary research, as specialists from different fields can utilise agent-based models without an in-depth understanding of the underlying mathematics. At the same time, mathematicians can still analyse the mathematical structure of the models concurrently (Grimm et al., 2020; Held et al., 2014; Monti et al., 2023). The outcomes of this research are synthesised in Paper 5.

To develop the simulation for this study, we integrated various data sources, with the initial dataset originating from Lantmäteriet. This comprehensive geodatabase served as the foundation for initialising the simulation. Figure 3.7 presents the different data sources integrated to develop the simulation base.

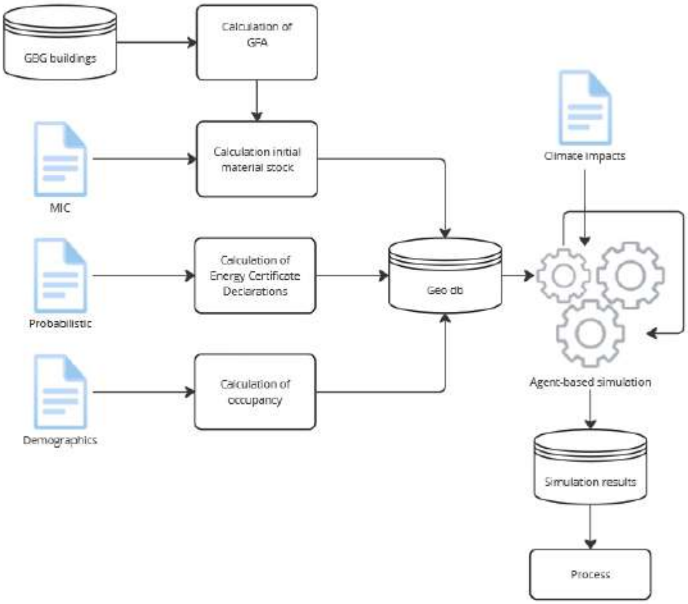


Figure 3.7: Data preparation for base information for simulation of Construction and Demolition

Initially, the database comprised data on residential buildings throughout Gothenburg. These records contained essential information about the geographical area and each building. By leveraging details on building height, we estimated the Gross Floor Area (GFA). Subsequently, outliers were meticulously removed from the database, resulting in a refined dataset of buildings, each accompanied by its corresponding GFA.

The subsequent phase involved augmenting the database with information about the materials used in each building. Material intensity coefficients, referenced from the research conducted by Gontia et al. (2018), were employed. This comprehensive study covered material intensity across the entirety of Sweden. The database categorised different materials per GFA based on various typologies, accounting for whether it was a single or multi-family dwelling and the decade of construction. Information from Boverket (Swedish housing authority) was used to translate each material to a specific value of CO_2e.

Given our interest in understanding the potential impact of the energy certificate declarations policy on the new housing stock in the city, we sought to incorporate information about energy performance. As citywide implementation of energy performance data was still under development, we adopted a stochastic and probabilistic approach to define an Energy Performance Declaration (EPD) for each building. This approach considered both the age of the buildings and the materials used, such as wood, concrete, or brick.

The final piece completing the initial state puzzle involved integrating population data from the city of Gothenburg at a grid resolution of 1 kilometre. This data was incorporated by analysing buildings' distribution and heights within each grid. Consequently, we estimated the number of people and households associated with each grid. The resulting database encapsulated crucial details such as the year of construction, building materials, building height, typology (single or multi-family), and energy performance declarations. This comprehensive database served as the cornerstone for initiating our simulation. The subsequent section describes the agent-based simulation process and the various scenarios explored during its development. Figure 3.8 shows the overall processes in the simulation. The simulation features four key agents: building, recycler, planner, and city area, with buildings serving as the primary agents.

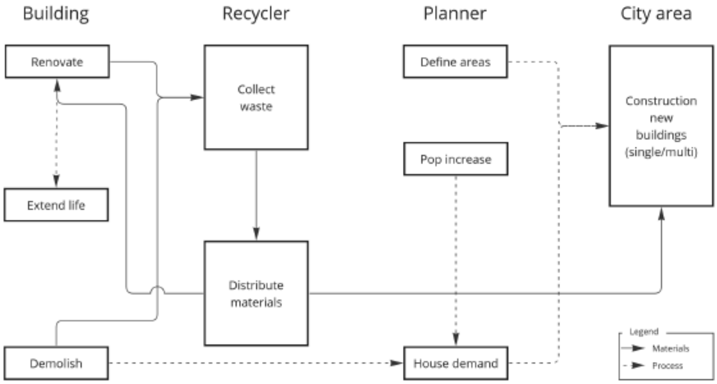


Figure 3.8: Agents present in the simulation and their scheduling

The simulation is run from 2010 until 2100, and every step is five years. In this model, each building acts as an independent decision-making entity, determining when to renovate or undergo demolition. Renovation triggers a demand for materials, be they virgin or recycled, and demolition increases the recycled material at the recycler. Figure 3.9 shows a schema of the processes of the buildings. This flow diagram shows the different processes each building faced during the simulation. Based on the year of construction, the model assumed an estimated end of life of the buildings, and when this time approaches, they must be renovated or demolished. On the one hand, renovations require materials; on the other hand, demolitions make materials available for reuse. Material available for reuse can eventually be used in new constructions.

Although the model anticipates multiple recyclers, it operates with a single

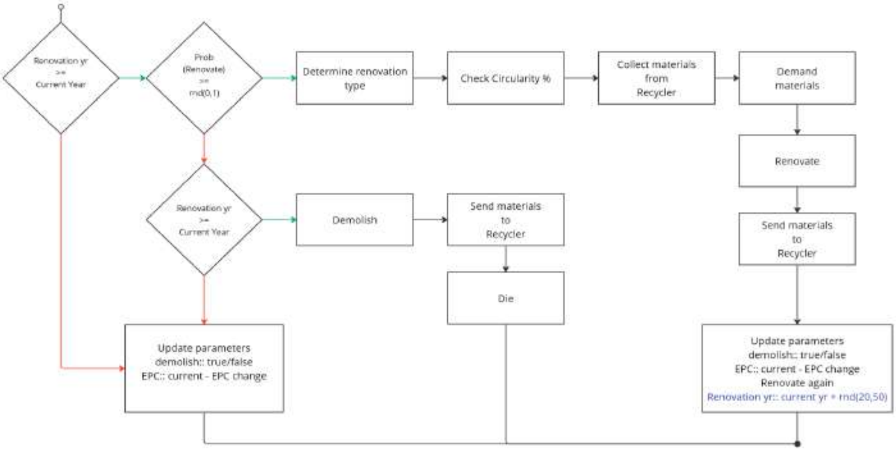


Figure 3.9: Actions modelled for the buildings life cycle

recycler, functioning as a material collection and distribution broker. The recycler is the last agent to execute the simulation, handling aggregations and CO_2e estimations. The fact that the model can include several recyclers allows one to study the problem's logistic side. The planner, another essential agent, considers population increases and lost housing due to demolitions. Population demographics inform the construction of new houses, crucial for replenishing housing stock lost in demolitions. Influenced by a parameter defining housing technology percentages, the model allocates the population demand across single or multi-family units. The implementation dynamically adjusts the distribution, impacting material requirements and the city's embodied carbon. The city area agent defines areas based on the population grid, leveraging officially published data with attached population information. Over 200 squares, serving as agents, receive input from the planner regarding the required number of buildings. At each step, these squares decide whether to build or not. While the current model employs a random selection process, it is adaptable to incorporate diverse building rules, such as prioritising high-density areas first or experimenting with alternative building sequences.

Finally, after the heuristics of the model were coded into the ABM, the simulation was able to perform as expected. The simulations were run several times with different parameter settings to study how changes in the system affect the overall system performance regarding material use and environmental footprint.

Solid Waste Management in low- and high-density city areas

Two distinct urban scenarios were selected in the city of Gothenburg to explore the role of urban planning in the behaviour of waste sorting. A map of the recycling stations in the town was used to do so. In Sweden, in response to the producer responsibility law, companies affiliated with a non-profit organisation called Förpacknings- och Tidningsinsamlingen (FTI) - in English Packaging and Paper Collection - place and maintain recycle stations across the city. Residents must dispose of plastics, metals, glass, papers, and other recyclable materials here. FTI then collects and recycles this material. Figure 3.10 shows a map of the location of the recycling stations provided FTI.

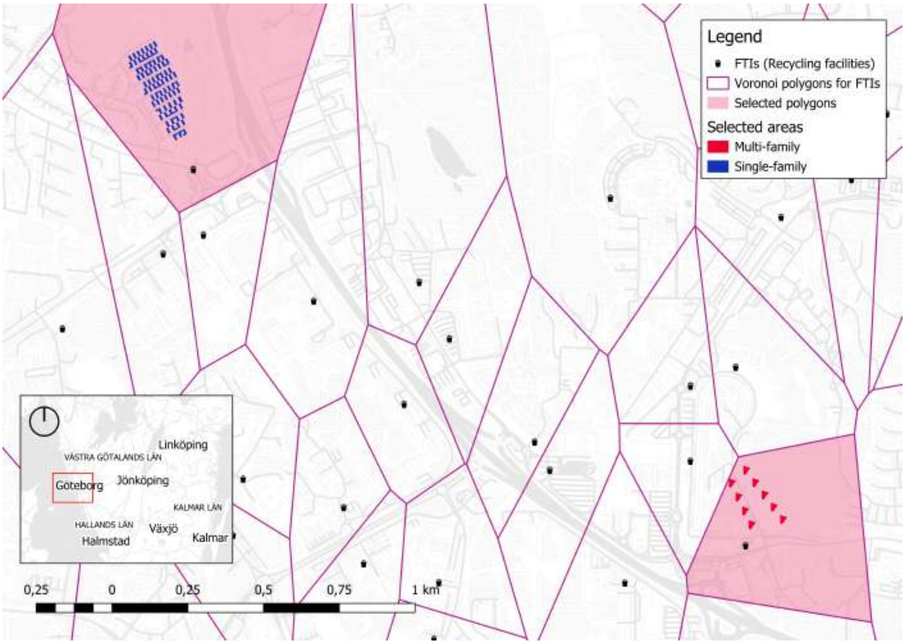
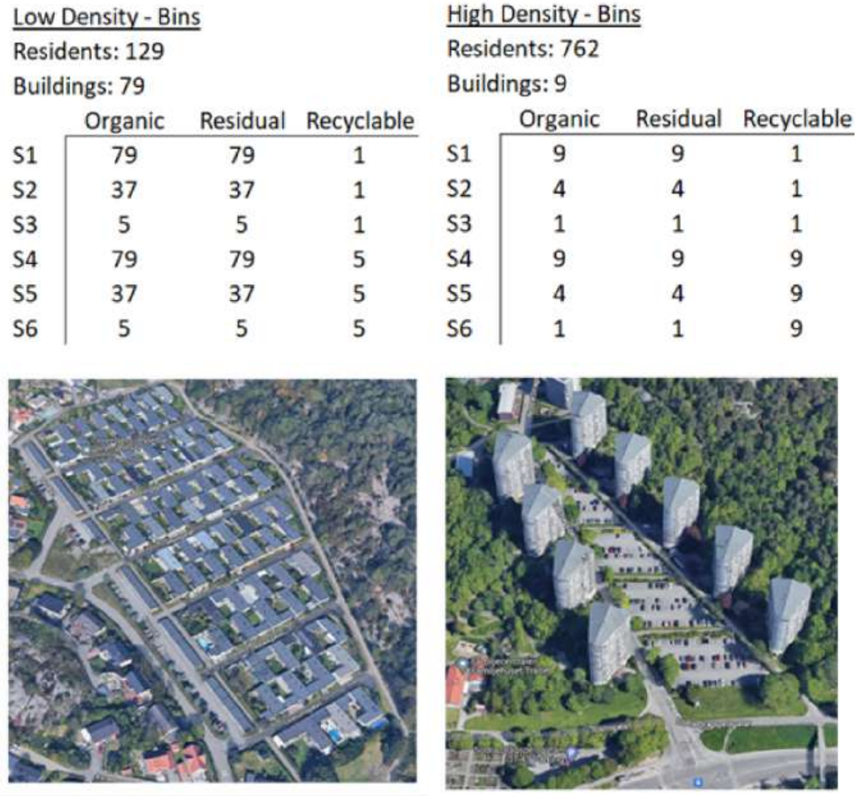


Figure 3.10: Map of recycling stations in Gothenburg. Voronoi polygons, per station and selected case study of single- and multi-family buildings.

The map includes Voronoi polygons that delineate proximal areas around each recycling station. Finally, it explored two city areas that mainly contained a residential typology. The map shows the location of a low-population-density neighbourhood of single-family buildings within one of the Voronoi areas. The process was then repeated to locate a higher population density area with multi-family buildings.

The characteristics of these two areas are presented in Figure 3.11. The low-density case study has 79 houses, and 129 residents live here. In this case, every house owns two waste bins: one for residual waste and another for exclusive disposal of organic material. Figure 3.10 shows only one recycling station is found within this neighbourhood's Voronoi area. The high-density scenario is represented by an area with nine buildings and 762 residents.

In both scenarios, there are multiple urban situations (S1 – S6). Situation 1 (S1) represents the current situation. In situations 2 and 3 (S2 & S3), the recycling station is kept in the same place as in S1. Still, the number of residual and organic bins is reduced so that the distance to bins increases and the interaction between agents increases. In situations 4, 5, and 6, the number of recycling stations increased while keeping the locations of the residual and organic bins from S1, S2, and S3. To sum up, S1, S2, and S3 allow the study of the effect of the current location of the recycling station while increasing the distance to dispose of residuals and organics. Then, S4, S5 and S6 allow the study of the effect of reducing the distance of the recycling stations while the distance to the other bins increases.



Low Density - Bins
Residents: 129
Buildings: 79

	Organic	Residual	Recyclable
S1	79	79	1
S2	37	37	1
S3	5	5	1
S4	79	79	5
S5	37	37	5
S6	5	5	5

High Density - Bins
Residents: 762
Buildings: 9

	Organic	Residual	Recyclable
S1	9	9	1
S2	4	4	1
S3	1	1	1
S4	9	9	9
S5	4	4	9
S6	1	1	9

Figure 3.11: Selected urban scenarios to study residential waste sorting. Google images of areas and characteristics.

Finally, the model assumes that, on average, the resident produces 723 grams of waste (115 of organics, 430 of residual and 178 of recyclables. According to the Swedish Waste Management Report, approximately 60% of the waste found in the residual bins could be recycled, and almost 200 kg of waste per person was collected in 2021 (42kg of food waste and 157kg of residual). This information was complemented with the amounts of recyclable material recovered by FTI (65kg) to determine the number of recyclable wastes. With these figures, we can estimate that residents who do not sort waste and throw all waste in the same container will be adequately throwing the amount that genuinely belongs to residuals, 60%.

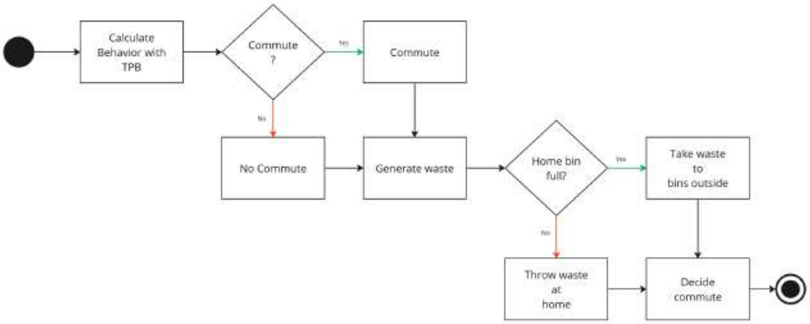


Figure 3.12: Residents behaviour heuristics in the ABM

Methods

The primary purpose of this application was to explore the relationship between the behaviour of residents and the placement of various waste bins. Exploration of this application required first developing and deploying surveys to determine waste sorting behaviour. The development of the survey, data collection and statistical analysis are presented in Paper 4. The data collected from the surveys were analysed using factor analysis and the Structural Equation Model (SEM) to study the determinants of waste sorting. The results from this study helped to understand and explore the intricate behaviour of waste sorting.

The relationship between the location of bins, the behaviour of residents and the amounts of sorted waste are exposed with a simulation. Paper 3 presents the development of a simulation that integrated the results from Paper 4 and embedded the residential behaviour to asses various urban scenarios. The model was developed using a spatially explicit Agent-based Model (ABM), and the model development was documented in Paper b using the Overview, Design concepts, and Details (ODD) protocol Grimm et al. (2006).

The ABM of residential waste sorting contains various agents, such as residents, buildings, households, waste bins and bin collectors. Buildings and households are agents used to initialise the world, and waste bins are the placeholders of the material disposed of by the agents. Since this study aims to showcase the relevance of ABM in urban planning for resource management in cities, only the model's main characteristics are described in this section.

The model was developed to represent a whole year, and every step in the simulation represents a third of a day. During each step, the residents execute actions defined in their daily routines. The main agents of the model are the urban residents. Based on their behaviours, the residents make different decisions on how to sort their waste. Each agent has a designated home with the closest organic, residual, and recyclable waste bins and a workplace. During each step, the agent follows a daily routine that includes commuting to work, generating waste, defining their behaviour, disposing of the trash at home and later transferring it to the waste bins.

Figure 3.12 presents the residents' actions during every simulation step. First, each agent calculates their behaviour using as a framework a behavioural model. Second, the agent's commute is based on the probability of heading to work. The waste generated away from home is outside the scope of this study. The agents staying at home receive a sum of organic, residual, and recyclable waste they need to dispose of in their waste bins at home.

After a functional model that met the standards was developed, its performance was assessed through a sensitivity analysis. This enabled insight into how varying inputs influenced the model's outputs. The model was utilised and documented multiple times using a particular set of parameters.

Chapter 4

Results

4.1 General framework for waste and resources in cities

Given the outstanding challenges of digitalisation in the waste and resources management domain and inspired by the examples from other domains, two objectives were addressed. First, a general framework is proposed to manage knowledge about city waste and resources. The approach uses ERM Framework to offer a data model about city waste and resources. Second, parts of the model are then applied to different CE strategies and tested to what extent such a model holds other purposes within the domain.

The primary outcome of the framework development was the data model for the circular flow of waste and resources in city regions (CFWR). As described in Paper 1, it contributes to mapping relevant stakeholders that manage city resources. Moreover, the data model was designed to map in space how material flows in, moves around and exits urban systems.

The first step was to produce a general representation of the minimum components needed to describe the flow of waste and resources in a general descriptive way. The conceptual diagram in Figure 4.1 proposes four main possible actions (in circles): (a) using, (b) generating, (c) transforming, and (d) storing. Different actors can perform these actions, and each can perform many activities within the system. Then, we wanted to incorporate the relation to space (5), and as physical objects, waste and resources are materialised in space. Usually, the materials are in specific spaces or objects called containers (1). Finally, transportation was included in the representation because it contributes to moving the sums of materials across space.

This conceptual diagram was translated and formalised using ERM, a foundation for creating a relational database schema. Figure 4.2 presents the proposed ERM of waste and resource management in city regions, focusing on the relationships between entities so that these can be described and visualised correctly. The attributes of each entity were extended in a relational database schema.

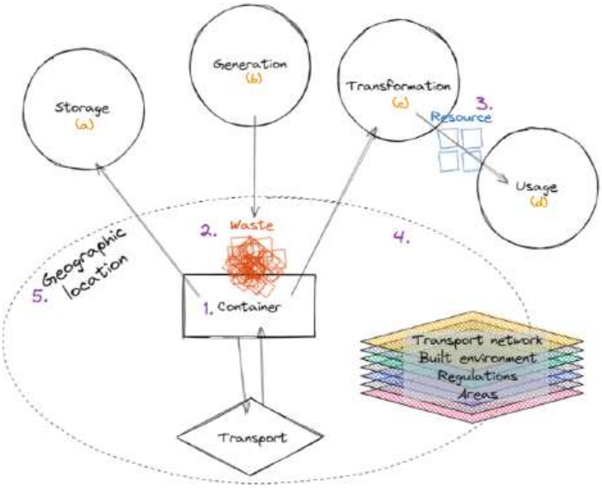


Figure 4.1: The Conceptual Diagram of Circular Flow of Waste and Resources

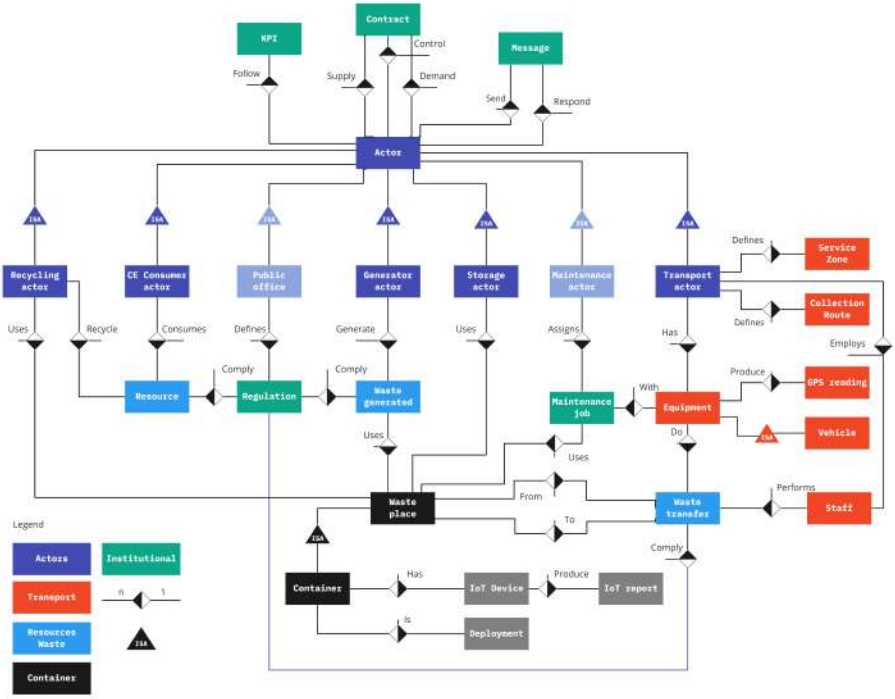


Figure 4.2: Entity Relationship Model (ERM) for waste and resources management - Rein85 notation

The development of such a model would not have been possible without the various interviews and inputs from different actors. The model results from collecting challenges and perspectives from other potential data users. Municipal officials and practitioners were consulted about their information needs and current practices. The model was instantiated for different cases and tested to see if such a model could be of use for other cases. More specifically, the model was implemented for the cases of (i) municipal waste sorting, (ii) industrial symbiosis and (iii) construction and demolition. In the following subsection, the three cases are presented and further explored.

Stakeholders considered the entity-paradigm framework to discuss CE strategies. More specifically, in the cases where simulations or agent-based models were considered, the ERM was formally implemented as class diagrams, which have been made public for future and constant improvement. Besides showing what data is available and how each class relates to another, these data models enable stakeholders to discuss what other information is missing and give an idea of what metrics and KPIs can be derived to evaluate the system.

The final data modelling step was the translation of the Circular Flow of Waste and Resources ERM to a relational data model schema. As a final step of this study, it demonstrates how the ERD can be implemented in a relational database schema containing 27 tables and 281 fields. An online version of the model is presented online at https://dbdocs.io/Urban-JonathanCohen/Waste2Resources. The following examples reinforce the understanding of the data model and illustrate the attributes that define a class in more detail. Figure 4.3 shows a part of the model as seen in Paper 1.

The model shows that the Actor is a central class of this data model that can represent a city's household, productive, recreational or administrative units. Actors (i) are of many types, (ii) can employ resources, (iii) must comply with regulations, (iv) communicate with other actors, (v) set objectives, and (vi) define operation details.

Waste generated holds a registry with information about who generated the waste (actor ID), what type and how much was generated, and where it was placed (waste place ID). Moreover, a relationship between Regulation and Waste generated stipulates what regulations apply to a given waste type.

Containers are among the most frequently addressed entities in waste-related smart city applications. This class's attributes include location, colour, type of waste that it should contain or capacity, and identify a particular waste container in the system. Containers can also be embedded with IoT Devices that produce various readings on the status of the bin, its content (i.e., current capacity, temperature, humidity, open lid), and its surroundings (i.e., sun exposure, temperature, image). A single container can have multiple devices, generating readings with a specific frequency.

Waste transfers have two Waste Place IDs indicating a starting and an ending container, and they have a timestamp that shows when the waste transfer job was performed and what waste types and amounts were transferred. Moreover, it is connected to Equipment and Staff to retrieve information from those tables. The complete data model schema can be found in an open-source

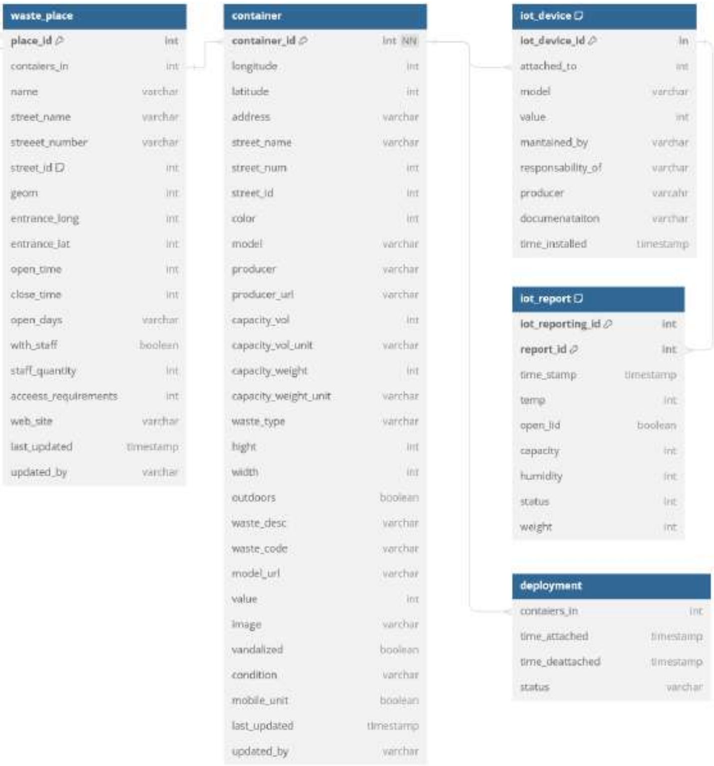


Figure 4.3: Relational data model schema for containers.

repository in dbml and SQL formats for PostgreSQL. Also, an interactive version has been uploaded for visual exploration.

Application to Residential waste sorting

The application of residential waste sorting developed in Paper 1 contributed to set methodological foundations for the pursuit of Paper 2, Paper 3 and Paper b. The application of the general framework for the case of residential waste sorting is presented in Figure4.4. The diagram shows how information can be organised in a city performing a test of deploying IoT devices into a part of the city. Besides showing specific actors and components of the model, the model also shows how devices and reporting relate to waste containers and the logistics of waste management. The diagram is limited to organic waste, and this case was based on interviews with municipality officials from the city of Helsingborg, Sweden.

The exploration of the behavioural aspects and simulation resulted in the need to organise the information about the system. In particular, Figure 4.5 shows the class diagram created for the simulations.

In this diagram, the generators are the residents, and their internal charac-

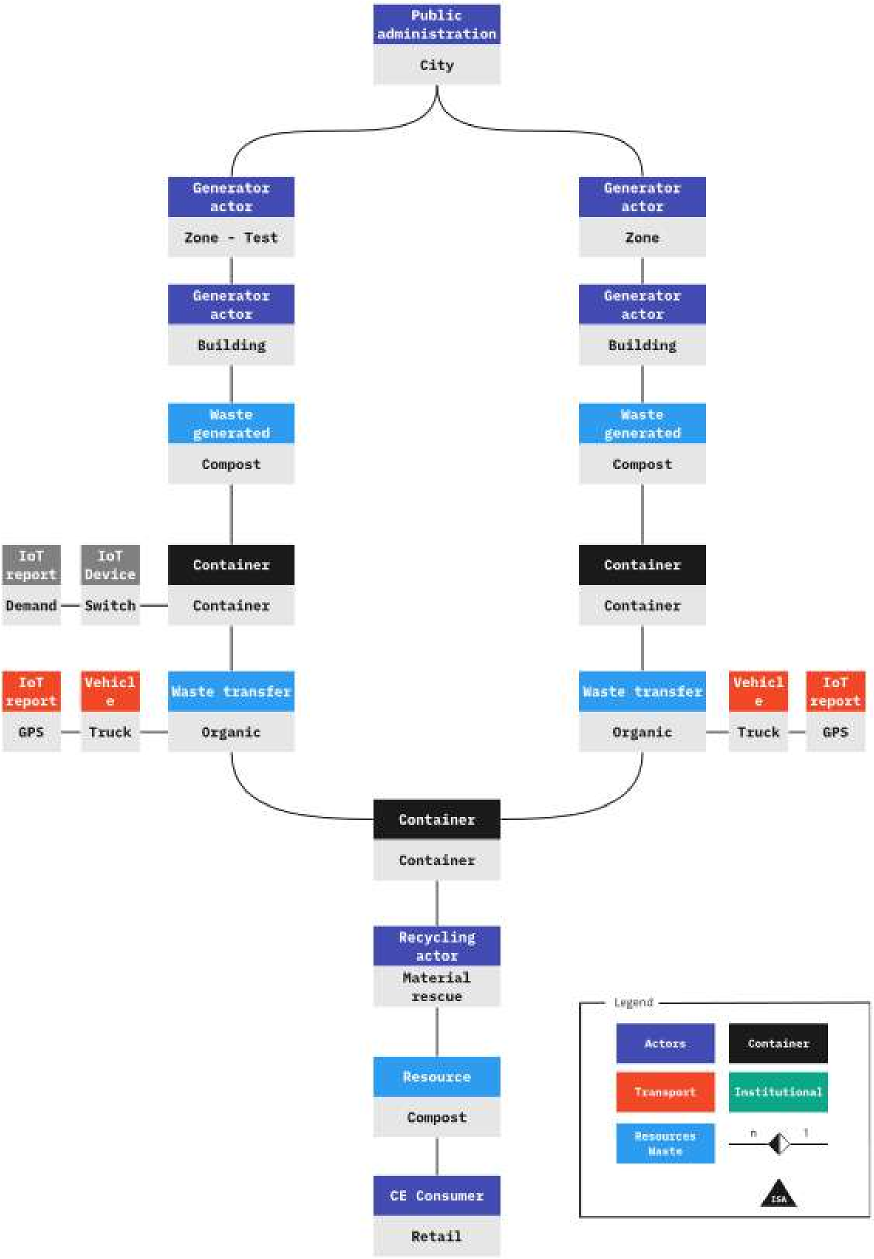


Figure 4.4: ERD for residential waste

teristics were expanded beyond the initial delimitations of Paper 1. Moreover, waste containers, in this case bins, were present both inside the resident's homes and outside on the street. In both cases and following the literature, the characteristics of this company affected how citizens behaved and, ultimately,

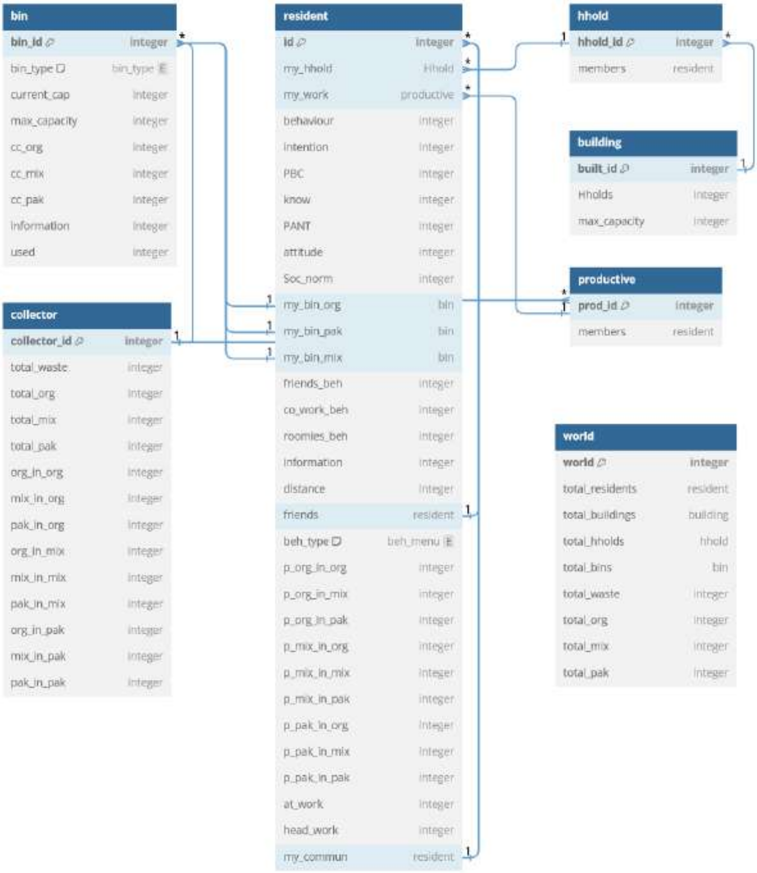


Figure 4.5: Class diagram of residential waste sorting

the amount of adequately sorted waste in the system.

Paper 2 and Paper 3 focused on the development of an ABM of residential waste sorting. In the first study, the model was developed, and the results were explored. The second study of waste sorting was used to calibrate the agent-based model. This study aimed to simulate the behaviour of residents towards waste sorting to study how different urban scenarios can be explored to improve the percentage of waste sorting.

Application to Construction & demolition

The second application focussed on the C&D sector. In this case, the ERM was based on interviews with the stakeholders and government officials from Buenos Aires. Inshigts from the interviews were collected and used to build the application for the C&D. The outputs of this application impacted the simulation presented in Paper 5. Figure 4.6 presents the ERM for the C&D, and in this case, the actors are set to construction sites, and the model shows various waste streams generated while constructing. The model further develops the logistics of mobilising materials from one construction site to the recycling actor. The diagram presents how IoT can track vehicles and quantify how materials flow due to C&D activities.

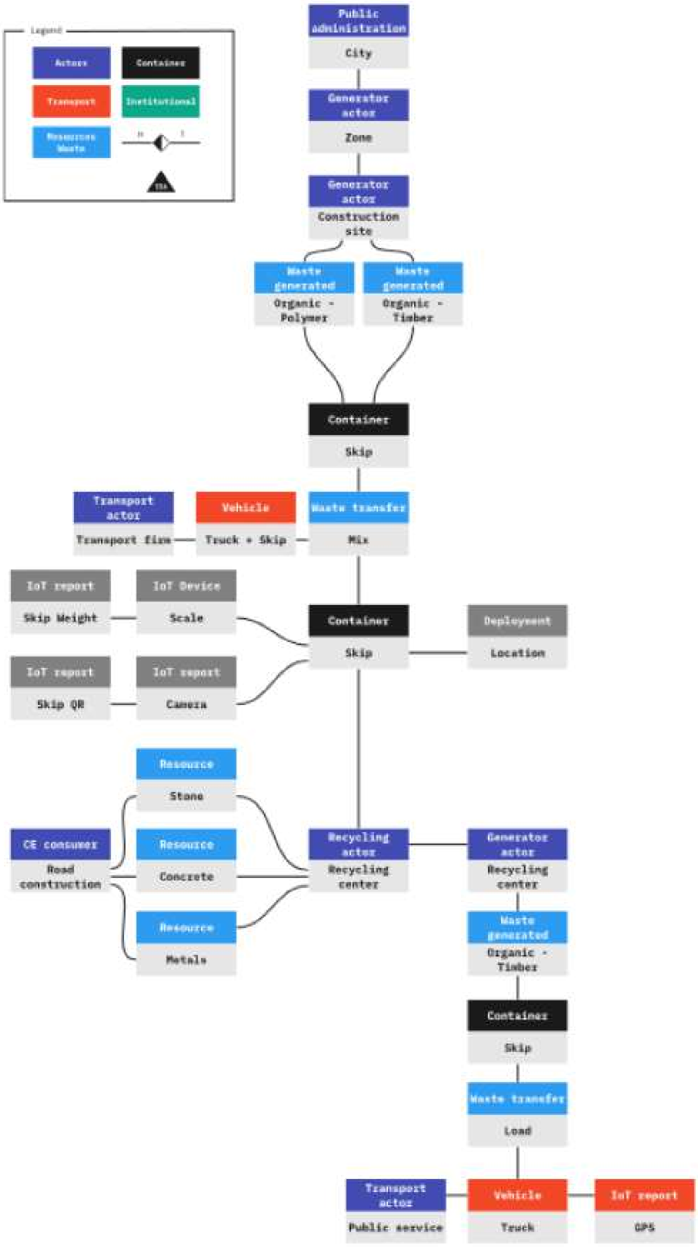


Figure 4.6: ERD for C&D

Application to Industrial Symbiosis

Figure 4.7 presents the ERD for Industrial symbiosis and a generic example of exchanges between two industries. The model proposes capturing and standardising information about waste generated from the industries to facilitate information sharing across sectors. The model shows how two industries could use such a model to understand the potential to share by-products. In this case, the model introduces regulatory aspects to consider when materialising changes.

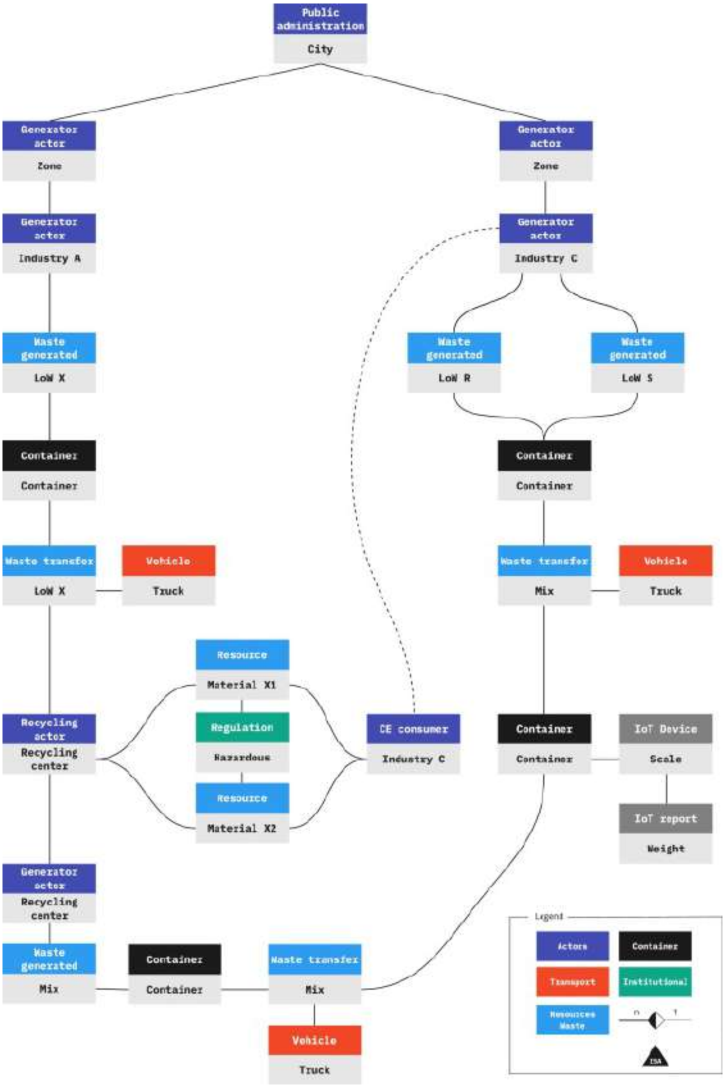


Figure 4.7: ERD model for Industrial Symbiosis

The study capitalises on standardisation concerning industry and waste codes to implement a top-down approach connecting industries that produce waste with those capable of utilising these resources in their transformation processes. The results from this application are presented in Paper 2

4.2 Contributions to enrich Urban Metabolism´s Framework

The various applications presented before were further expanded to investigate how the spatial, temporal and behavioural aspects can be analysed and modelled to enrich the UM framework. Figure 4.8 presents a map of the contributions of each article about the three dimensions that this thesis is exploring. Despite being an abstract diagram of the position of each study, their relative position indicates how much they contributed to enriching the understanding of specific material flows.

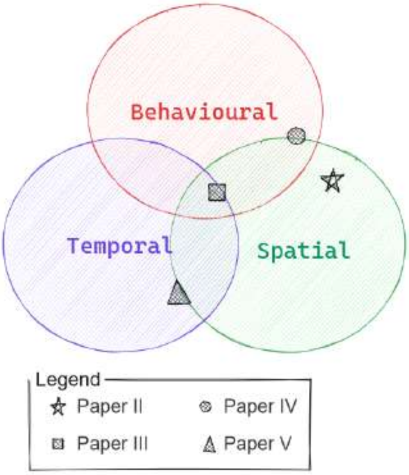


Figure 4.8: Positioninig of papers within the three dimensions explored

4.2.1 Spatial dimension

The significance of incorporating the spatial dimension is evident in Paper 2, Paper 3 and Paper 5.

In exploring industrial symbiosis in Paper 2, the consideration of space significantly enhanced the depth of analysis regarding potential industrial exchanges across firms. This study aimed to identify likely industrial waste exchanges using a top-down approach. Figure 4.9 shows the increase of potential industrial exchanges when using the proposed method, demanding a method to process this result to determine what likely exchanges will occur. The methodology involved applying this analysis to the case of wood waste, resulting in a comprehensive combination of all firms producing the by-product and those with the potential to utilise these materials. The outcome was a dense and extensive network of firms, a practical implementation of which would have been challenging.

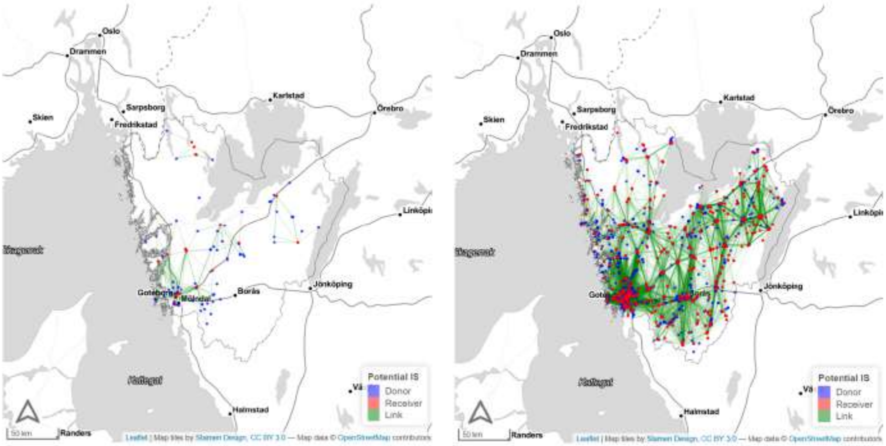


Figure 4.9: Maps showing the difference between two exchange opportunities with and without using the top-down approach

The 159,630 potential IS links were analysed by distance and NACE code, i.e. type of waste for reuse. Figure 4.10 shows histograms of the relationships between Donors of sawdust and potential Recipients. The histograms depict the number of firms located near a waste producer. Upon a closer look, different patterns start to emerge. Firms classified with the NACE code 162 are in higher concentrations approximately 40 km from any Donor. This fact can be contrasted with NACE code 101, for which a higher concentration is less than 20km from the Donor. Incorporating firm locations was pivotal in producing comprehensive results on potential exchanges, effectively narrowing down possibilities based on spatial distance. Without considering the distance, using the results in practice would be difficult because the match-making method identifies all theoretically possible waste exchanges, which are so many possible that the result becomes unusable. The results open the door to exploring the costs of adopting different closing loop scenarios.

Further investigation using information about distances can facilitate information across firms that can potentially benefit from the exchanges.

In Paper 3, the location of the bins affects how well residents behave. Although this information was based on the survey results, it was implemented in the Agent-based simulation. This simulation was used to explore how different spatial scenarios, in terms of placement of bins, affect the percentage of adequately sorted waste. One high and a low-density scenario was proposed, and other waste bin placements were tested within each scenario.

The simulation results show how the residents' average behaviour changes as the bin's waste placement moves. In general, the more bins, the better-behaved residents. Despite this fact, which was expected because the model was based

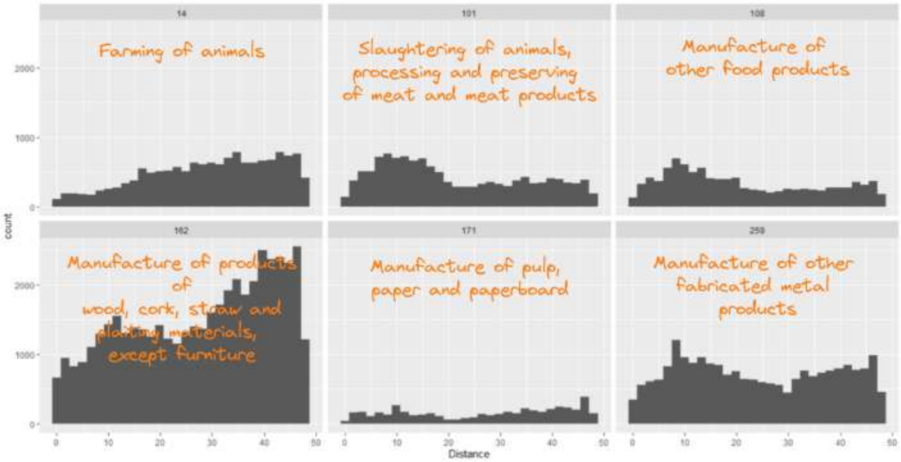


Figure 4.10: Distribution of distance across firms that potentially can share bi-products

on the results from the survey done in Paper 4, it was not expected to find that putting closer recyclable bins. Recycling improved because people could sort the residual and organic waste better. Figure 4.11 presents results from the corresponding scenarios.

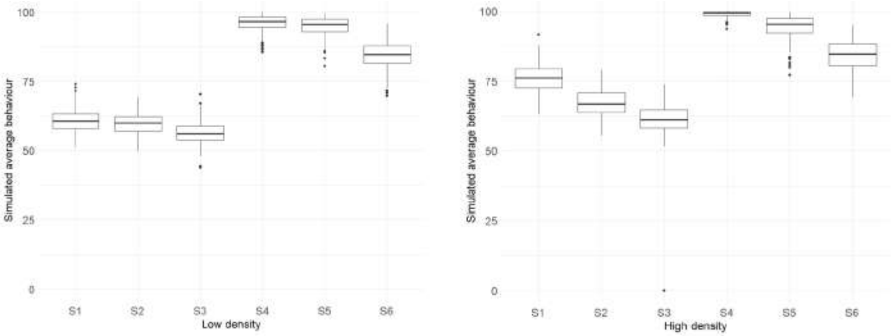


Figure 4.11: Average behaviour across urban scenarios

Finally, in Paper 5, the spatial dimension has not been fully explored since the transportation of resources affects emissions and costs. Yet, the model departs from a specific spatial organisation, which results in implications for spatial planners. Because the city has a history and the development of it has followed a particular logic, building typologies and construction years are clustered. One can find multi-family neighbourhoods or areas where the wooden structures are predominant. This spatial organisation of the buildings determines how the simulation will play out. For example, Figure 4.12 shows the result of potential accumulated demolitions by 2100. Although this is simulated information, far in the future, this exact map can be generated for a specific parameter specification in a particular year, enabling the municipality and developers to know where resources will become available in the city.

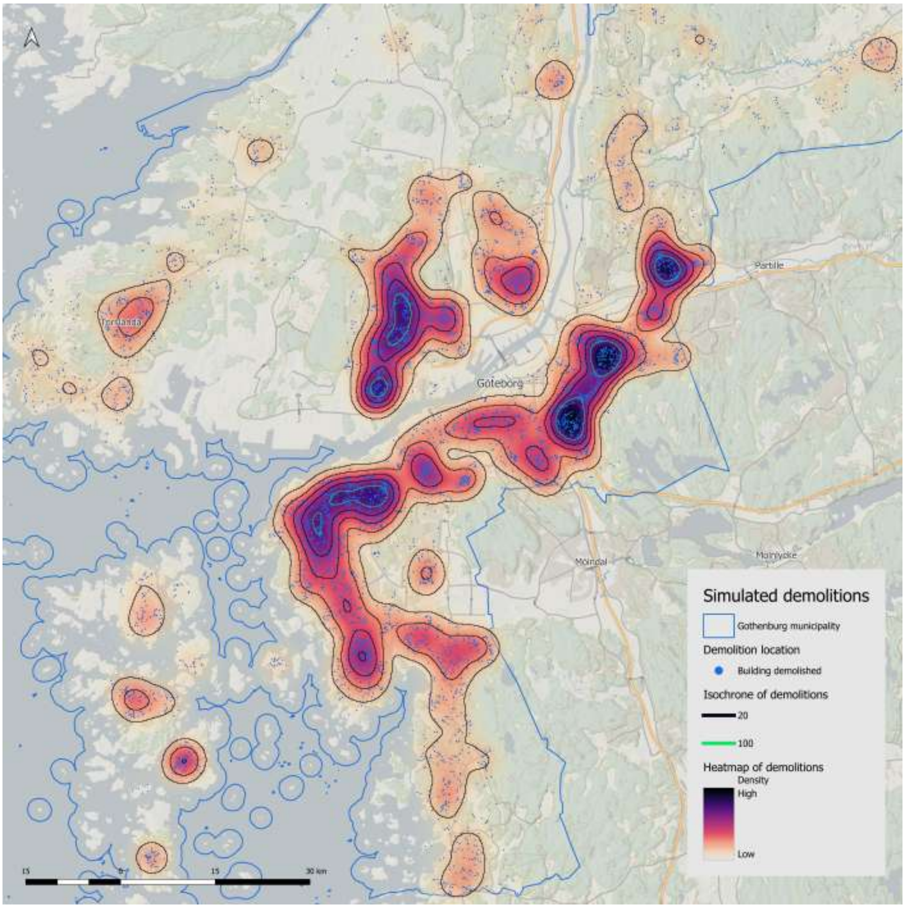


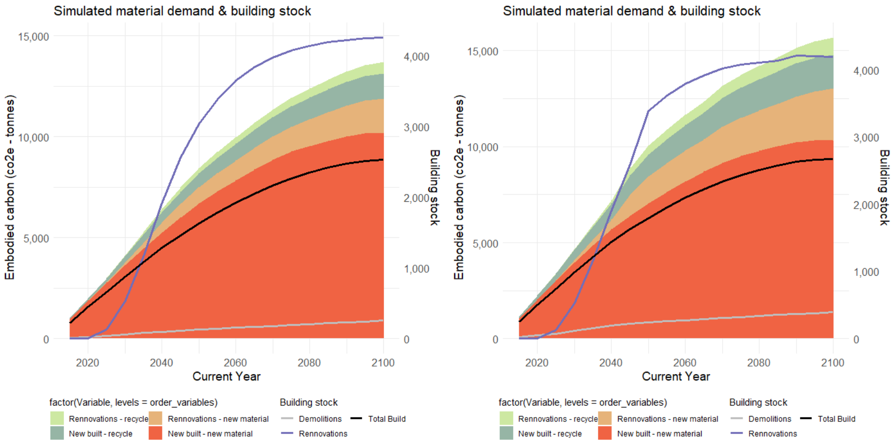
Figure 4.12: Heatmap of simulated demolitions by the year 2100

4.2.2 Temporal dimension

The significance of incorporating the temporal dimension is evident in Paper 5 and to a lesser extent in Paper 3.

The temporal aspect is crucial in simulating the construction and demolition activities Paper 5. As buildings are demolished or renovated, bricks, glass, or gypsum become available for reuse. Therefore, there is a temporal interaction between these resources and the material demand for renovations and new constructions. The main objective of this study was to reflect on how the needs and availability of resources played out. Understanding this matter is crucial to determine how much material reuse is possible and to what extent environmental goals can be achieved with specific policies within a particular time frame.

Figure 4.13 shows the simulated results of two scenarios. All the parameters are set equal. The only change introduced to the system was that 2045 no buildings with an Energy Performance Declaration with label F would be permitted. Consequently, there are forced renovations or demolitions of the buildings stock. The plot shows lines of demolished, renovated, and new constructions and areas of embodied carbon in the system.



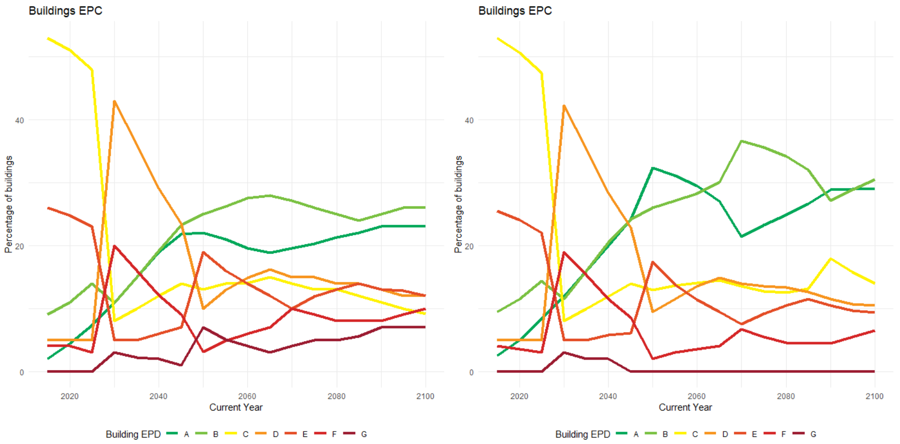
(a) No regulation (b) With regulation

Figure 4.13: Evolution of the embodied carbon, co2 savings and building stock dynamics

As a result of the introduction of a new regulation, the building stock changed in terms of its characteristics. Figure 4.14 shows how the building stock changes over time. It can be noted that in the scenario to the right, the scenario with regulation, there are no buildings with an EPD label F, but that meant that the number of buildings with performance A and B increased, mainly because the implementation of the law, according to the model, will force demolitions, and to accommodate housing need of the city, new buildings will be needed to be constructed.

By introducing time in the model, it is also possible to trace the various materials represented in the simulation. Figure 4.15 shows the materials captured from the renovations and demolitions. The matrix of plots shows how the material availability changes with the level of demolitions and the proportion of single-family buildings, keeping the rest of the parameters constant. For instance, it can be appreciated that as demolitions increase, the amount of materials increases. Moreover, because of the different building typologies used in this investigation, the percentage of single families decreases, and the amount of wool becomes available. Also, the plots show that bricks are a material available, so it is reasonable to find ways of reusing this material.

Finally, in Paper 3, the temporal dimensions play a role because waste sorting behaviour is updated during the simulations. This fact allows the



(a) No regulation (b) With regulation

Figure 4.14: Evolution of the building stock´s Energy Performance

modeller to introduce shocks to the system or to evaluate how some variables evolve. For example, changes in the frequency at which the waste bins get emptied affect the perception of how clean bins are, and this change impacts how residents behave. A second example of shocks can occur if the level of the available information in the bin impacts how sound residents behave. As the agents' behaviour of how to sort waste changes, the behaviour of other agents is affected, starting a positive chain reaction in the system that is only possible to notice with the incorporation of the temporal dimension. This is particularly interesting when looking at the role of information and the frequency with which the bins are cleaned up.

4.2.3 Behavioural dimension

The significance of incorporating the behavioural dimension is evident in two applications. First, in the residential waste sorting case study, in Paper 3 and Paper 4. While the survey pursued in Paper 4 focused on exploring the TPB for waste sorting in Gothenburg, in Paper 3, a simulation incorporating this information was developed to study how the percentage of waste sorting changes under different scenarios. Second, in Paper 5, when exploring the effect of adopting different material reuse strategies in the C&D sector.

In the case of waste sorting, previous research suggests that residents sort their waste based on their behaviours. Despite various behavioural theories and models used to explore behaviour, the TPB is predominant in studies of waste sorting behaviour and in modelling the adoption of green strategies or lifestyle changes.

Paper 3 explored the use of TPB to waste sorting in Gothenburg. The correlation matrix from the survey results, depicted in 4.16, showcases the critical variables under investigation. The first row highlights average behaviour,

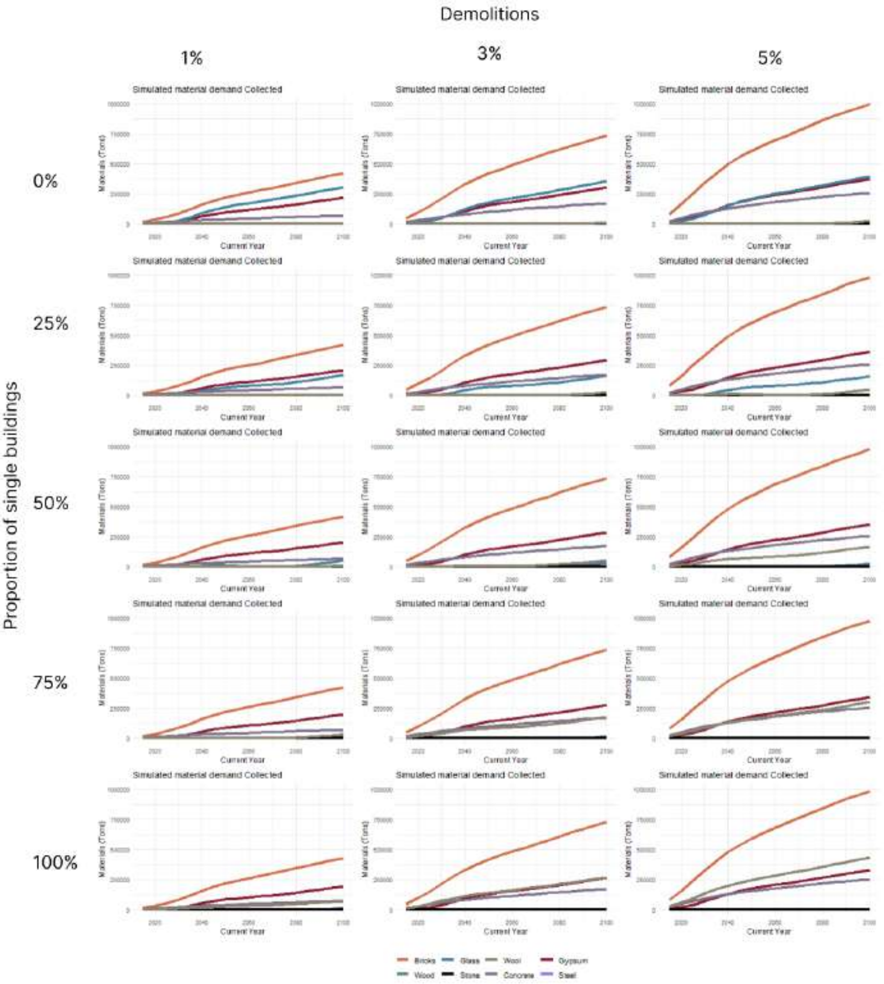


Figure 4.15: Captured materials under different parameter values. Average across simulations.

revealing a positive correlation with attitude, perceived behavioural control, and knowledge. Interestingly, the relationship between behaviour and the distance to organic waste disposal is negative. This finding holds significance, indicating that residents tend to exhibit less waste sorting behaviour when the distance to the organic waste disposal site is more significant. Essentially, a longer distance translates to reduced engagement in segregating waste materials.

Furthermore, the study identified an inverse relationship between the distance to recyclables and satisfaction levels with waste collection services. Residents who experience shorter distances to recyclables express higher satisfaction with waste collection services.

The survey results underwent processing, employing structural equation modelling to explore the relationship between drivers and waste sorting beha-

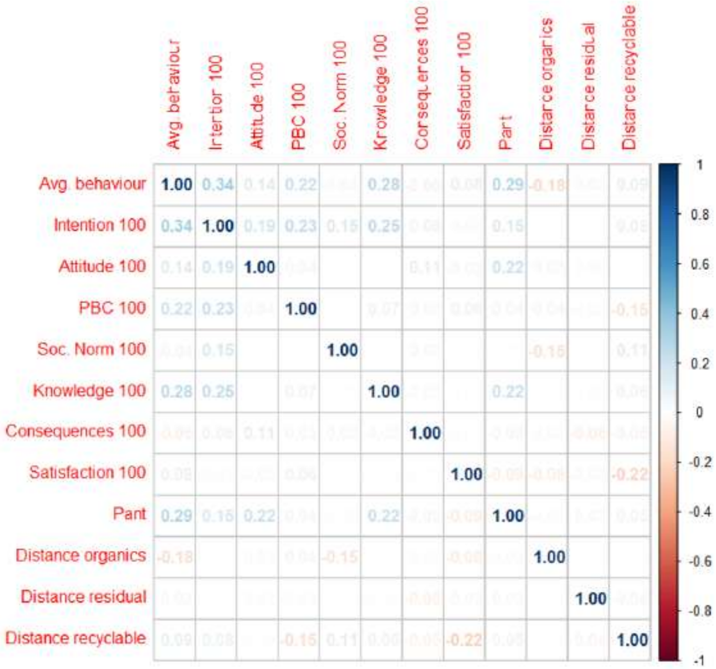


Figure 4.16: Correlation matrix of Behavioural and self-declared waste separation

viour. Figure 4.17 illustrates the outcomes of the statistical approach used to determine the drivers of waste sorting. Examining the path diagram, one can observe how various drivers impact waste sorting behaviour. Notably, distance negatively influences behaviour, and the TPB-related variables directly affect intention and indirectly affect behaviour.

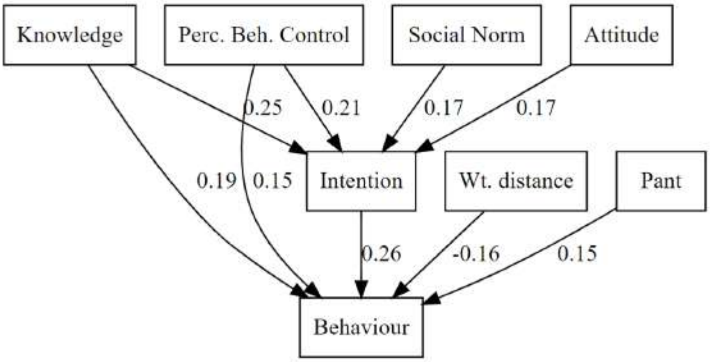


Figure 4.17: Path diagram extracted after Structural Equation Model

Crucially, residents who recycle their bottles and packaging as part of the

Swedish return system or PANT are likelier to exhibit enhanced waste sorting behaviours. This highlights the positive impact of recycling practices on overall waste management behaviour.

In the study of C&D, the behaviour is defined as the percentage of recyclable material used for renovations and new construction. In this study, a simulation included various variables that reflect decisions about the amount of renovations and demolitions and the percentage of material to be reused in the projects. This preliminary model can analyse how materials flow and the resulting embodied carbon in the system. Figure 4.18 shows a table with the maximum and minimum values of CO_2e, and the values inside have been normalised with these values. The highest level of emissions can be found when the percentage of reused material is 0 for new constructions and renovations. Interestingly, as the number of demolitions increases, the rate of CO2e increases, reaching up to 24.8% savings. The figure contributes to showing how sensible the results are while changing parameters.

While the information shown in Figure 4.18 may seem intuitive, it underscores the importance of new constructions in embodied carbon compared to renovations. This table shows the average resulting Co2e for the various simulations. The role of renovations is pivotal in influencing the environmental performance of buildings during their lifecycle. The simulation suggests that urban policies should prioritise new constructions over renovations. However, further investigation is warranted to comprehend how environmental impacts are distributed across different building phases. Additionally, it's crucial to explore to what extent promotions for renovations, leading to higher material demands and potentially better energy performance, outweigh the costs of new materials required for those renovations.

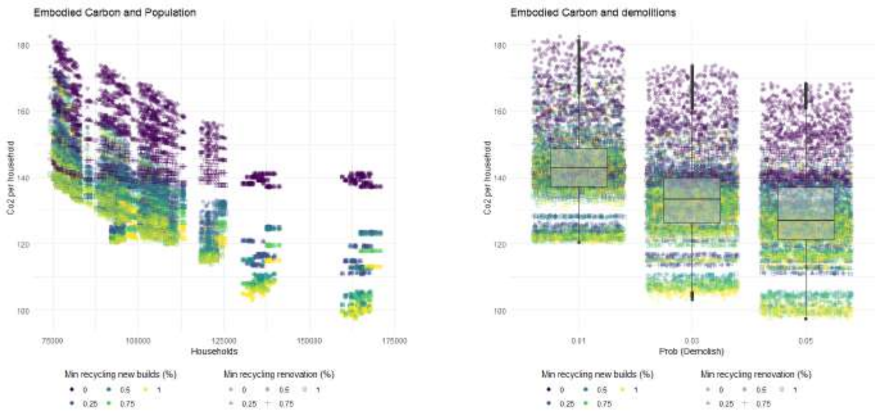
Figure 4.19 shows the simulations' results for various parameter combinations. The figure can effectively show how the main variables of the model affect the amount of CO2e released. In this case, the figure shows Co2e per the resulting number of households in the city.

Table 4.1 presents a regression model based on the simulation outcomes. Regression analysis is a valuable tool for quantifying the significance and contribution of each parameter in the models. Since the regression model is based on the simulation, it is expected to detect significance, yet we are interested in the magnitude of the coefficient. In this case, the dependent variable is the percentage of CO_2e saving. In this case, we can see that the regression model contributes to explaining the relationships shown in Figure 4.19. The regression indicates that the two main variables determining the percentage of savings are the reuse of recycled materials for new construction.

Moreover, the regression model was also run for the scenario of Energy Performance regulations. Table 4.1 shows the difference between the outcomes between these scenarios. These results are shown in Figure 4.20, which presents the distribution of the percentage saving in CO_2e under these scenarios. The models without regulation perform on average worse than the scenario with law, showing an average difference of 5%.

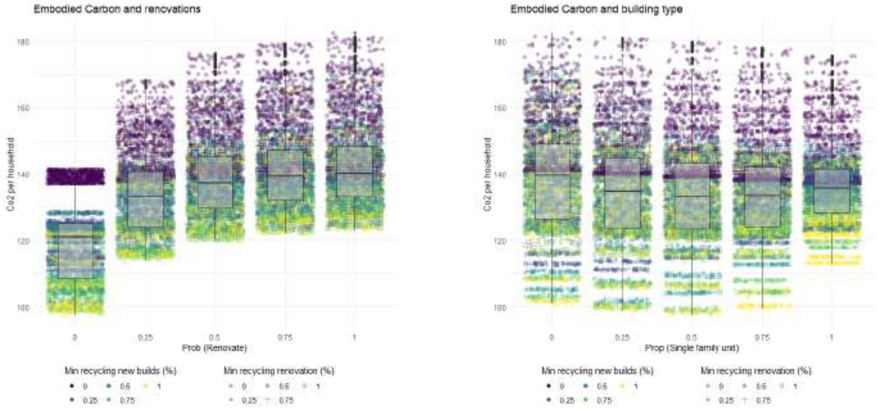
co2 max:	14110	Demolitions																								
co2 min:	10605	0.01																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	5.4	7.3	7.8	7.2	4.6	2.2	3.5	4.4	3.9	1.1	1.6	3.5	4.5	3.0	0.7	1.7	3.6	3.5	3.1	0.2	2.0	3.1	3.1	2.9	**0.0**
0	0.25	15.8	18.1	17.8	15.8	10.8	8.7	12.7	15.9	17.0	13.1	7.2	11.5	15.0	15.9	13.6	6.9	11.3	13.8	15.5	13.7	6.8	10.6	13.4	15.4	13.8
0	0.5	17.1	19.3	19.3	17.2	10.9	9.7	15.7	18.5	18.0	14.0	8.1	14.4	18.6	17.8	14.9	7.7	14.3	17.9	18.2	15.3	7.6	13.7	17.9	18.3	15.4
0	0.75	17.5	19.4	19.7	17.9	13.5	10.6	17.8	19.3	18.9	16.4	9.0	17.5	19.7	19.0	16.7	8.6	17.6	19.3	19.3	16.9	8.6	16.9	19.3	19.4	16.9
0	1	17.5	19.4	19.7	18.1	14.9	11.4	18.3	19.7	19.4	17.0	9.8	18.2	20.3	19.5	17.3	9.4	18.7	19.8	19.8	17.3	9.3	18.4	19.8	19.8	17.3
0.25	0	5.4	7.3	7.8	7.2	4.6	5.7	7.1	7.9	7.4	4.6	6.0	7.8	8.8	7.4	5.0	6.3	8.2	8.1	7.8	4.9	6.8	7.5	7.9	7.7	4.8
0.25	0.25	15.8	18.1	17.8	15.8	10.8	11.8	15.7	18.7	18.2	14.3	11.0	15.2	18.7	18.1	15.4	10.9	15.3	17.7	18.4	15.7	11.0	14.8	17.5	18.5	15.9
0.25	0.5	17.1	19.3	19.3	17.2	10.9	12.7	18.3	19.5	18.8	14.8	11.8	18.0	20.1	19.1	16.1	11.7	18.2	19.7	19.5	16.4	11.8	17.7	19.7	19.6	16.5
0.25	0.75	17.5	19.4	19.7	17.9	13.5	13.6	18.9	20.0	19.5	16.9	12.8	19.1	20.8	19.8	17.5	12.6	19.7	20.4	20.2	17.7	12.7	18.6	20.4	20.2	17.7
0.25	1	17.5	19.4	19.7	18.1	14.9	14.3	19.2	20.2	19.8	17.3	13.5	19.6	21.1	20.2	17.7	13.4	20.3	20.6	20.5	17.8	13.5	20.1	20.6	20.5	17.9
0.5	0	5.4	7.3	7.8	7.2	4.6	9.2	10.6	11.4	10.9	8.1	10.2	12.1	13.1	11.7	9.3	10.9	12.8	12.7	12.4	9.5	11.5	12.7	12.7	12.5	9.6
0.5	0.25	15.8	18.1	17.8	15.8	10.8	14.9	18.7	19.9	19.2	15.4	14.9	18.9	20.8	19.7	16.9	15.1	19.4	20.4	20.2	17.3	15.3	19.1	20.4	20.3	17.4
0.5	0.5	17.1	19.3	19.3	17.2	10.9	15.7	19.4	20.3	19.5	15.7	15.7	20.0	21.3	20.0	17.2	15.9	20.7	20.9	20.4	17.6	16.1	20.5	20.9	20.6	17.7
0.5	0.75	17.5	19.4	19.7	17.9	13.5	16.6	19.7	20.5	19.9	17.3	16.6	20.4	21.6	20.4	17.9	16.8	21.1	21.1	20.8	18.1	17.0	20.9	21.1	20.9	18.2
0.5	1	17.5	19.4	19.7	18.1	14.9	17.2	19.8	20.6	20.1	17.5	17.1	20.5	21.6	20.6	18.1	17.4	21.2	21.1	20.9	18.2	17.7	21.0	21.2	21.0	18.3
0.75	0	5.4	7.3	7.8	7.2	4.6	12.9	14.3	15.2	14.6	11.9	14.8	16.6	17.6	16.2	13.9	15.8	17.7	17.5	17.3	14.3	16.5	17.7	17.7	17.5	14.6
0.75	0.25	15.8	18.1	17.8	15.8	10.8	18.3	20.2	20.9	20.1	16.4	19.0	21.1	22.1	20.7	18.1	19.5	21.8	21.6	21.2	18.4	20.0	21.6	21.7	21.3	18.5
0.75	0.5	17.1	19.3	19.3	17.2	10.9	18.8	20.3	21.0	20.1	16.4	19.4	21.1	22.1	20.7	18.1	19.9	21.8	21.6	21.2	18.4	20.3	21.6	21.7	21.3	18.5
0.75	0.75	17.5	19.4	19.7	17.9	13.5	18.9	20.3	21.0	20.4	17.8	19.5	21.1	22.1	21.0	18.5	20.0	21.8	21.6	21.4	18.6	20.4	21.6	21.7	21.5	18.7
0.75	1	17.5	19.4	19.7	18.1	14.9	18.9	20.3	21.0	20.6	18.0	19.5	21.1	22.2	21.1	18.6	20.0	21.8	21.7	21.5	18.7	20.4	21.6	21.7	21.5	18.7
1	0	5.4	7.3	7.8	7.2	4.6	16.4	17.8	18.7	18.2	15.4	19.0	20.8	21.8	20.5	18.1	20.2	22.1	22.0	21.7	18.8	21.1	22.3	22.3	22.1	19.2
1	0.25	15.8	18.1	17.8	15.8	10.8	20.9	22.2	22.8	22.1	18.4	22.3	23.8	24.8	23.5	20.9	23.0	24.8	24.6	24.2	21.4	23.6	24.7	24.8	24.5	21.6
1	0.5	17.1	19.3	19.3	17.2	10.9	20.9	22.2	22.9	22.0	18.4	22.3	23.8	24.8	23.4	20.9	23.0	24.8	24.6	24.2	21.4	23.5	24.7	24.8	24.5	21.6
1	0.75	17.5	19.4	19.7	17.9	13.5	20.8	22.2	22.9	22.3	19.7	22.2	23.8	24.8	23.7	21.1	23.0	24.8	24.6	24.4	21.6	23.5	24.7	24.8	24.6	21.8
1	1	17.5	19.4	19.7	18.1	14.9	20.8	22.2	22.9	22.5	19.9	22.2	23.8	**24.8**	23.8	21.2	23.0	**24.8**	24.6	24.4	21.6	23.5	24.7	**24.8**	24.6	21.8

Figure 4.18: Savings in Co2e as a percentage, from the worst scenario



(a) Embodied carbon per household and amount of households

(b) Embodied carbon per household and probability of demolition



(c) Embodied carbon per household and probability of renovations

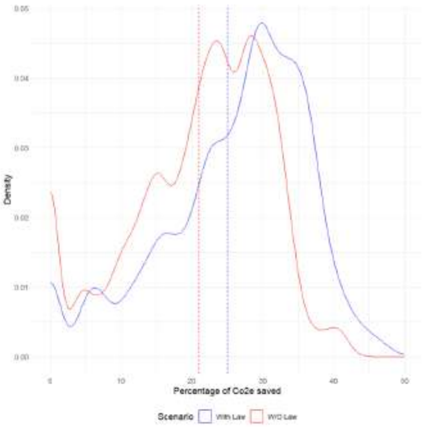
(d) Embodied carbon per household and proportion of single-family buildings

Figure 4.19: Changes in Co2e per household due to parameter changes. Results for the year 2100

4.3 Models as decision-support systems

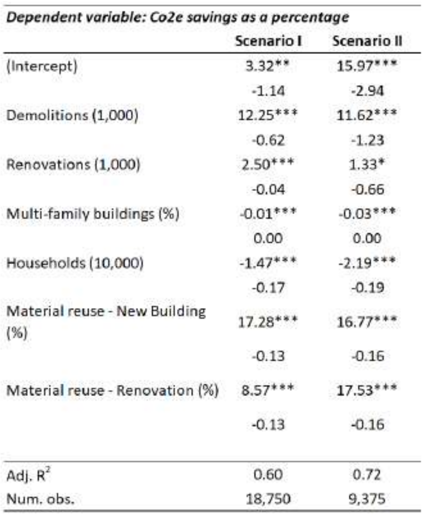
The models created during this project work as a DSS and can be used to explore scenarios and analyse the outcomes of different settings and eventually explore potential outcomes of policies. Figure 4.21 presents the resulting dashboards from the ABMS. Both models are open-source and available for future researchers to evaluate, apply and extend.

Besides running various simulations to explore the outcomes, these dashboards were created to enable the tracking of specific KPI in the virtual setting. The image below shows that the dashboards include a panel allowing users to easily input model changes by interacting with sliders or various nobs. On the



	W/o Law	W Law	t-value	p-value
Mean	21.1	25.9	-37.28	0.000
SD	9.8	10.4		

Figure 4.20: Distribution of CO_2e savings for simulations with and without regulation

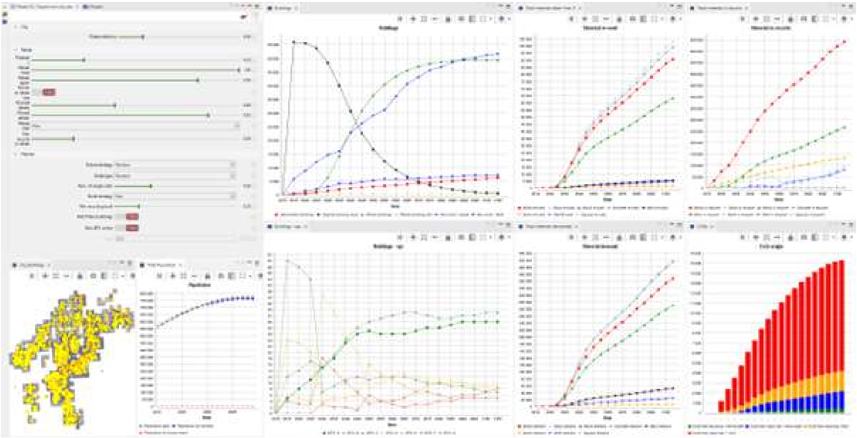


Dependent variable: Co2e savings as a percentage		
	Scenario I	**Scenario II**
(Intercept)	3.32**	15.97***
	-1.14	-2.94
Demolitions (1,000)	12.25***	11.62***
	-0.62	-1.23
Renovations (1,000)	2.50***	1.33*
	-0.04	-0.66
Multi-family buildings (%)	-0.01***	-0.03***
	0.00	0.00
Households (10,000)	-1.47***	-2.19***
	-0.17	-0.19
Material reuse - New Building (%)	17.28***	16.77***
	-0.13	-0.16
Material reuse - Renovation (%)	8.57***	17.53***
	-0.13	-0.16
Adj. R^2	0.60	0.72
Num. obs.	18,750	9,375

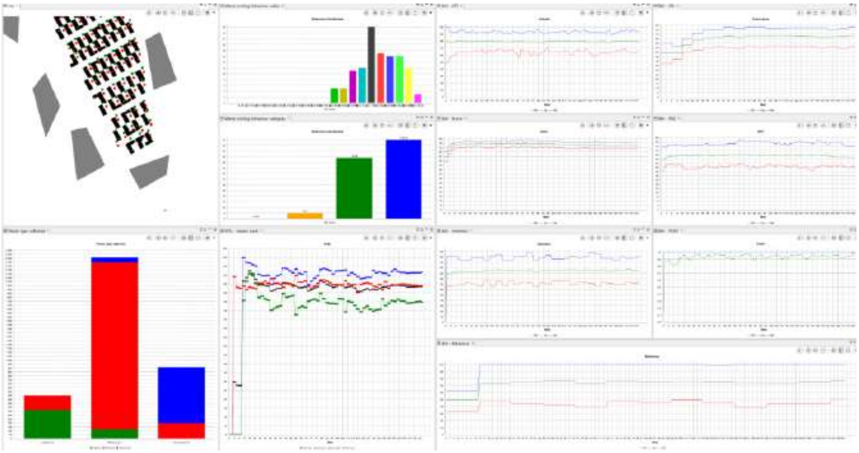
Table 4.1: Contribution to CO_2e savings in buildings

right hand, maps and charts were designed to study the simulation as they are executed.

Although both models use specific case studies, the heuristics developed can be modified and applied in other locations, or the values of parameters can be changed easily. In the case of waste sorting, the values that define the TPB can be altered for other locations, and various urban situations were explored using other bin placements. Similarly, in the case of Construction and Demolition, the dashboard of the model can be used to specify the different parameters to be explored. Changes in the probability of demolition or the percentage of material to be recycled can be changed before or during the simulation. Moreover, other parameters, such as the MFA or amount of embodied CO_2e, are listed in the model to represent low-cost changes.



(a) Construction and demolition



(b) Residential waste separation

Figure 4.21: Model dashboard and control panel

Chapter 5

Conclusion and Discussion

5.1 Conclusion

The results presented above contributed to achieving the various aims and objectives and answering the research questions. RQ1 was mainly addressed in Paper 1 because it provides a theoretical proposition about how to model data about waste and resources. Moreover, the development of the applications also contributed to demonstrating the use of UA to enrich UM. At the same time, these applications also contributed to showing how UA can incorporate the spatial, temporal and behavioural dimensions. This exploration of these applications also provides insights to answer RQ2.

5.1.1 RQ1: How can Urban Analytics methods contribute to urban material flow analysis?

This thesis has expanded the research application of UA by exploring data models and simulations for resources in city regions. The data model developed in Paper 1 provides a framework to consider data needs and how data relates to different entities within various urban systems. The data model was tested and used in the other applications pursued in this thesis, showing its potential. Although different contexts will use different parts and modify them according to the specific needs of their data models, it is crucial to have these. As more solutions are built on top of these technologies, extending analysis over time and across regions would be easier. As new data sources and models become available, the field of resources and waste will be a step closer to engaging with digitalisation. The applications developed during this project demonstrate how these methods used during this research project can be used to introduce the spatial, temporal and behavioural aspects of studying the metabolism of cities. These simulations can also be used to explore scenarios and create synthetic information about the results to deliver insights about these simulations.

5.1.2 RQ2: How can the UMframework be enriched to support urban strategies aimed at closing material loops?

This dissertation discusses the benefits of incorporating space, time, and behaviour. Studying material flows in urban areas can benefit from considering the details of urban processes. In this dissertation, only a set of examples was explored. Still, this initial proposition can be further developed to establish more formal links between behavioural, spatial and material flow changes, as presented in 5.1. For example, the location of waste bins impacts the amount of waste that is being adequately sorted, or considering time when studying material circularity in the construction sector could help to think about what house typologies should be developed depending on the materials being released in specific moments. This thesis contributes to exposing some of these links using computer models. Because these models are open-source, future researchers can expand, modify and correct these contributions.

The analysis developed during this project illustrated the use of UA techniques to complement information about material stock and flows in cities. Although the models do not directly connect to the UM framework, there is potential to inform material stock and flow accounting. The models presented here successfully managed to increase the granularity of information necessary to enrich UM

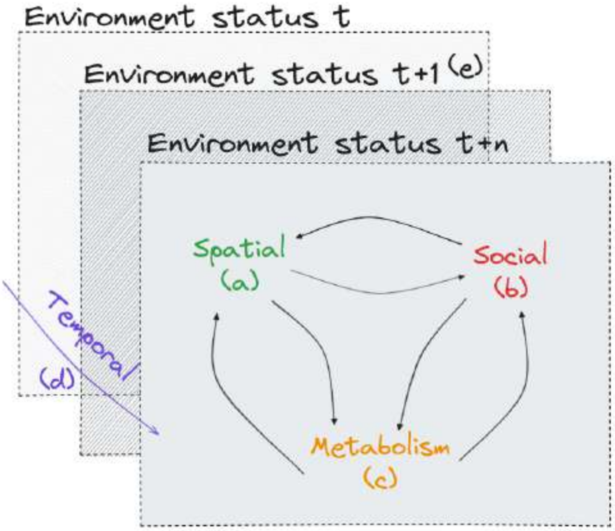


Figure 5.1: The interrelationship between space, behaviour, metabolism and the status of the environment

5.2 Discussion

The overarching aim of this thesis has been to enrich the field of UM by using tools and methods from UA. More specifically, this research improved the information about the processes behind material flow in cities and developed digital tools to enrich UM´s framework. Moreover, specific applications have addressed how spatial, temporal and behavioural aspects determine city material flows. This chapter summarises the main findings of this dissertation.

5.2.1 The importance of data standards and open-source

The theoretical contribution of this thesis was the development of a General Data Model for Waste and Resources. This contribution departed from a conceptual model, translated to an ERM and finally implemented in a relational database. The data model is perceived as a crucial technology that fosters the digitalisation process for resources. At the moment of the development of the data model, there needs to be more information available about how resources flow in city areas. The creation and management of this information are critical to assessing progress in the CE and, ultimately, the environment.

The data model is expected to spark discussions about adopting data standards. Developing such models and adopting data standards will facilitate reproducibility and interoperability and ensure that data about the environment is stored adequately. These characteristics enable data analysis to be easily reproduced, and it is crucial to trace progress over time and compare across different areas.

The resulting digital developments of this research project have been uploaded as open-source so that future researchers and practitioners can use, modify, and extend them. More specifically, advancing towards a more transparent science of cities is crucial because the simulations rely on assumptions and initial conditions. A strategy to move in this direction is to disclose the models and make them publicly available.

5.2.2 Expanding Urban Metabolism´s framework

The research conducted in this project aims to foster discussions about the need for standardised data and processes to streamline the study of urban and regional metabolism. With the ever-increasing volume of information available about cities, there is a growing opportunity to develop standardised methods to track their evolution in almost real-time. This, in turn, will enable us to exercise better control over the use and distribution of resources. Data availability in the correct format will also increase the transparency and reproducibility of methods to measure material use.

Furthermore, the models and analyses proposed in this project enhance the level of detail in city material flows. In some cases, such as construction and demolition or residential waste sorting, the link to resources has been more direct than in industrial symbiosis. These models can be used to evaluate hypothetical scenarios and assess how changes in the spatial distribution of actors in the city can affect these material flows.

5.2.3 Expanding the areas of application of Urban Analaytics

By developing the data model and engaging in the various applications, the thesis has expanded the areas of study of UA. The simulations and data analysis contributed to including the spatial, temporal and behavioural domains in the studies pursued. This research has shown how including these aspects is essential to understanding city material flows. Despite the contributions presented in this thesis, more work is needed to understand and better articulate the existing relationships between urban, behavioural and material changes.

First, integrating spatial variables was proven relevant for the waste sorting Paper 3 and industrial symbiosis applications Paper 2. In both cases, the primary variable considered was the distance between various urban elements. In one case, the distance to bins can determine the resident's behaviour towards waste sorting. In the case of industrial symbiosis, distance can be used to restrict possible interactions between industries.

Despite not being explored in the case of construction and demolition, space plays a role in logistics, so the distance between construction sites and recycling stations is expected to impact the results gathered to this point.

The temporal dimension in Paper 5 was a critical characteristic of the model that enabled the study of material flows for the construction and demolition sectors. In this case, because demolitions and renovations release materials, reuse possibilities are restricted by the available amounts. Moreover, studying this topic about time can help understand what materials will become available and adjust the housing supply based on these materials (in time and amounts).

The study of how behaviour affected material flows was direct and clear in the case of residential waste sorting. In this study, the psychological characteristics of the residents determine how they sort their waste, and this impacts the number of materials collected by the municipalities. Furthermore, in the simulation of construction and demolition, the behaviours can not be assigned to a specific actor, but they deal with aggregated behaviour observed at a city level. The results from this model can be used to understand how much emissions can be saved under various scenarios and how material availability might change depending on preferences regarding future constructions.

5.2.4 Contributions to planning

The models developed in this thesis linked multiple aspects of the built environment with how materials flow in cities. First, the data model can be used to guide the digitalisation process in municipalities. The data model can be seen as a blueprint of what information is needed and how these entities relate. Adequate management of this information enables the systematic study of the effect of urban policies on the environment.

Moreover, the two simulations about municipal waste and the construction and demolition sectors offer a virtual laboratory to explore what-if scenarios. These models were developed to allow researchers and urban planners to study the effect of different conditions. More specifically, in the case of Paper 3, the model offers a platform where different situations with waste bins' location and maintenance affect how residents sort their wastes. The model can also explore behavioural changes in the population and other contexts.

Because of the virtual nature of these models, experimental designs can be used to test and evaluate the effect of different urban policies. For example, in Paper 5, the simulation can reflect upon how different policies affecting building energy performance can affect the construction materials flowing in and out of the city.

5.3 A virtual laboratory: exploring what-if scenarios

The decision-support system created through the simulations for WM and C&D can be a powerful tool for urban planners and policymakers. By exploring different initialisation conditions and varying combinations of parameters, the system can help decision-makers make informed decisions. For instance, in the case of waste sorting, the model can be used to determine the potential effect of the placement of waste bins under various situations. It can also explore changes in the core behavioural model and coefficients, leading to better waste management outcomes. Figure 4.21 presents the resulting dashboards from the ABMS.

Similarly, in the case of C&D, the simulations can guide overall urban policy by promoting renovations, increasing the ratio of demolitions or determining different housing typologies. For example, the model can be used to explore the most effective ways to encourage eco-friendly building practices and to choose the best housing typologies for the population's needs. The simulations are not intended to predict the city's future but can expose learnings from urban processes, which can spark discussions and lead to better urban planning decisions.

In both cases, the ABM developed during this project can be used during workshops and to ignite conversations between the government and various stakeholders. Moreover, the fact that the models were built with open-source software enables these models to be modified, corrected, and extended according to different needs in the future. The resulting simulations provide a virtual setting to explore and discuss the consequences of policies and various territorial settings that otherwise would require exploring these scenarios without exploring how those changes might affect the outcomes.

Overall, the decision-support system created through the simulations can be an excellent tool for urban planners and policymakers, providing valuable insights into urban processes and helping to guide urban policy decisions.

5.3.1 Contributions to agent-based models

Finally, the research developed in Paper 2 has direct implications for the field of agent-based modelling. More specifically, it shows how to integrate a behavioural theory into the agents in the simulation. Although previous contributions to the field of waste management have addressed this topic, the integration was done at an individual level for the first time. Furthermore, the model demonstrates how an ABM can be used to establish a link between behavioural theories and properly sorted waste successfully. Previous efforts to study behaviour fall short of making the connections to waste amounts or material purity. This study has demonstrated a research path towards its integration. Even though these models rely on assumptions, initial conditions and modelling decisions, they can bridge various urban domains and catalyse discussions about the effects of different spatial configurations.

5.4 Limitations

Throughout this research, several limitations were faced. One significant challenge revolved around the reliance on modelling assumptions. The applications explored in this research heavily depended on assumptions about parameters. To overcome data limitations, I found it necessary to synthesise data using informed guesses, which were meticulously documented. However, the inherent uncertainty arising from unknown initial states of systems or the impossibility of using actual data to model different systems somewhat compromised the precision of the results.

Another facet of the research landscape pertained to modelling decisions. As revealed by different studies, alterations in the order of processes could significantly impact model results. This realisation underscored the need for further testing to comprehend how specific model decisions influenced outcomes, prompting a recommendation for additional research in this direction.

Data acquisition emerged as a significant barrier, mainly due to the lack of open data, posing a considerable obstacle to academia and the pursuit of sustainable city regions. The developed data model, while theoretical, demanded extensive datasets for testing. In the study of individual waste recycling, the absence of microdata motivated the development of simulations, necessitating data collection for validation and calibration.

The limitation extended to the dissertation's conceptualisation of CE. While addressing institutional and societal changes, CE's broader conceptualisation required a nuanced evaluation model. Beyond the measurable aspects like material extraction or recycling, the model needed to consider changes in consumer perceptions. This called for an embrace of the multi-dimensional nature of the concept, particularly in the context of the relationship between the built environment and performance. The co-creation of spaces, for instance, was identified as a potential avenue to enhance environmental awareness and a sense of belonging, indirectly contributing to decoupling effects through improved trust and social capital.

Expanding the focus to resources, the dissertation fell short of addressing other CE strategies, prompting a reflection on the necessity to broaden methods and tools. This involved revising the proposed data model to incorporate knowledge regarding other CE strategies, such as the sharing economy or design for circularity. Introducing new classes to capture production processes, including material sourcing, modularity, and efforts to extend product lifespan, became imperative to accommodate circular design principles.

The multi-stakeholder paradigm of CE, with the roles of citizens or bottom-up voices, remained unexplored. To comprehensively assess how spatial planning could promote CE, it became apparent that more attention should be given to integrating new perspectives and narratives.

In pursuing enriching knowledge about material flows in city regions, the studies undertaken during this PhD project highlighted the need for explicit links to global metrics and MFA or LCA. This necessitated interdisciplinary work to establish direct and precise links, further strengthening the understanding of how processes affect material flows. The term “coupling models” encapsulated this need for more explicit connections and interdisciplinary collaboration.

5.5 Future research

After the research activities were pursued under the scope of this dissertation, several research directions were identified. I recommend that future studies provide tools and methods to bring more details to analysing material and energy flows in city regions. Moreover, the emphasis on the recommendations lies in the fundamental concept of open source and aiming for reproducibility interoperability across multiple domains Saltelli et al., 2020. Partially, this work has contributed by sharing the source code and data of the studies pursued here.

Applying Network Modeling in Construction and Demolition Sector

Incorporating network modelling into the construction and demolition sector offers enhanced analysis and optimisation opportunities. However, existing ABM techniques are computationally demanding and limited in their scope to track specific materials. To overcome these limitations, there’s potential to integrate LCA for a broader range of materials or components. Transitioning to more efficient computation methods, such as graph or network-based techniques, could enable the inclusion of additional materials or components, thereby enhancing scalability and applicability.

Developing Decision Support Systems

Developing DSS tailored for policymakers and industry stakeholders is essential for advancing sustainability in the construction and demolition sector. Expanding these systems to include spatial and temporal analysis can provide valuable insights into the potential for circularity improvements in different areas. These systems can be fine-tuned by engaging stakeholders, including policymakers and industry representatives, to address specific challenges and support informed decision-making regarding logistics and infrastructure investments for circularity enhancement.

Connecting environmental and economic models

While existing models, such as the waste sorting model, offer insights into behaviour patterns, bridging the gap between model outputs and real-world environmental and economic consequences is necessary. Expanding these models to incorporate decision-making's environmental and financial burdens would require additional layers of analysis and integration with relevant data sources. This expansion would empower researchers and policymakers to assess the true impact of policies on waste management practices, facilitating more informed and sustainable decision-making processes.

Developing dynamic models of Industrial Symbiosis

Industrial symbiosis models are crucial in promoting resource efficiency and collaboration among industries. However, current models often face limitations regarding data availability and dynamic policy integration. Translating these models into a rule-based framework can enhance their adaptability and responsiveness to changing dynamics and policies within industrial ecosystems. Addressing data limitations through assumptions and engaging stakeholders can facilitate the refinement of the model, ensuring its relevance and effectiveness in promoting industrial symbiosis and circular economy principles.

Developing regional metrics to determine circularity potential

Creating a map of potential industrial symbiosis or resource circulation offers policymakers a strategic tool for developing location-specific policies to promote sustainability. This map identifies available resources within a territory, such as raw materials and waste streams, and assesses their suitability for reuse or recycling. Additionally, it estimates the environmental impact of resource utilisation, including CO_2 emissions or other damages. By integrating spatial analysis, data collection, and stakeholder input, policymakers can prioritise interventions that maximise resource efficiency while minimising environmental harm. This map serves as a roadmap for targeted policies that support circular economy practices and sustainable development goals.

Bibliography

Allen, L., O'Connell, A., & Kiermer, V. (2019). How can we ensure visibility and diversity in research contributions? how the contributor role taxonomy (CRediT) is helping the shift from authorship to contributorship. *Learned Publishing*, *32*(1), 71–74. https://doi.org/10.1002/leap.1210 (cit. on p. vii).

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling*, *55*(3), 362–381. https://doi.org/https://doi.org/10.1016/j.resconrec.2010.11.002 (cit. on pp. 17, 18).

Andrea Caragliu, C. D. B., & Nijkamp, P. (2011). Smart cities in europe. *Journal of Urban Technology*, *18*(2), 65–82. https://doi.org/10.1080/10630732.2011.601117 (cit. on p. 6).

Antikainen, R., Lazarevic, D., & Seppälä, J. Circular economy: Origins and future orientations (H. Lehmann, Ed.). In: *Factor x: Challenges, implementation strategies and examples for a sustainable use of natural resources* (H. Lehmann, Ed.). Ed. by Lehmann, H. Cham: Springer International Publishing, 2018, pp. 115–129. ISBN: 978-3-319-50079-9. https://doi.org/10.1007/978-3-319-50079-9_7 (cit. on p. 17).

Arup. (2023). *The role of cities in the transition towards a circular economy* [Accessed: 7th May 2024]. https://www.arup.com/perspectives/the-role-of-cities-in-the-transition-towards-a-circular-economy (cit. on p. 5).

Athanassiadis, A. Urban metabolism and open data: Opportunities and challenges for urban resource efficiency (S. Hawken, H. Han & C. Pettit, Eds.). In: *Open cities | open data* (S. Hawken, H. Han & C. Pettit, Eds.). Ed. by Hawken, S., Han, H., & Pettit, C. Singapore: Springer Nature Singapore, 2020, pp. 177–196. ISBN: 9789811366048 9789811366055. https://doi.org/10.1007/978-981-13-6605-5_8 (cit. on p. 7).

Athanassiadis, A., Crawford, R. H., & Bouillard, P. Overcoming the 'black box' approach of urban metabolism. In: In *Living and learning: Research for a better built environment.* 49th International Conference of the Architectural Science Association. Melbourne, 2015, 547–556 (cit. on pp. 6, 7, 28).

Barles, S. (2009). Urban metabolism of paris and its region. *Journal of Industrial Ecology*, *13*(6), 898–913. https://doi.org/https://doi.org/10.1111/j.1530-9290.2009.00169.x (cit. on p. 28).

Bassi, A. M., Bianchi, M., Guzzetti, M., Pallaske, G., & Tapia, C. (2021a). Improving the understanding of circular economy potential at territorial level using systems thinking. *Sustainable Production and Consumption*, *27*, 128–140. https://doi.org/https://doi.org/10.1016/j.spc.2020.10.028 (cit. on pp. 22, 23).

Bassi, A. M., Bianchi, M., Guzzetti, M., Pallaske, G., & Tapia, C. (2021b). Improving the understanding of circular economy potential at territorial level using systems thinking. *Sustainable Production and Consumption*, *27*, 128–140. https://doi.org/https://doi.org/10.1016/j.spc.2020.10.028 (cit. on p. 24).

Batty, M. (2011). Building a science of cities. *CITIES*. https://doi.org/10.1016/j.cities.2011.11.008 (cit. on p. 6).

Batty, M. (2019). Urban analytics defined. *Environment and Planning B: Urban Analytics and City Science*, *46*(3), 403–405. https://doi.org/10.1177/2399808319839494 (cit. on pp. 6, 29).

Bauwens, T., Hekkert, M., & Kirchherr, J. (2020). Circular futures: What will they look like? [Publisher: Elsevier]. *Ecological Economics*, *175*, 106703. https://doi.org/10.1016/j.ecolecon.2020.106703 (cit. on p. 21).

Blomsma, F., & Brennan, G. (2017). The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *Journal of Industrial Ecology*, *21*(3), 603–614. https://doi.org/10.1111/jiec.12603 (cit. on pp. 17, 20).

Blum, N., Haupt, M., & Bening, C. (2020). Why “circular” doesn’t always mean “sustainable”. *Resources, Conservation and Recycling*, *162*, 105042. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105042 (cit. on p. 20).

Bocken, N., Bakker, C., & de Pauw, I. Product design and business model strategies for a circular economy (R Setchi, R. Howlett & I. Salinas, Eds.) [SDM’2015, Second international conference on sustainable design and manufacturing, Seville, Spain ; Conference date: 12-04-2015 Through 14-04-2015]. English. In: *Kes transactions on sustainable design and manufacturing sdm’2015* (R Setchi, R. Howlett & I. Salinas, Eds.). Ed. by Setchi, R, Howlett, R., & Salinas, I. SDM’2015, Second international conference on sustainable design and manufacturing, Seville, Spain ; Conference date: 12-04-2015 Through 14-04-2015. Future Technology Press, 2015, 277–296. ISBN: 978-1-911108-00-9 (cit. on pp. 5, 17, 18).

Bolger, K., & Doyon, A. (2019). Circular cities: Exploring local government strategies to facilitate a circular economy [Publisher: Taylor & Francis]. *European Planning Studies*, *27*(11), 2184–2205. https://doi.org/10.1080/09654313.2019.1642854 (cit. on p. 22).

Bond, A. J., Dockerty, T., Lovett, A., Riche, A. B., Haughton, A. J., Bohan, D. A., Sage, R. B., Shield, I. F., Finch, J. W., Turner, M. M., & Karp, A. (2011). Learning how to deal with values, frames and governance in sustainability appraisal. *Regional Studies*, *45*(8), 1157–1170. https://doi.org/10.1080/00343404.2010.485181 (cit. on p. 20).

Boulding, K. The economics of the coming spaceship earth. In: In *Environmental quality issues in a growing economy*. 1966, pp. 3–14 (cit. on p. 16).

Brglez, K., Perc, M., & Lukman, R. K. (2023). The complexity and interconnectedness of circular cities and the circular economy for sustainability. *Sustainable Development*, sd.2766. https://doi.org/10.1002/sd.2766 (cit. on p. 25).

Brown, M. T. (2004). A picture is worth a thousand words: Energy systems language and simulation [Through the MACROSCOPE: the legacy of H.T. Odum]. *Ecological Modelling*, *178*(1), 83–100. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2003.12.008 (cit. on p. 27).

Campbell-Johnston, K., Cate, J. t., Elfering-Petrovic, M., & Gupta, J. (2019). City level circular transitions: Barriers and limits in amsterdam, utrecht and the hague [Publisher: Elsevier Ltd]. *Journal of Cleaner Production*, *235*, 1232–1239. https://doi.org/10.1016/j.jclepro.2019.06.106 (cit. on p. 22).

Carlos Tapia, G. P., Marco Bianchi, & Bassi, A. M. (2021). Towards a territorial definition of a circular economy: Exploring the role of territorial factors in closed-loop systems. *European Planning Studies*, *29*(8), 1438–1457. https://doi.org/10.1080/09654313.2020.1867511 (cit. on p. 24).

Circle Economy. (2020). *Circularity Gap Report 2020* (tech. rep.). Circle Economy. https://www.circularity-gap.world/ (cit. on p. 4).

City of Gothenburg. (2021). Environment and Climate Programme for the City of Gothenburg 2021–2030 [Accessed: February 3, 2024]. (Cit. on p. 40).

Collins, A., Galli, A., Hipwood, T., & Murthy, A. (2020). Living within a One Planet reality: The contribution of personal Footprint calculators. *Environmental Research Letters*, *15*(2). https://doi.org/10.1088/1748-9326/ab5f96 (cit. on p. 3).

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., & Worrell, E. (2019). Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, *151*, 104498. https://doi.org/10.1016/j.resconrec.2019.104498 (cit. on p. 19).

Coskun, A., Metta, J., Bakırlıoğlu, Y., Çay, D., & Bachus, K. (2022). Make it a circular city: Experiences and challenges from european cities striving for sustainability through promoting circular making. *Resources, Conservation and Recycling*, *185*, 106495. https://doi.org/https://doi.org/10.1016/j.resconrec.2022.106495 (cit. on p. 21).

Cui, X. (2022). A circular urban metabolism (CUM) framework to explore resource use patterns and circularity potential in an urban system. *Journal of Cleaner Production*, *359*, 132067. https://doi.org/10.1016/j.jclepro.2022.132067 (cit. on p. 6).

Céspedes Restrepo, J. D., & Morales-Pinzón, T. (2018). Urban metabolism and sustainability: Precedents, genesis and research perspectives. *Resources, Conservation and Recycling*, *131*, 216–224. https://doi.org/10.1016/j.resconrec.2017.12.023 (cit. on pp. 6, 9).

Davis, C., Nikolic, I., & Dijkema, G. P. J. Integrating life cycle analysis with agent based modeling: Deciding on bio-electricity. In: In *2008 first international conference on infrastructure systems and services: Building networks for a brighter future (INFRA)*. 2008 First International Conference on Infrastructure Systems and Services: Building Networks for a Brighter Future (INFRA). 2008, November, 1–6. https://doi.org/10.1109/INFRA.2008.5439641 (cit. on p. 29).

De Jong, M., Joss, S., Schraven, D., Zhan, C., & Weijnen, M. (2015). Sustainable – smart – resilient – low carbon – eco – knowledge cities; making sense of a multitude of concepts promoting sustainable urbanization. *Journal of Cleaner Production*, *109*, 25–38. https://doi.org/10.1016/j.jclepro.2015.02.004 (cit. on p. 21).

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., & Ioppolo, G. (2021). A systematic review for measuring circular economy: The 61 indicators. *Journal of Cleaner Production*, *281*, 124942. https://doi.org/10.1016/j.jclepro.2020.124942 (cit. on p. 19).

Dijst, M. (2013). Space-time integration in a dynamic urbanizing world: Current status and future prospects in geography and giscience: Space-time integration in geography and giscience. *Annals of the Association of American Geographers*, *103*(5), 1058–1061. https://doi.org/10.1080/00045608.2013.792171 (cit. on p. 6).

Dijst, M., Worrell, E., Böcker, L., Brunner, P., Davoudi, S., Geertman, S., Harmsen, R., Helbich, M., Holtslag, A. A., Kwan, M. P., Lenz, B., Lyons, G., Mokhtarian, P. L., Newman, P., Perrels, A., Ribeiro, A. P., Rosales Carreón, J., Thomson, G., Urge-Vorsatz, D., & Zeyringer, M. (2018). Exploring urban metabolism—towards an interdisciplinary perspective. *Resources, Conservation and Recycling*, *132*, 190–203. https://doi.org/10.1016/j.resconrec.2017.09.014 (cit. on pp. 6, 8).

Dolczewski, M. (2022). Semi-structured interview for self-esteem regulation research. *Acta Psychologica*, *228*, 103642. https://doi.org/10.1016/j.actpsy.2022.103642 (cit. on p. 36).

Domenech, T., & Bahn-Walkowiak, B. (2019). Transition towards a resource efficient circular economy in europe: Policy lessons from the EU and the member states. *Ecological Economics*, *155*, 7–19. https://doi.org/10.1016/j.ecolecon.2017.11.001 (cit. on p. 19).

D'Amico, G., Arbolino, R., Shi, L., Yigitcanlar, T., & Ioppolo, G. (2022). Digitalisation driven urban metabolism circularity: A review and analysis of circular city initiatives. *Land Use Policy*, *112*, 105819. https://doi.org/10.1016/j.landusepol.2021.105819 (cit. on p. 29).

Ellen MacArthur Foundation. (2018). The circular economy opportunity for urban & industrial innovation in china. *Circular Economy Perspectives Series*, 1–166. https://doi.org/10.1038/531435a (cit. on p. 5).

ESPON. (2019). *CIRCTER - Circular Economy and Territorial Consequences - Draft Final Report* (tech. rep.). ESPON. https://www.espon.eu/sites/default/files/attachments/CIRCTERInceptionReport.pdf (cit. on p. 5).

ESPON. (2020). *Circular economy and territorial consequences (circter)* (tech. rep.). ESPON EGTC. Luxembourg. https://www.espon.eu/circular-economy (cit. on pp. 15, 24).

ESPON. (2020). *Circular economy and territorial consequences (CIRCTER)*. ESPON European Group on Territorial Cohesion and Spatial Planning. https://www.espon.eu/circular-economy (cit. on p. 21).

European Commission. (2018). *Delivering the Sustainable Development Goals at local and regional level Recommendations to the European Commission by the subgroup on "SDGs at local and regional level" of the Multi-Stakeholder Platform on the Implementation of the Sustainable* (tech. rep.). European Commision. http://unsdsn.org/wp-content/uploads/2016/07/9.1.8.-Cities-SDG-Guide.pdf (cit. on p. 4).

European Commission. (2020). *A new Circular Economy Action Plan For a cleaner and more competitive Europe* (Communication from the Commission No. COM/2020/98 final) (Accessed on 7th May 2024). European Commission. (Cit. on pp. 5, 19).

European Commission. (2023). Waste framework directive. (Cit. on p. 16).

European Commission. Directorate General for Research and Innovation. (2022). *Circular cities & regions initiative: Methodology for the implementation of a circular economy at the local and regional scale.* Publications Office. Retrieved February 11, 2024, from https://data.europa.eu/doi/10.2777/068045 (cit. on p. 25).

European Commission. Directorate General for Research and Innovation., Tecnalia., ECORYS., AIT. & EGEN. (2022). *Circular cities & regions initiative: Methodology for the implementation of a circular economy at the local and regional scale.* Publications Office. Retrieved February 8, 2024, from https://data.europa.eu/doi/10.2777/068045 (cit. on pp. 7, 15).

European Commission. Statistical Office of the European Union. (2019). *Sustainable development in the european union: Monitoring report on progress towards the SDGs in an EU context: 2019 edition.* Publications Office. Retrieved January 29, 2024, from https://data.europa.eu/doi/10.2785/44964 (cit. on p. 4).

European Commission. Statistical Office of the European Union. (2022). *Sustainable development in the european union: Monitoring report on progress towards the SDGs in an EU context : 2023 edition.* Publications Office. Retrieved January 29, 2024, from https://data.europa.eu/doi/10.2785/403194 (cit. on p. 4).

European Parliament. (2020). Resolution on the european green deal. (2019/2956(rsp)). Retrieved February 21, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020IP0005 (cit. on p. 4).

Ferrão, P., & Fernández, J. E. (2013). *Sustainable urban metabolism.* MIT press. (Cit. on p. 27).

Ferrão, P., & Fernández, J. E. (2013, August). *Sustainable Urban Metabolism.* The MIT Press. https://doi.org/10.7551/mitpress/8617.001.0001 (cit. on p. 26).

Figge, F., Thorpe, A. S., & Gutberlet, M. (2023). Definitions of the circular economy: Circularity matters. *Ecological Economics*, *208*, 107823. https://doi.org/10.1016/j.ecolecon.2023.107823 (cit. on pp. 19, 21).

Fischer-Kowalski, M. (2011). *Decoupling natural resource use and environmental impacts from economic growth: A report of the working group on decoupling to the international resource panel.* UNEP United Nations Environment Programme, International Resource Panel. (Cit. on p. 15).

Fischer-Kowalski, M. (1998). Society's metabolism: The intellectual history of materials flow analysis, part i, 1860– 1970. *Journal of Industrial Ecology*, *2*(1), 61–78. https://doi.org/10.1162/jiec.1998.2.1.61 (cit. on p. 8).

Fischer-Kowalski, M., & Hüttler, W. (1998). Society's metabolism: The intellectual history of materials flow analysis, part II, 1970-1 998. *Journal of Industrial Ecology*, *2*(4), 107–136. https://doi.org/10.1162/jiec.1998.2.4.107 (cit. on p. 8).

Foster, G., & Saleh, R. (2021). The circular city and adaptive reuse of cultural heritage index : Measuring the investment opportunity in europe [Publisher: Elsevier B.V.]. *Resources, Conservation & Recycling*, *175*, 105880. https://doi.org/10.1016/j.resconrec.2021.105880 (cit. on p. 19).

Foundation, E. M. (2015a). *Growth within: A circular economy vision for a competitive europe.* https://www.ellenmacarthurfoundation.org/publications/growth-within-a-circular-economy-vision-for-a-competitive-europe (cit. on p. 17).

Foundation, E. M. (2015b). Towards a circular economy: Business rationale for an accelerated transition, 20 (cit. on p. 17).

Fusco Girard, L., & Nocca, F. (2019). Moving towards the circular economy/city model: Which tools for operationalizing this model? *Sustainability*, *11*(22). https://doi.org/10.3390/su11226253 (cit. on p. 24).

Gao, C. C., Gao, C. C., Song, K., & Fang, K. (2020). Pathways towards regional circular economy evaluated using material flow analysis and system dynamics [Publisher: Elsevier]. *Resources, Conservation and Recycling*, *154*, 104527. https://doi.org/10.1016/j.resconrec.2019.104527 (cit. on p. 6).

Geiser, K. (2001, May). *Materials Matter: Toward a Sustainable Materials Policy.* The MIT Press. https://doi.org/10.7551/mitpress/4475.001.0001 (cit. on p. 17).

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The circular economy – a new sustainability paradigm? [Publisher: Elsevier Ltd]. *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048 (cit. on pp. 15, 16, 20).

Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in china: An evaluation and critical analysis [Publisher: Elsevier Ltd]. *Journal of Cleaner Production*, *23*(1), 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005 (cit. on p. 19).

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy : the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007 (cit. on p. 4).

Global Footprint Network. (2023). *Global footprint network* [Accessed: 16th December 2023]. https://www.footprintnetwork.org/ (cit. on p. 3).

Golubiewski, N. (2012). Is there a metabolism of an urban ecosystem? an ecological critique. *AMBIO*, *41*(7), 751–764. https://doi.org/10.1007/s13280-011-0232-7 (cit. on p. 5).

Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., & Österbring, M. (2018). Material-intensity database of residential buildings: A case-study of sweden in the international context [50 citations (Crossref) [2023-03-20]]. *Resources, Conservation and Recycling*, *130*, 228–239. https://doi.org/10.1016/j.resconrec.2017.11.022 (cit. on pp. 9, 28, 40, 42).

Graute, U. (2016). Local authorities acting globally for sustainable development. *Regional Studies*, *50*(11), 1931–1942. https://doi.org/10.1080/00343404.2016.1161740 (cit. on p. 4).

Gravagnuolo, A., Angrisano, M., & Fusco Girard, L. (2019). Circular economy strategies in eight historic port cities: Criteria and indicators towards a circular city assessment framework. *Sustainability*, *11*(13), 3512. https://doi.org/10.3390/su11133512 (cit. on p. 21).

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jørgensen, C., Mooij, W. M., Müller, B., Pe'er, G., Piou, C., Railsback, S. F., Robbins, A. M., . . . DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, *198*(1), 115–126. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2006.04.023 (cit. on p. 47).

Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A. S. A., Milles, A., Nabe-Nielsen, J., Polhill, J. G., Radchuk, V., Rohwäder, M.-S., Stillman, R. A., Thiele, J. C., & Ayllón, D. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *Journal of Artificial Societies and Social Simulation*, *23*(2), 7 (cit. on p. 42).

Guibrunet, L., & Sánchez Jiménez, A. (2023). The current and potential role of urban metabolism studies to analyze the role of food in urban sustainability. *Journal of Industrial Ecology*, *27*(1), 196–209. https://doi.org/https://doi.org/10.1111/jiec.13361 (cit. on p. 6).

Gupta, S., Chen, H., Hazen, B. T., Kaur, S., & Gonzalez, E. D. R. S. (2019a). Circular economy and big data analytics: A stakeholder perspective. *Technological Forecasting and Social Change*, *144*, 466–474. https://doi.org/https://doi.org/10.1016/j.techfore.2018.06.030 (cit. on p. 15).

Gupta, S., Chen, H., Hazen, B. T., Kaur, S., & Santibañez Gonzalez, E. D. (2019b). Circular economy and big data analytics: A stakeholder perspective. *Technological Forecasting and Social Change*, *144*(June 2018), 466–474. https://doi.org/10.1016/j.techfore.2018.06.030 (cit. on p. 36).

Gura, K. S., Nica, E., Kliestik, T., & Puime-Guillén, F. (2023). Circular economy in territorial planning strategy: Incorporation in cluster activities and economic zones. *Environmental Technology & Innovation*, *32*, 103357. https://doi.org/https://doi.org/10.1016/j.eti.2023.103357 (cit. on p. 5).

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the european union and the world in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. https://doi.org/https://doi.org/10.1111/jiec.12244 (cit. on p. 4).

Haas, W., Krausmann, F., Wiedenhofer, D., Lauk, C., & Mayer, A. (2020a). Spaceship earth's odyssey to a circular economy - a century long perspective. *Resources, Conservation and Recycling*, *163*(August), 105076. https://doi.org/10.1016/j.resconrec.2020.105076 (cit. on p. 4).

Haas, W., Krausmann, F., Wiedenhofer, D., Lauk, C., & Mayer, A. (2020b). Spaceship earth's odyssey to a circular economy - a century long perspective [Publisher: Elsevier]. *Resources, Conservation and Recycling*, *163*, 105076. https://doi.org/10.1016/j.resconrec.2020.105076 (cit. on p. 6).

Hedberg, A., & Sipka, S. (2020). *The circular economy: Going digital*. European Policy Centre. https://www.epc.eu/en/publications/The-circular-economy-Going-digital¸30c848 (cit. on p. 7).

Held, F. P., Wilkinson, I. F., Marks, R. E., & Young, L. (2014). Agent-based modelling, a new kind of research. *Australasian Marketing Journal (AMJ)*, *22*(1), 4–14. https://doi.org/10.1016/j.ausmj.2013.12.003 (cit. on p. 42).

Hicks, A. (2022). Seeing the people in LCA: Agent based models as one possibility. *Resources, Conservation & Recycling Advances*, *15*, 200091. https://doi.org/https://doi.org/10.1016/j.rcradv.2022.200091 (cit. on p. 29).

Huang, Q., Zheng, X., Liu, F., Hu, Y., & Zuo, Y. (2018). Dynamic analysis method to open the "black box" of urban metabolism. *Resources, Conservation and Recycling*, *139*, 377–386. https://doi.org/https://doi.org/10.1016/j.resconrec.2018.09.010 (cit. on p. 8).

Hägerstrand, T. (1976). Geography and the study of interaction between nature and society. *Geoforum*, *7*(5), 329–334. https://doi.org/10.1016/0016-7185(76)90063-4 (cit. on p. i).

Johansson, N., & Henriksson, M. (2020). Circular economy running in circles? a discourse analysis of shifts in ideas of circularity in swedish environmental policy. *Sustainable Production and Consumption*, *23*, 148–156. https://doi.org/10.1016/j.spc.2020.05.005 (cit. on p. 17).

Kalmykova, Y., & Rosado, L. Urban metabolism as framework for circular economy design for cities. In: In *Proceedings of the world resources forum 2015*. Chalmers University of Technology. 2015 (cit. on pp. 9, 28).

Kalmykova, Y., Rosado, L., & Lisovskaja, V. (2015). Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels. *19*(5), 837–852. https://doi.org/10.1111/jiec.12336 (cit. on p. 25).

Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018a). Circular economy - From review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling*, *135*, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034 (cit. on p. 8).

Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018b). Circular economy – from review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling*, *135*, 190–201. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.10.034 (cit. on p. 22).

Kennedy, C., Pincetl, S., & Bunje, P. (2011a). The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution*, *159*(8), 1965–1973. https://doi.org/https://doi.org/10.1016/j.envpol.2010.10.022 (cit. on pp. 5, 8).

Kennedy, C., Pincetl, S., & Bunje, P. (2011b). The study of urban metabolism and its applications to urban planning and design [Selected papers from the conference Urban Environmental Pollution: Overcoming Obstacles to Sustainability and Quality of Life (UEP2010), 20-23 June 2010, Boston, USA]. *Environmental Pollution*, *159*(8), 1965–1973. https://doi.org/https://doi.org/10.1016/j.envpol.2010.10.022 (cit. on pp. 6, 28).

Kennedy, C., Cuddihy, J., & Engel-Yan, J. (2007). The changing metabolism of cities. *Journal of Industrial Ecology*, *11*(2), 43–59. https://doi.org/https://doi.org/10.1162/jie.2007.1107 (cit. on pp. 8, 28).

Kennedy, C., & Hoornweg, D. (2012a). Mainstreaming urban metabolism. *Journal of Industrial Ecology*, *16*(6), 780–782. https://doi.org/https://doi.org/10.1111/j.1530-9290.2012.00548.x (cit. on p. 5).

Kennedy, C., & Hoornweg, D. (2012b). Mainstreaming urban metabolism. *Journal of Industrial Ecology*, *16*(6), 780–782. https://doi.org/https://doi.org/10.1111/j.1530-9290.2012.00548.x (cit. on p. 7).

Kennedy, C., & Hoornweg, D. (2012c). Mainstreaming urban metabolism. *Journal of Industrial Ecology*, *16*(6), 780–782. https://doi.org/10.1111/j.1530-9290.2012.00548.x (cit. on pp. 9, 15, 27).

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(September), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005 (cit. on pp. 17, 23).

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the circular economy (revisited): An analysis of 221 definitions. *Resources, Conservation and Recycling*, *194*, 107001. https://doi.org/https://doi.org/10.1016/j.resconrec.2023.107001 (cit. on pp. 17–20).

Koide, R., Yamamoto, H., Nansai, K., & Murakami, S. (2023). Agent-based model for assessment of multiple circular economy strategies: Quantifying product-service diffusion, circularity, and sustainability. *Resources, Conservation and Recycling*, *199*, 107216. https://doi.org/https://doi.org/10.1016/j.resconrec.2023.107216 (cit. on p. 29).

Kolkwitz, M., Luotonen, E., & Huuhka, S. (2023). How changes in urban morphology translate into urban metabolisms of building stocks: A framework for spatiotemporal material flow analysis and a case study. *Environment and Planning B: Urban Analytics and City Science*, *50*(6), 1559–1576. https://doi.org/10.1177/23998083221140892 (cit. on pp. 8, 28).

Korhonen, J., Nuur, C., Feldmann, A., & Birkie, S. E. (2018). Circular economy as an essentially contested concept. *Journal of Cleaner Production*, *175*, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111 (cit. on p. 20).

Krausmann, F., Lauk, C., Haas, W., & Wiedenhofer, D. (2018). From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. *Global Environmental Change*, *52*, 131–140. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2018.07.003 (cit. on p. 3).

Kristensen, H. S., & Mosgaard, M. A. (2020). A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? [269 citations (Crossref) [2023-04-26]]. *Journal of Cleaner Production*, *243*, 118531. https://doi.org/10.1016/j.jclepro.2019.118531 (cit. on p. 20).

Lachmund, J. The city as ecosystem: Paul duvigneaud and the ecological study of brussels (N. provided, Ed.; 1st). In: *Spatializing the history of ecology* (N. provided, Ed.; 1st). Ed. by provided, N. 1st. Not provided: Routledge, 2017. Chap. 8, p. 21 (cit. on p. 27).

Lan, K., & Yao, Y. (2019). Integrating life cycle assessment and agent-based modeling: A dynamic modeling framework for sustainable agricultural systems. *Journal of Cleaner Production*, *238*, 117853. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.117853 (cit. on p. 29).

Lanau, M., & Liu, G. (2020). Developing an urban resource cadaster for circular economy: A case of odense, denmark [PMID: 32131592]. *Environmental Science & Technology*, *54*(7), 4675–4685. https://doi.org/10.1021/acs.est.9b07749 (cit. on pp. 9, 28).

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., & Thomas, C. J. (2012). Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustainability Science*, *7*(SUPPL. 1), 25–43. https://doi.org/10.1007/s11625-011-0149-x (cit. on p. 34).

Lavers Westin, A., Kalmykova, Y., Rosado, L., Oliveira, F., Laurenti, R., & Rydberg, T. (2019). Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption. *Journal of Cleaner Production*, *226*, 526–539. https://doi.org/10.1016/j.jclepro.2019.04.036 (cit. on pp. 9, 28).

Lawrence, M. G., Williams, S., Nanz, P., & Renn, O. (2022). Characteristics, potentials, and challenges of transdisciplinary research. *One Earth*, *5*(1), 44–61. https://doi.org/10.1016/j.oneear.2021.12.010 (cit. on p. 34).

Li, H., & Kwan, M.-P. (2018). Advancing analytical methods for urban metabolism studies. *Resources, Conservation and Recycling*, *132*, 239–245. https://doi.org/10.1016/j.resconrec.2017.07.005 (cit. on p. 15).

Lucertini, G., & Musco, F. (2020). Circular urban metabolism framework. *One Earth*, *2*(2), 138–142. https://doi.org/https://doi.org/10.1016/j.oneear.2020.02.004 (cit. on pp. 4, 6, 8, 15).

Lucertini, G., & Musco, F. Circular city: Urban and territorial perspectives (L. Amenta, M. Russo & A. Van Timmeren, Eds.) [Series Title: GeoJournal Library]. In: *Regenerative territories* (L. Amenta, M. Russo & A. Van Timmeren, Eds.). Ed. by Amenta, L., Russo, M., & Van Timmeren, A. Vol. 128. Series Title: GeoJournal Library. Cham: Springer International Publishing, 2022, pp. 123–134. ISBN: 978-3-030-78535-2 978-3-030-78536-9. https://doi.org/10.1007/978-3-030-78536-9_7 (cit. on p. 25).

Martin Calisto Friant, P. B. W. J. V. V., Katie Reid, & Salomone, R. (2023). Sustainable circular cities? analysing urban circular economy policies in amsterdam, glasgow, and copenhagen. *Local Environment*, *28*(10), 1331–1369. https://doi.org/10.1080/13549839.2023.2206643 (cit. on pp. 5, 22).

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2019). Measuring progress towards a circular economy: A monitoring framework for economy-wide material loop closing in the EU28. *Journal of Industrial Ecology*, *23*(1), 62–76. https://doi.org/10.1111/jiec.12809 (cit. on pp. 6, 19).

Mazur-Wierzbicka, E. (2021). Circular economy: Advancement of european union countries [Publisher: Springer Berlin Heidelberg]. *Environmental Sciences Europe*, *33*(1). https://doi.org/10.1186/s12302-021-00549-0 (cit. on p. 20).

Meadows, D. H., Meadows, D. l., Randers, J., & III, W. W. B. (1972). *The limits to growth: A report for the Club of Rome's project on the predicament of mankind*. Universe Books. (Cit. on p. 3).

Mhatre, P., Panchal, R., Singh, A., & Bibyan, S. (2021). A systematic literature review on the circular economy initiatives in the european union [Publisher: Elsevier B.V.]. *Sustainable Production and Consumption*, *26*, 187–202. https://doi.org/10.1016/j.spc.2020.09.008 (cit. on p. 20).

Micolier, A., Loubet, P., Taillandier, F., & Sonnemann, G. (2019). To what extent can agent-based modelling enhance a life cycle assessment? answers based on a literature review. *Journal of Cleaner Production*, *239*, 118123. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.118123 (cit. on p. 29).

Mies, A., & Gold, S. (2021). Mapping the social dimension of the circular economy. *Journal of Cleaner Production*, *321*, 128960. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.128960 (cit. on pp. 19, 20).

Miller, R., & Brewer, J. (2003). The A-Z of Social Research. https://doi.org/10.4135/9780857020024NV-0 (cit. on p. 34).

Monti, C., Pangallo, M., De Francisci Morales, G., & Bonchi, F. (2023). On learning agent-based models from data [Number: 1 Publisher: Nature Publishing Group]. *Scientific Reports*, *13*(1), 9268. https://doi.org/10.1038/s41598-023-35536-3 (cit. on p. 42).

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., De Meester, S., & Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, *146*, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045 (cit. on p. 19).

Moreau, V., Sahakian, M., van Griethuysen, P., & Vuille, F. (2017). Coming full circle: Why social and institutional dimensions matter for the circular economy. *Journal of Industrial Ecology*, *21*(3), 497–506. https://doi.org/https://doi.org/10.1111/jiec.12598 (cit. on p. 20).

Morphet, J., & Morphet, R. (2019). *New urban agenda: New urban analytics* (tech. rep.). The Bartlett Centre for Advanced Spatial Analysis, The MacArthur Project. (Cit. on p. 15).

Murray, A., Skene, K., & Haynes, K. (2017). The circular economy: An interdisciplinary exploration of the concept and application in a global context. *Journal of Business Ethics*, *140*(3), 369–380. https://doi.org/10.1007/s10551-015-2693-2 (cit. on pp. 17, 21).

Newman, P. W. (1999a). Sustainability and cities: Extending the metabolism model. *Landscape and Urban Planning*, *44*(4), 219–226. https://doi.org/10.1016/S0169-2046(99)00009-2 (cit. on pp. 6, 7).

Newman, P. W. (1999b). Sustainability and cities: Extending the metabolism model. *Landscape and Urban Planning*, *44*(4), 219–226. https://doi.org/https://doi.org/10.1016/S0169-2046(99)00009-2 (cit. on pp. 8, 28).

Nielsen, P., Tukker, A., Weidema, B., Lauridsen, E., Notten, P., & Eder, P. (2004). *Environmental impact of the use of natural resources* (tech. rep. No. EUR 21485 EN) (JRC29113). European Commission. (Cit. on p. 16).

Oakdene Hollins. (2017). *Towards a circular economy – waste management in the EU* (Publication Title: Scientific Foresight Unit (STOA) ISBN: 9789284615483). https://doi.org/10.2861/978568 (cit. on p. 19).

OECD. (2019). *Global material resources outlook to 2060.* https://doi.org/https://doi.org/https://doi.org/10.1787/9789264307452-en (cit. on p. 3).

OECD. (2019, February 12). *Global material resources outlook to 2060: Economic drivers and environmental consequences.* OECD. https://doi.org/10.1787/9789264307452-en (cit. on p. 3).

OECD. (2020). *A territorial approach to the Sustainable Development Goals* (tech. rep.). OECD Urban Policy Reviews. https://doi.org/https://doi.org/10.1787/e86fa715-en (cit. on p. 4).

Paiho, S., Mäki, E., Wessberg, N., Paavola, M., Tuominen, P., Antikainen, M., Heikkilä, J., Rozado, C. A., & Jung, N. (2020). Towards circular cities—conceptualizing core aspects. *Sustainable Cities and Society*, *59*, 102143. https://doi.org/https://doi.org/10.1016/j.scs.2020.102143 (cit. on pp. 23, 24).

Papageorgiou, A., Henrysson, M., Nuur, C., Sinha, R., Sundberg, C., & Vanhuyse, F. (2021). Mapping and assessing indicator-based frameworks for monitoring circular economy development at the city-level. *Sustainable Cities and Society*, *75*, 103378. https://doi.org/https://doi.org/10.1016/j.scs.2021.103378 (cit. on p. 22).

Papangelou, A., Bahers, J.-B., & Aissani, L. (2023). Drivers of urban metabolism: Toward a framework for urban transformations. *Journal of Industrial Ecology*, *27*(5), 1389–1405. https://doi.org/10.1111/jiec.13435 (cit. on pp. 8, 9).

Parchomenko, A., Nelen, D., Gillabel, J., & Rechberger, H. (2019). Measuring the circular economy - a multiple correspondence analysis of 63 metrics. *Journal of Cleaner Production*, *210*, 200–216. https://doi.org/10.1016/j.jclepro.2018.10.357 (cit. on p. 19).

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., & Spangenberg, J. H. (2019). *Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability.* European Environmental Bureau. https://eeb.org/library/decoupling-debunked/ (cit. on p. 21).

Patricio, J., Angelis-dimakis, A., Castillo-castillo, A., Kalmykova, Y., & Rosado, L. (2017). Method to identify opportunities for CCU at regional level — Matching sources and receivers. *Journal of CO2 Utilization*, *22*(September), 330–345. https://doi.org/10.1016/j.jcou.2017.10.009 (cit. on pp. 9, 28).

Patricio, J., Kalmykova, Y., & Rosado, L. (2020). A method and databases for estimating detailed industrial waste generation at different scales – With application to biogas industry development. *Journal of Cleaner Production*, *246*, 118959. https://doi.org/10.1016/j.jclepro.2019.118959 (cit. on pp. 8, 28).

Perera, A. T. D., Nik, V. M., & Chen, e. a., Di. (2020). Quantifying the impacts of climate change and extreme climate events on energy systems. *Nature Energy*, *5*, 150–159. https://doi.org/10.1038/s41560-020-0558-0 (cit. on p. 4).

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., & Hauschild, M. Z. (2022). Outside the safe operating space of the planetary boundary for novel entities [PMID: 35038861]. *Environmental Science & Technology*, *56*(3), 1510–1521. https://doi.org/10.1021/acs.est.1c04158 (cit. on p. 3).

Pincetl, S., Bunje, P., & Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape* *and Urban Planning*, *107*(3), 193–202. https://doi.org/10.1016/j.landurbplan.2012.06.006 (cit. on p. 6).

Planning and Building Committee. (2014). Development Strategy Göteborg 2035 [Approved by the Planning and Building Committee in February 2014]. (Cit. on p. 40).

Polk, M. (2014). Achieving the promise of transdisciplinarity: a critical exploration of the relationship between transdisciplinary research and societal problem solving. *Sustainability Science*, *9*(4), 439–451. https://doi.org/10.1007/s11625-014-0247-7 (cit. on p. 33).

Porse, E., Derenski, J., Gustafson, H., Elizabeth, Z., & Pincetl, S. (2016). Structural, geographic, and social factors in urban building energy use: Analysis of aggregated account-level consumption data in a megacity. *Energy Policy*, *96*, 179–192. https://doi.org/10.1016/j.enpol.2016.06.002 (cit. on p. 8).

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain* (tech. rep.) (English translation of the report 'Circulaire economie: Innovatie meten in de keten', PBL publication number: 2544. Corresponding author: jose.potting@pbl.nl). PBL Netherlands Environmental Assessment Agency. The Hague. (Cit. on p. 16).

Prendeville, S., Cherim, E., & Bocken, N. (2018). Circular cities: Mapping six cities in transition. *Environmental Innovation and Societal Transitions*, *26*, 171–194. https://doi.org/10.1016/j.eist.2017.03.002 (cit. on pp. 21, 24).

Raimbault, J., Broere, J., Somveille, M., Serna, J. M., Strombom, E., Moore, C., Zhu, B., & Sugar, L. (2020). A spatial agent based model for simulating and optimizing networked eco-industrial systems. *Resources, Conservation and Recycling*, *155*, 104538. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.104538 (cit. on p. 29).

Ramage, M., & Shipp, K. (2020). Howard odum. In *Systems thinkers* (pp. 85–94). Springer London. https://doi.org/10.1007/978-1-4471-7475-2_9 (cit. on p. 27).

Rapport, D., & Friend, A. (1979). Towards a comprehensive framework for environmental statistics: A stress-response approach. *Statistics Canada 11-510,Ottawa* (cit. on p. 8).

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? — exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.08.027 (cit. on p. 16).

Renn, O. (2021). Transdisciplinarity: Synthesis towards a modular approach. *Futures*, *130*, 102744. https://doi.org/10.1016/j.futures.2021.102744 (cit. on p. 33).

Rittel, H, & Webber, M. (1973). Planning problems are wicked problems. (Cit. on p. 5).

Ritzén, S., & Sandström, G. (2017). Barriers to the circular economy – integration of perspectives and domains. *Procedia CIRP*, *64*, 7–12. https://doi.org/10.1016/j.procir.2017.03.005 (cit. on p. 21).

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., . . . Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. https://doi.org/10.1038/461472a (cit. on p. 3).

Rodriguez-Anton, J. M., Rubio-Andrada, L., Celemín-Pedroche, M. S., & Alonso-Almeida, M. D. M. (2019). Analysis of the relations between circular economy and sustainable development goals. *International Journal of Sustainable Development & World Ecology*, *26*(8), 708–720. https://doi.org/10.1080/13504509.2019.1666754 (cit. on p. 20).

Romanello, M., McGushin, A., Di Napoli, C., Drummond, P., Hughes, N., Jamart, L., Kennard, H., Lampard, P., Solano Rodriguez, B., Arnell, N., Ayeb-Karlsson, S., Belesova, K., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Chu, L., Ciampi, L., Dalin, C., . . . Hamilton, I. (2021). The 2021 report of the lancet countdown on health and climate change: Code red for a healthy future. *The Lancet*, *398*(10311), 1619–1662. https://doi.org/10.1016/S0140-6736(21)01787-6 (cit. on p. 4).

Rosado, L., Kalmykova, Y., & Patrício, J. (2016). Urban metabolism profiles. an empirical analysis of the material flow characteristics of three metropolitan areas in sweden. *Journal of Cleaner Production*, *126*, 206–217. https://doi.org/10.1016/j.jclepro.2016.02.139 (cit. on pp. 8, 9, 25, 28).

Rosado, L., Niza, S., & Ferrão, P. (2014). A material flow accounting case study of the lisbon metropolitan area using the urban metabolism analyst model. *Journal of Industrial Ecology*, *18*(1), 84–101. https://doi.org/https://doi.org/10.1111/jiec.12083 (cit. on pp. 6, 9).

Saltelli, A., Bammer, G., Bruno, I., Charters, E., Di Fiore, M., Didier, E., Nelson Espeland, W., Kay, J., Lo Piano, S., Mayo, D., Pielke Jr, R., Portaluri, T., Porter, T. M., Puy, A., Rafols, I., Ravetz, J. R., Reinert, E., Sarewitz, D., Stark, P. B., & et al. (2020). Five ways to ensure that models serve society: A manifesto. *Nature*, *582*(7813), 482–484. https://doi.org/10.1038/d41586-020-01812-9 (cit. on p. 77).

Sauvé, S., Bernard, S., & Sloan, P. (2016). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development*, *17*, 48–56. https://doi.org/https://doi.org/10.1016/j.envdev.2015.09.002 (cit. on p. 34).

Savini, F. (2019). The economy that runs on waste: Accumulation in the circular city. *Journal of Environmental Policy & Planning*, *21*(6), 675–691. https://doi.org/10.1080/1523908X.2019.1670048 (cit. on p. 22).

Schmidt, D. N. (2022). Summary for policymakers: Climate change 2022: Impacts, adaptation and vulnerability. contribution of working group ii to the sixth assessment report of the intergovernmental panel of climate change (ipcc) (cit. on p. 4).

Schroeder, P. (2018). The Relevance of Circular Economy Practices to the Sustainable Development Goals. *23*(1), 77–95. https://doi.org/10.1111/jiec.12732 (cit. on p. 20).

Shahrokni, H., Levihn, F., & Brandt, N. (2014). Big meter data analysis of the energy efficiency potential in stockholm's building stock. *Energy and Buildings*, *78*, 153–164. https://doi.org/10.1016/j.enbuild.2014.04.017 (cit. on p. 28).

Sikdar, S. (2019). Circular economy: Is there anything new in this concept? *Clean Technologies and Environmental Policy*, *21*(6), 1173–1175. https://doi.org/10.1007/s10098-019-01722-z (cit. on p. 16).

Sileryte, R., Sabbe, A., Bouzas, V., Meister, K., Wandl, A., & van Timmeren, A. (2022). European waste statistics data for a circular economy monitor: Opportunities and limitations from the amsterdam metropolitan region. *Journal of Cleaner Production*, *358*, 131767. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131767 (cit. on p. 28).

Sileryte, R., Wandl, A., & Timmeren, A. (2023). A bottom-up ontology-based approach to monitor circular economy: Aligning user expectations, tools, data and theory. *Journal of Industrial Ecology*, *27*. https://doi.org/10.1111/jiec.13350 (cit. on p. 28).

Silva, E. A., Healey, P., Harris, N., & Van Den Broeck, P., eds. *The routledge handbook of planning research methods* (0th ed.). 0th ed. Routledge, 2014, August 21. ISBN: 978-1-317-91703-8. https://doi.org/10.4324/9781315851884 (cit. on pp. 33, 34).

Silvestri, F., Spigarelli, F., & Tassinari, M. (2020). Regional development of circular economy in the european union: A multidimensional analysis [Publisher: Elsevier Ltd]. *Journal of Cleaner Production*, *255*, 120218. https://doi.org/10.1016/j.jclepro.2020.120218 (cit. on p. 20).

Singleton, A., & Arribas-Bel, D. (2021). Geographic data science. *Geographical Analysis*, *53*(1), 61–75. https://doi.org/https://doi.org/10.1111/gean.12194 (cit. on p. 6).

Smeets, E., Weterings, R., et al. (1999). Environmental indicators: Typology and overview (cit. on p. 28).

Song, Y. A., Gil, J. A., Wandl, A. A., & Timmeren, A. v. A. (2018). Evaluating sustainable urban development using urban metabolism indicators in urban design. http://rcin.org.pl/igipz/Content/86608/PDF/WA51_110712_r2018-t34_EuropaXXI-Song.pdf (cit. on p. 28).

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *Anthropocene Review*, *2*(1), 81–98. https://doi.org/10.1177/2053019614564785 (cit. on p. 3).

Steward T.A. Pickett, M. C., Brian McGrath, & Felson, A. J. (2014). Ecological resilience and resilient cities. *Building Research & Information*, *42*(2), 143–157. https://doi.org/10.1080/09613218.2014.850600 (cit. on p. 26).

Storey, V. C. (1991). Relational database design based on the entity-relationship model. *Data and Knowledge Engineering*, *7*(1), 47–83. https://doi.org/10.1016/0169-023X(91)90033-T (cit. on p. 36).

Superti, V., Merino-Saum, A., Baur, I., & Binder, C. (2021). Unraveling how the concept of circularity relates to sustainability: An indicator-based meta-analysis applied at the urban scale. *Journal of Cleaner Production*, *315*, 128070. https://doi.org/10.1016/j.jclepro.2021.128070 (cit. on pp. 19, 22).

Sweco. (2023). *Circular city transformation* [Accessed: 7th May 2024]. https://www.swecogroup.com/wp-content/uploads/sites/2/2023/02/Report-by-Sweco_Circular-City-Transformation_A4.pdf (cit. on p. 5).

Tscherning, K., Helming, K., Krippner, B., Sieber, S., & Paloma, S. G. Y. (2012a). Does research applying the DPSIR framework support decision making? *Land Use Policy*, *29*(1), 102–110. https://doi.org/10.1016/j.landusepol.2011.05.009 (cit. on p. 8).

Tscherning, K., Helming, K., Krippner, B., Sieber, S., & y Paloma, S. G. (2012b). Does research applying the dpsir framework support decision making? *Land Use Policy*, *29*(1), 102–110. https://doi.org/https://doi.org/10.1016/j.landusepol.2011.05.009 (cit. on p. 28).

Tseng, M.-L., Tan, R. R., Chiu, A. S. F., Chien, C.-F., & Kuo, T. C. (2018). Circular economy meets industry 4.0: Can big data drive industrial symbiosis? *Resources, Conservation and Recycling*, *131*, 146–147. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.12.028 (cit. on p. 15).

United Nations. (2008). Spatial Planning - Key Instrument for Development and Effective Governance with Special Reference to Countries in Transition. *Economic Commission for Europe*, 1–56 (cit. on p. 5).

United Nations Conference of Housing and Sustainable Urban Development. (2016). Habitat III, New Urban Agenda. (October), 24 (cit. on p. 4).

United Nations Human Settlements Programme. (2020, October 31). Unpacking the value of sustainable urbanization [Series Title: World Cities Report]. In *World cities report 2020* (pp. 43–74). UN. https://doi.org/10.18356/c41ab67e-en (cit. on p. 4).

Vadén, T., Lähde, V., Majava, A., Järvensivu, P., Toivanen, T., Hakala, E., & Eronen, J. T. (2020). Decoupling for ecological sustainability: A categorisation and review of research literature. *Environmental Science & Policy*, *112*, 236–244. https://doi.org/10.1016/j.envsci.2020.06.016 (cit. on p. 21).

Velenturf, A. P., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption*, *27*, 1437–1457. https://doi.org/https://doi.org/10.1016/j.spc.2021.02.018 (cit. on p. 20).

Verga, G. C., & Khan, A. Z. (2022). Space matters: Barriers and enablers for embedding urban circularity practices in the brussels capital region. *Frontiers in Built Environment*, *8*. https://doi.org/10.3389/fbuil.2022.810049 (cit. on pp. 23, 24).

Vicedo-Cabrera, A. M., Scovronick, N., & Sera, e. a., Francesco. (2021). The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change*, *11*, 492–500. https://doi.org/10.1038/s41558-021-01058-x (cit. on p. 4).

Walmsley, T. G., Ong, B. H., Klemeš, J. J., Tan, R. R., & Varbanov, P. S. (2019). Circular integration of processes, industries, and economies. *Renewable and Sustainable Energy Reviews*, *107*, 507–515. https://doi.org/10.1016/j.rser.2019.03.039 (cit. on p. 21).

Wang, M.-H., Ho, Y.-S., & Fu, H.-Z. (2019). Global performance and development on sustainable city based on natural science and social science research: A bibliometric analysis. *Science of The Total Environment*, *666*, 1245–1254. https://doi.org/10.1016/j.scitotenv.2019.02.139 (cit. on p. 21).

Wang, N., Lee, J. C. K., Zhang, J., Chen, H., & Li, H. (2018). Evaluation of urban circular economy development: An empirical research of 40 cities in china [Publisher: Elsevier Ltd]. *Journal of Cleaner Production*, *180*, 876–887. https://doi.org/10.1016/j.jclepro.2018.01.089 (cit. on p. 22).

Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P. W., Gleeson, T., Cornell, S. E., Steffen, W., Bai, X., & Rockström, J. (2022). A planetary boundary for green water. *Nature Reviews Earth & Environment* (cit. on p. 3).

Wegener, M. (1998). Gis and spatial planning. *Environment and Planning B: Planning and Design*, *25*(7), 48–52. https://doi.org/10.1177/239980839802500709 (cit. on p. 5).

Weisz, H., & Steinberger, J. K. (2010). Reducing energy and material flows in cities. *Current Opinion in Environmental Sustainability*, *2*(3), 185–192. https://doi.org/https://doi.org/10.1016/j.cosust.2010.05.010 (cit. on p. 28).

Williams, J. (2023). Circular cities: Planning for circular development in european cities. *European Planning Studies*, *31*(1), 14–35. https://doi.org/10.1080/09654313.2022.2060707 (cit. on pp. 21, 23).

Wolman, A. (1965). The metabolism of cities. *Scientific American*, *213*, 179–190. https://doi.org/10.1038/scientificamerican0965-178 (cit. on p. 26).

World Economic Forum. (2015). *Intelligent assets: Unlocking the circular economy potential* (Report No. REF 081215). World Economic Forum. https://www3.weforum.org/docs/WEF_Intelligent_Assets_Unlocking_the_Cricular_Economy.pdf (cit. on p. 7).

Wu, K.-J., Hou, W., Wang, Q., Yu, R., & Tseng, M.-L. (2022). Assessing city's performance-resource improvement in china: A sustainable circular economy framework approach. *Environmental Impact Assessment Review*, *96*, 106833. https://doi.org/https://doi.org/10.1016/j.eiar.2022.106833 (cit. on p. 22).

Zeller, V., Towa, E., Degrez, M., & Achten, W. M. (2019). Urban waste flows and their potential for a circular economy model at city-region level. *Waste Management*, *83*, 83–94. https://doi.org/10.1016/j.wasman.2018.10.034 (cit. on p. 22).

Zhang, Y., Yang, Z., & Yu, X. (2015). Urban metabolism: A review of current knowledge and directions for future study. *Environmental Science & Technology*, *49*(19), 11247–11263. https://doi.org/10.1021/acs.est.5b03060 (cit. on pp. 6–9, 15).

Zhao, Q., Yu, P., Mahendran, R., Huang, W., Gao, Y., Yang, Z., Ye, T., Wen, B., Wu, Y., Li, S., & Guo, Y. (2022). Global climate change and human health: Pathways and possible solutions. *Eco-Environment & Health*, *1*(2), 53–62. https://doi.org/https://doi.org/10.1016/j.eehl.2022.04.004 (cit. on p. 4).

Part II

Appended Papers

Paper I

An entity-relationship model of the flow of waste and resources in city-regions: Improving knowledge management for the circular economy

J. Cohen & J. Gil

Resources, Conservation & Recycling Advances 12 (September 2021)

12 (2021) 200058

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

An entity-relationship model of the flow of waste and resources in city-regions: Improving knowledge management for the circular economy

Jonathan Cohen*, Jorge Gil

Department of Architecture and Civil Engineering, Chalmers University of Technology, Sven Hultins gata 6, SE-412 96 Göteborg, Sweden

ARTICLE INFO

Keywords:
Circular cities
Waste management
Circular economy
Industry 4.0
Entity-relationship model
SQL

ABSTRACT

Waste and resources management is one of the domains where urban and regional planning can transition towards a Circular Economy, thus slowing environmental degradation. Improving waste and resources management in cities requires an adequate understanding of multiple systems and how they interact. New technologies contribute to improve waste management and resource efficiency, but knowledge silos hinder the possibility of delivering sound holistic solutions. Furthermore, lack of compatibility between data formats and diverse definitions of the same concept reduces information exchange across different urban domains. This paper addresses the challenge of organising and standardising information about waste and resources management in city regions.

Given the amount and variety of data constantly captured, data models and standards are a crucial element of Industry 4.0. The paper proposes an Entity-Relationship Model to harmonise definitions and integrate information on waste and resources management. Furthermore, it helps to formalise the components of the system and their relationships. Semi-structured interviews with government officials, mobile app developers and academics provided insights into the specific system and endorsed the model. Finally, the paper illustrates the translation of the ERM into a relational database schema and instantiates Waste Management and industrial Symbiosis cases in Buenos Aires (ARG) and Helsingborg (SWE) to validate its general applicability. The data model for the Circular Flow of Waste and Resources presented here enhances traditional waste management perspectives by introducing Circular Economy strategies and spatial variables in the model. Thus, this research represents a step towards unlocking the true potential of Industry 4.0.

Introduction

The current linear economy, based on "take-make-dispose", is unsustainable; in the year 2020, only 8.6% of global resources were being reused (Circle Economy 2020). To satisfy the material needs of this traditional economic system, we need 1.7 Planet Earths (Lin et al. 2018), forcing life to operate beyond its safe limits (Steffen et al. 2015). Humans need to act urgently to avoid irreversible damage to the environment (Policymakers 2018). Thus, the Circular Economy (CE) paradigm has gained momentum among academics, practitioners, and policymakers as a promising alternative. This paradigm seeks to maximise resources utilisation by following the 3Rs principle: Reduce, Reuse, and Recycle. The CE focus on eco-effectiveness instead of eco-efficiency (Toxopeus, De Koeijer, and Meij 2015) by decoupling economic growth from the extraction of natural resources (Kjaer et al. 2019).

Simultaneously, cities play a crucial role in meeting the Paris Agreement and Sustainable Development Goals (SDGs) (European Commission 2018; OECD 2020). Although urban areas only occupy 2% of the world's total land area, they are hotspots of resources consumption and resulting wastes (Themelis 2019). Cities are globally responsible for producing 70% of the wealth, 70% of the waste, and 70% of the greenhouse gases (United Nations Conference of Housing and Sustainable Urban Development 2016).

The Circular Cities Hub[1] defines a Circular City as a place where (1) "resources can be cycled between urban activities, within city regions" and (2) "cities can be designed so that land and infrastructure can be reused/recycled over time". One area of spatial planning that can directly contribute to (1) is waste management (Gravagnuolo, Angrisano, and Girard 2019; ESPON (European Spatial Planning Observation Network) 2019), and solving this problem requires a holistic approach

---

* Corresponding author at: halmers University of Technology: Chalmers tekniska hogskola, Sweden.
E-mail address: jonathan.cohen@chalmers.se (J. Cohen).

[1] http://circularcitieshub.com

https://doi.org/10.1016/j.rcradv.2021.200058
Received 23 July 2021; Received in revised form 2 September 2021; Accepted 8 September 2021

that integrates knowledge from different domains.

According to P. Hall a systems approach must be adopted when dealing with spatial planning issues, and that planning should be "[...] exploratory and instructive. It should aim to help communities think clearly and logically about resolving their problems (...). In other words, it should aim to provide a resource for democratic and informed decision-making" (Hall 1992, Ch. 1 & 9) and technological ubiquity and open-data can contribute to materialise these ideas. Moreover, he reminds us that computer-aided systems ('cybernated planning') do not necessarily imply making planning more straightforward but making it more flexible. By considering more information, planning becomes 'potentially' more rational. As more information is needed to tackle complex challenges, the need for adequate Information Systems and Knowledge Management (KM) also increases (Reyes-Córdoba, Sharratt, and Arizmendi-Sánchez 2008; Israilidis, Odusanya, and Mazhar 2021).

An entire ecosystem of new technologies is being developed and deployed to improve waste and resources management. In industrial terms, this is often known as the fourth Industrial Revolution or Industry 4.0, and known as intelligent, data-driven, smart, or digital cities in urban studies and with regards to city management. Digitisation processes (such as IoT, big data, and information processing) are fundamental to achieving several of the SDGs (Batty et al. 2012; Lang et al., 2018). Waste management has used these technologies for (i) Data capture and development of sensor-based technologies, (ii) Data transmission and communication, (iii) Testing capabilities and IoT experiments, and (iv) Tracking routing and achieving efficient operations (Esmaeilian et al. 2018; Hannan et al. 2015). Digitalisation processes have shown to improve resource use in city regions, for instance, addressing resource scarcity (Perkins et al. 2014), material criticality (danger) (Chauhan, Jakhar, and Chauhan 2021; Chou and Fan 2010), or the financial burden on local authorities (Huang et al. 2018; Oliveira Neto et al. 2017).

Although Industry 4.0 is supporting spatial planning processes and the CE, data continues to be sparse and heterogeneous in frequency, geography and quality, and solutions overlap, making it difficult to track progress towards the CE. The development and use of common data standards can enhance collaboration and information exchange between governmental agencies (Kontokosta 2018). (Lam 2005) reports that "lack of architecture interoperability" and "incompatible technical standards" are fundamental barriers for e-government integration; hence, the importance of data standardisation and of adopting a standard data model to secure a common definition of concepts. Comprehensive reviews of how industry 4.0 is contributing to deliver CE and more sustainable production practices agree that future research needs to take a multidisciplinary approach to include different perspectives (Alnajem, Mostafa, and ElMelegy 2021). In particular, Lang et al., 2021 highlight the need "for a well-understood digitization standard, and each stage of this process needs to be clarified and proceeded." More specifically, lack of standardisation is among the most critical barriers to developing smart waste management systems (Sharma et al. 2020; Rajput and Singh 2018). One can identify a mismatch between the amount of data generated to manage waste and resources, and the capacity to handle these new data sources to deliver sustainable urban planning and waste management.

Looking at other urban planning domains, one can find examples where this mismatch has been addressed. The General Transit Feed Specification [2](GTFS) is a data standard for public transport services that has revolutionised how public transport is managed and studied in cities. Thanks to this development, both logistic operations have improved, citizens can plan their trips more easily (Bob 2000, Ch. 10), and numerous digital tools and research projects have been delivered. In terms of information integration, Land Use and Transportation Integration Models (LUTI) empirically explore the relationship between the land use and transport systems. The integrated modelling of these urban systems has allowed planners to explore future scenarios and analyse how their realisation might impact urban dynamics (Acheampong and Silva 2015). Finally, CityGML [3] is an open data standard developed to represent and exchange 3d city models. Besides being an example of how a data standard can ease information exchange for different application domains, it allows models to be expanded and scaled up. Since adopters of the standard share the same point of departure -database structure-, it is easy to develop extensions for new urban domains such as water and energy systems.

Given the outstanding challenges of digitalisation in the waste and resources management domain, and inspired by the examples from other domains, the objective of this study is to improve KM for the CE in city regions by proposing a data model for Circular Flow of Waste and Resources (CFWR). On the one hand, data models offer researchers and practitioners that work with resource usage a structured means to store and query data. On the other hand, standardising data inputs and outputs allows researchers and practitioners to build scalable analytical tools. This study considers waste management in its most comprehensive form, where waste is a by-product of human activity with potential value for reuse as a resource. The scope is limited to the process of closing material loops by focusing on the following phases of a typical supply chain cycle: Collection and Disposal, Recycling and Recovery, Circular Inputs and Manufacturing (Kalmykova, Sadagopan, and Rosado 2018). The study adopts a methodology that includes an on-desk literature survey, a data model development process, and stakeholder engagement through interviews for both knowledge acquisition and validation of the results.

The paper is organised as follows. Section 2 presents previous efforts to manage knowledge about waste and resources by developing data standards or models. Section 3 describes the methodology, followed by Section 4 presenting the results: a conceptual diagram of the system, formalised into an Entity-Relationship model (ERM), and translated into a relational database schema for demonstration purposes. Section 5 illustrates how the model can be applied, and was validated using four cases relevant to waste management and industrial symbiosis. The paper concludes by discussing the results and giving indications for future research.

Related work

This section reviews efforts to manage knowledge about waste and resources in city regions in a context of digitalisation. The first part covers significant contributions that use elements of Industry 4.0 to tackle environmental challenges, namely specific applications for waste management, industrial symbiosis and urban metabolism, showing what information is being captured and how it is stored. In the second part, existing (and developing) data standards and solutions to organise information about waste and resources are presented.

Industry 4.0 applications

As reviewed in (Esmaeilian et al. 2018), technological advancement in waste management has focused on 4 areas: data acquisition and sensor-based technologies; communication technologies and data transmission infrastructure; the capabilities of IoT systems in field experiments; and truck routing and scheduling for waste collection operations. After the review the authors suggest that a centralised waste management system is needed and they emphasise on the importance of collecting data on the lifecycle of products and the use of IoT to provide real-time data.

Several studies introduce devices to capture information about the status of waste bins, such as temperature, humidity, or current capacity

---

[2] https://developers.google.com/transit/gtfs

[3] https://www.ogc.org/standards/citygml

(Gutierrez et al. 2015). Information about the status of waste bins can be used to optimise collection routes, and real-time data can make this process even more efficient (Faccio, Persona, and Zanin 2011). In other cases, information about collection trucks, resource consumption, emissions, current position and time is being generated and used to optimise waste management operations (Arribas, Blazquez, and Lamas 2010; Bing et al. 2014). On a related note, the Trash Truck MIT [4] project uses 'digital dust' to map the flow of specific waste streams. By embedding GPS devices in waste objects, the researchers were able to gather accurate data about how waste moves in space and time, which is crucial to control what happens in the real world and validate plans and models.

Individual smartphones have also become devices for capturing data relevant to waste and resources management. UnWaste [5] and Litterati [6] are two examples of crowd-sourced platforms that allow users to upload data about waste disposed on streets and open spaces.

These new data sources can be relevant to planners when the information is integrated with social and built environment data sets. For instance, to identify if sufficient waste bins exist near littered objects, or if waste accumulates near specific activities such as fast-food chains or transportation hubs. Although all these projects focus on developing the IoT device and smartphone technology for data collection, and can enhance waste management operations, the importance of managing the data generated and of using an adequate database structure is recognised (Maksimovic 2016; Hannan and Zailah 2012). Medvedev et al. (2015) propose a Smart waste management system to reduce collection inefficiencies. Their system integrates real time operation data, cameras and sensors to populate a system that automatically improve several performance indicators. By incorporating surveillance cameras and dynamic routing, their system proves to improve collection times.

Vitorino de Souza, et al., (Vitorino de Souza Melaré et al. 2017) provide a systematic review of the various technologies used in Decision Support Systems (DSS) for waste management. They noted that the use of database technology was sparse, and consequently it was grouped with other tools and methods, making it impossible to discriminate the extent and purpose of use of this technology. Despite the variety of DSS created to address different operative and strategic questions in waste and resources management, these tools are hardly used in practice because of their limited or lacking support for interpreting the results. Furthermore, the spatial dimension relevant to city planning is mainly considered when studying logistics or location problems (Uran and Janssen 2003; Rubenstein-Montano 2000).

In a recent example, the Repair project [7] released an open-source Geo-design Decision Support Environment (GDSE) that can be used as a co-creation planning tool in workshops, to define spatial strategies for waste exchanges to support IS (Arciniegas et al. 2019). The tool is innovative since it provides a bottom-up approach, overcoming several of the barriers discussed in Uran and Janssen (2003). During the workshop, knowledge from experts is extracted and captured in the GDSE, and the data is stored in a geo-server. The tool integrates perspectives of various actors to understand how different circular economy strategies can affect resource usage in city-regions. The GDSE allows users to explore visually and interactively various territorial strategies, and contributes to illustrating the strong relationship between spatial planning and urban metabolism.

Although, it was designed as a co-creation tool, it relies on detailed information about waste flows in urban areas, so it would be important to detail what information and with what level of granularity is required to use the GDSE. This information could be valuable to design top-down approaches where algorithms are used to determine what scenarios provide better outcomes.

Metabolic studies of cities are known for being data intensive and obtaining the necessary data is critical and time-consuming. Metabolism of Cities [8] is an ambitious crowd-sourced effort that addresses this challenge by providing a hub of all the data needed to estimate the metabolic process of various cities. Although volunteers have initiated collecting information on more than 60 cities, data and documents can be uploaded without a strict protocol, resulting in variability in completeness and quality. A data standard or protocol could help solve this problem, and would provide a structured database for the tools developed to calculate urban metabolism. Shahrokni, Lazarevic, and Brandt (2015) try to reduce the existing data gap in urban metabolism studies by exploring how the Smart City paradigm can support urban metabolism calculations. Smart Citizens can contribute by providing individual spatial data about their consumption behaviours and daily practices, such as transportation or what and when they use electronic devices. These new bottom-up data are more granular than environmental statistics and might play an essential role in establishing urban metabolism concepts at a neighbourhood or household level.

GeoFluxus [9], a spin-off platform from the Repair project is a clear example of how spatial information about waste materials can be used to advise governments and industries to better use resources. It resembles in function an industrial symbiosis facilitator, and illustrates how digital platforms that organise this knowledge can have positive effects over enhancing industrial networks. Yet, after reviewing various IS networks, (Paquin and Howard-Grenville 2012; Domenech et al., 2018; Bacudio et al. 2016) conclude that there is a major need for harmonised frameworks to analyse and enhance industrial symbiosis practices. Efforts to reduce this gap have explored how semantic web technology can contribute to capture information about industries and automatically identify potential waste exchanges. For example, (Song et al. 2017) exploits information available in web sites of companies and extracts valuable data that is needed to understand if two firms could be matched to exchange resources. The process relies on other databases and projects with the objective of standardising information about waste, pollution or industrial processes. A comprehensive list of available data sources is provided in the study. Similar approaches were taken in (Ghali and Frayret 2019), (Cecelja et al. 2015), but in these cases ontologies are used to model tacit and explicit knowledge extracted from the industries' web sites. These latter studies are important first steps that show how public information on the internet can be exploited and organised to initiate industrial exchanges.

The works covered in this section illustrate how Industry 4.0 is improving waste and resource management. Significant IoT, data analytics and DSS are being developed and applied, but diversity and lack of harmonisation of data and models hinder their widespread usage. Recent bibliometric reviews (Alnajem, Mostafa, and ElMelegy 2021; Lang et al., 2021) identified that standardisation and clarification of processes through digitalisation are essential to materialise the CE. And as suggested by Chou and Fan (2010), effective KM can provide a shared background for constructing long-term solutions.

Data management and standards in waste and resources management

System integration is at the core of the Smart Cities paradigm, and developing and adopting data standards is essential to exchange information easily. For example, in the UK, Manchester municipality is working with Dsposal [10] to develop a data standard for residential waste recycling centres [11]. The project aims to harmonise information on Household Waste Recycling Centres across the municipality to overcome

---

[4] https://senseable.mit.edu/trashtrack/

[5] https://www.unwaste.io/

[6] https://www.litterati.org/

[7] http://h2020repair.eu/

[8] http://metabolismofcities.org

[9] https://www.geofluxus.com/

[10] https://dsposal.uk

[11] https://github.com/OpenDataManchester/Open3R

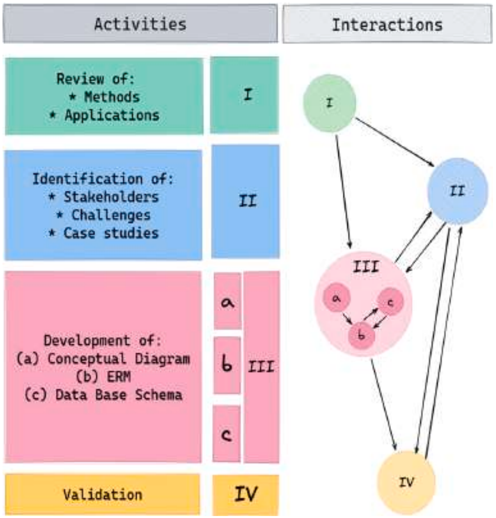


Fig. 1. Methodological stages and their interactions.

the challenge of information availability, variability, and quality. By adopting a data standard, the city expects to improve its waste management operations by providing reliable and uniform information to its citizens. Technology advances at a fast pace and individual actors can generate significant contributions outside government and academia, thus GitHub and other collaborative platforms need to be surveyed to capture the state of the art of industry 4.0 in various domains. For example, the Smart Data Models [12] initiative is currently hosting a data model of waste containers, that was not mentioned in the literature surveyed. The model includes an extensive description of the container object, container model specification and clusters of containers (named ’islands’) that can help municipalities to better manage such information.

Research on semantics and domain specific ontologies contributes to integrating heterogeneous systems, consequently plays a crucial role in multidisciplinary practices like sustainable urban planning. Web semantics apply ontological models to translate explicit knowledge about a domain by defining concepts and the relationships between them. These translations are computer readable, support executing calculation and automated processes, and in particular ontologies allow information interoperability across systems. For example, Howell, Rezgui, and Beach (2017) proposes an ontology to enhance water management systems by incorporating components of the demand-side. However, ontology construction is complex and requires the engagement of various experts to provide knowledge about city systems and how the technology can be deployed (Sattar et al. 2021; Ahmad et al. 2018). provide a methodology to construct ontologies using municipal waste management as a case study. They create an ontology called OntoWM for waste management and present how it can manage smart bins. The method used to construct OntoWM is useful for developing other data models and standards, like the ones presented later on in this paper.

The use of ontologies is used to tackle the challenge of dealing with radioactive waste materials, (Chou and Fan 2010) propose an architecture and data structure to exchange and store information systematically. The data model proves to be helpful by showing how an agent model can navigate the XML document to maintain and manage critical information of the system. Although, the radioactive waste system can be seen as simpler (i.e. in terms of diversity of actors and having only waste stream), this study contributes to comprehend the potential behind handling knowledge adequately. Throughout the study, one can appreciated the central role played by well structured databases, on which several stages of this development depend on.

While discussing the future of Industrial Ecology, (Davis, Nikolic, and Dijkema 2010) highlights that these studies require data sources that are usually ’unavailable, inaccessible, incomplete, incompatible, or unreliable’ (as cited in (Ravalde and Keirstead 2017)), and data standards and protocols could help to improve cohesion across the discipline. To handle industrial waste and support industrial symbiosis strategies, the Maestri Horizon 2020 project [13] created the first database of existing industrial symbiotic relationships. Using NACE codes [14] to categorise industrial activity, and List of Waste (LoW) codes [15] to define waste streams, it is possible to understand what industries have taken secondary materials as inputs (Baptista et al. 2018; Holgado et al. 2019; Ferrera et al. 2017). Using two standardised nomenclatures helps extract knowledge from the database by a wider community of stakeholders in a systematic way. Namely, (Patricio et al. 2017) exploits the database to explore all the possible industrial exchanges in a Swedish region for a specific industry sector. In another example, (Ravalde and Keirstead 2017) developed a first of its kind data set that contains information about 202 production methods, and illustrate how information about capacity, production method used, and materials needed to perform a specific process can be managed. Future studies can use the exact specification to estimate environmental impacts, in a comparable, replicable, and validated approach.

Fundamental research about databases and data standards are at the core of Industry 4.0 advancements. On the one hand, effective databases are needed to host data captured by the growing IoT applications. On the other hand, standards and protocols help in the digitalisation process by providing structured and comprehensive information that can be processed by machines. Several of the previously cited works have identified the mismatch between big data (i.e. large volume, velocity, veracity and variety) of data generated and the need to organise it. In the following section, the methodology used to develop a data model for waste and resources is detailed.

Methodology

The methodology followed in this study to develop the proposed data model for Circular Flow of Waste and Resources in city-regions (CFWR) adapts previous methods for building information systems (Storey 1991), and can be decomposed into four main activities: (i) Desk literature survey, (ii) Engagement with stakeholders, (iii) Development of the data model, and (iv) Validation using case studies. Activities (i) and (ii) helped understand the system, identify the problems and case studies, and set the solution’s scope in light of related efforts. With the support of these activities, the model was designed and developed in activity (iii), and activity (iv) was performed to demonstrate and evaluate the main output of this research. Fig. 1 presents the main activities carried out during this study and how they interact to achieve the paper’s primary goal. The process that led to the final version of this data model was organic and iterative. Further explanation of each of these activities can be found in the remainder of this section.

Desk literature survey

A desk literature survey was carried out on how Industry 4.0 has been used to improve the KM of waste and resources in cities and

---

[12] https://github.com/smart-data-models/dataModel.WasteManagement

[13] https://maestri-spire.eu/

[14] https://ec.Europa.EU/competition/mergers/cases/index/nace_all.html

[15] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02000D0532-20150601

Table 1
Interviews with stakeholders.

Stakeholder group	N	SI	SII	SIII	Total
Representatives of waste management units (public sector)	7	7	5	3	15
Tech developers	6	2	4	3	9
Domain experts (non-public)	4	-	4	3	7
Total interviews		9	13	9	30

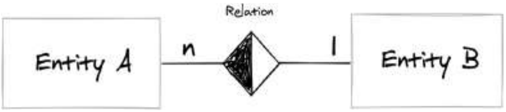


Fig. 2. ERM - notation Rein85.

regions. Scientific studies, grey literature, and technology projects were surveyed to identify the system components, the current challenges, and how information is being captured, used and managed. Moreover, this task was critical to identify potential case studies and stakeholders to interview. For academic articles, the Scopus database was queried using a combination of domain =-specific terms and specific tools or methods. Domain specific terms included: (i) Urban Metabolism, (ii) Circular Economy, (iii) Industrial Symbiosis, (iv) Waste Management. And tools and methods included: (i) UML OR Entity-Relationship Model (ERM) OR Conceptual, (ii) Knowledge management, (iii) Relational database OR Ontology OR Graph database OR SQL OR NOSQL OR POSTGRESQL, (iv) IoT OR ICT OR smart OR industry 4.0.

The survey was complemented with grey literature dealing with the CE and smart waste management systems to learn how these topics were being approached in practice, including Deloitte, IBM, Ellen Mac Arthur Foundation, and several governmental projects.

Finally, since the challenge of this research lies within the Industry 4.0 paradigm, new sources of knowledge such as source code repositories (e.g., GitHub) and mobile device applications (Apps) were also surveyed. Within GitHub, the following combination of keywords was searched: "Circular Economy", "Urban Metabolism", "Industrial Symbiosis", and "Waste Management". The main outcomes of this stage are reported in Section 2.

Engagement with Stakeholders

Semi-structured interviews and workshops with different stakeholders helped to complement and validate knowledge gained from the literature survey. Although there is no single method to develop a data model, using interviews to extract knowledge from stakeholders is common practice when developing digital solutions (Gupta et al. 2019). The interviews provided first-hand information on how waste materials are being managed by practitioners, and how the digitalisation process of information can enhance their practices. Table 1 provides information on the different stakeholders and interview stages.

Three groups of stakeholders were consulted at different stages: (i) public sector staff from municipal waste management or environmental departments; (ii) tech developers; (iii) domain experts from the fields of UM, CE and data management. Although all these stakeholders are working to halt environmental degradation by using resources more efficiently, their views and understanding of the system vary, thus are complementary. In order to gain a broader perspective on the domain and capture specificities of the system in various context stakeholders from different locations were contacted. The interviewees were from Buenos Aires, Rosario and San Isidro (Argentina), London and Manchester (United Kingdom), Maputo (Mozambique), Philadelphia (United States) and Gothenburg and Helsingborg (Sweden).

Three types of interviews were performed. During the first round of interviews (SI), initial contact was established. Semi-structured interviews were used to understand better the actors' challenges and how the system was operating. The second interaction took the form of a workshop (SII), where a first version of the data model was presented to verify if any system components were missing. This workshop was helpful to map the different actors and their roles in the system. Finally, the last interviews (SIII) validated the model applied to the specific use cases of each stakeholder and explored how KM could be used in their practice.

Data model development

The third stage of the study involved developing the data model of CFWR in cities in three steps: first, developing a conceptual diagram; then, formalising the model into an ERM; finally, translating the ERM into a database schema, in this case, using a relational database.

The objective of the conceptual diagram was to identify the different components of the waste and resources management system, an abstraction needed to develop more formal models. The proposed conceptual diagram was developed based on knowledge acquired in the previous two stages and is consistent with the meta-model used to create OntoWM (Kultsova et al. 2016). It was used during the interviews to validate the system components, to capture how they can be interconnected, and to identify the attributes of each of these components.

The conceptual diagram was then formalised into an ERM using the enhanced ERM notation (Chen 1976). The ERM provides a more detailed representation of the system components as entities, explicitly defines their relations, and defines the set of characteristics that describes those entities as attributes. Fig. 2, shows two entities related to each other. The diamond shape in the middle indicates the cardinality of the relationship, where there can be many (n) of Entity A related to one (1) Entity B.

For instance, a waste bin is an entity, and colour is one of its possible attributes. The waste bin can be owned by a firm (another entity), thus ownership defines the relationship between the firm and a waste bin, of which a firm can own many.

The development of the ERM is a crucial step towards a database architecture. Entities, attributes and relationships can be translated into different types of database management systems such as hierarchical, graph, or relational. In this case, we used a relational database schema to demonstrate how the ERM can be implemented. A relationship is a formal link between two entities or in this case tables. Usually, there is an ID attribute that will be used to connect information between them.

The ERM was constructed using DataBase Markdown Language (DBML) [16], an open-source Domain Specific Language (DSL) used to define and document the database schema. Using a built-in Command Line Interface (CLI), a PostgreSQL database schema was generated.

Validation using case studies

Finally, with insights from the interviews and literature survey, four case studies were selected and formalised using the ERM for waste and resources management in the cities of Buenos Aires (Argentina) and Helsingborg (Sweden). Two municipal Waste Management (MSW) and two Industrial Symbiosis (IS) case studies were instantiated and evaluated using a set of competency questions. These questions, relevant to the stakeholders' practice, are used to understand to what extent the database developed can respond to domain-specific questions (Tolle 2021). Then, once the ERM was applied to represent the case studies, a final round of interviews was used to warrant that the model could describe, analyse, and manage knowledge of different waste streams in cities or regions.

---

[16] https://www.dbml.org/home/

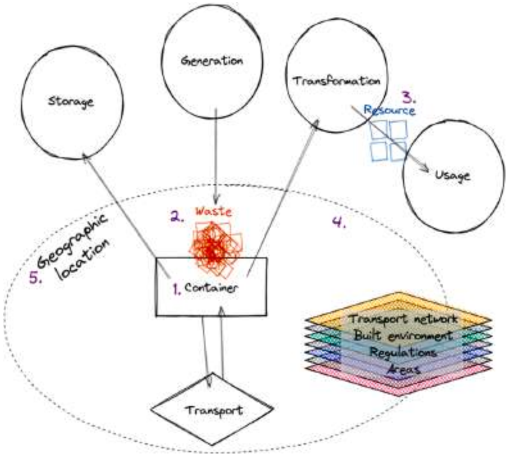


Fig. 3.. The Conceptual diagram of Circular Flow of Waste and Resources.

Results

Conceptual diagram of circular flow of waste and resources

The Conceptual Diagram of CFWR is general and captures the minimum set of components required to describe various waste and resources management related scenarios. The conceptual diagram presented in Fig. 3 is described below.

Any urban or regional system is composed of numerous and diverse actors who, while using, producing or consuming products, generate waste (residual material) and it needs to be handled adequately. Consequently, Waste (1 in Fig. 3) is any substance or object that an actor discards, intends to or is required to discard; it cannot be sold or purchased, has no market value and is associated with a cost. Although the actors in such systems can be diverse, their actions about waste can be generalised into five roles, represented as circles in Fig. 3:

- Generation: Every time, there is a process that generates waste.
- Recycling: By various means, any waste or part of it is transformed into a resource that can be reintroduced in the market for its use as energy or materials.
- Storage: Whenever waste materials are stored over a period of time, for instance, in a transfer station or a landfill.

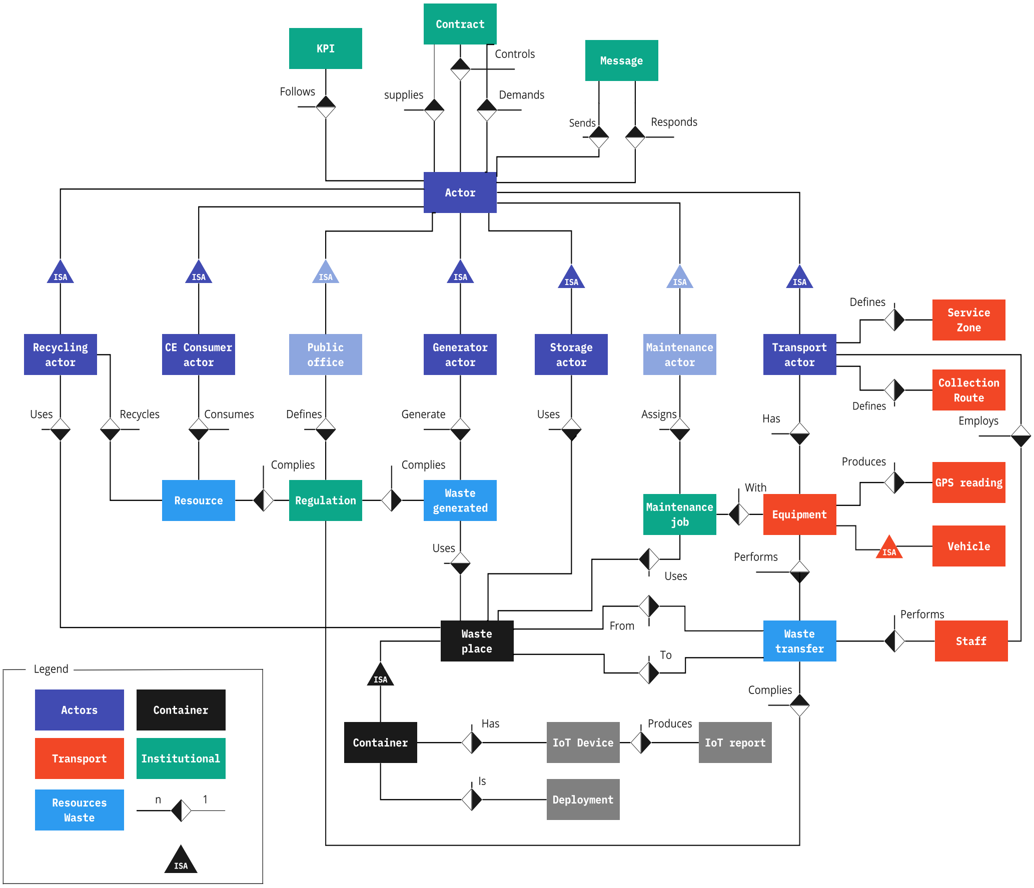


Fig. 4.. Entity Relationship Model (ERM) for waste and resources management - Rein85 notation.

waste_place	
place_id	**int**
contaiers_in	int
name	varchar
street_name	varchar
streeet_number	varchar
street_id	int
geom	int
entrance_long	int
entrance_lat	int
open_time	int
close_time	int
open_days	varchar
with_staff	boolean
staff_quantity	int
acceess_requirements	int
web_site	varchar
last_updated	timestamp
updated_by	varchar

container	
container_id	**int**
longitude	int
latitude	int
address	varchar
street_name	varchar
street_num	int
street_id	int
color	int
model	varchar
producer	varchar
producer_url	varchar
capacity_vol	int
capacity_vol_unit	varchar
capacity_weight	int
capacity_weight_unit	varchar
waste_type	varchar
hight	int
width	int
outdoors	boolean
waste_desc	varchar
waste_code	varchar
model_url	varchar
value	int
image	varchar
vandalized	boolean
condition	varchar
mobile_unit	boolean
last_updated	timestamp
updated_by	varchar

iot_device	
iot_device_id	**in**
attached_to	int
model	varchar
value	int
mantained_by	varchar
responsability_of	varchar
producer	varcahr
documenataiton	varchar
time_installed	timestamp

deployment	
contaiers_in	int
time_attached	timestamp
time_deattached	timestamp
status	varchar

Fig. 5.. Relational data model schema for containers.

- Usage: After a waste material gets recycled, it is ready for another or the same actor to use it.
- Transportation: Every time waste material is moved from one Container to another, there is a need for Transportation.

An actor with the role Generation produces different waste streams (1 in Fig. 3) that are disposed of in Containers (2 in Fig. 3). These containers are places of waste materials that can be found in geographic locations (5 in Fig. 3) of actors. Actors with the role Transportation can move these waste materials from one container to another. This movement of material means from the place where it was generated to a place associated with another actor, for example with the role Storage. Actors with the role Recycling contribute to reintroducing disposed materials into the system by transforming them into Resources (3 in Fig. 3). Recycling activities are crucial to delivering sustainability and range from cleaning, sorting or more complex resource manipulations. Waste transformed into resources is ready for actors with the role Usage.

The (conceptual diagram) also includes place-specific characteristics (4 in Fig. 3) that determine the geographic and institutional context and highlight how the waste and resources system can integrate (or be integrated with) other systems. Regulations, institutions, built environment, demographics and jurisdictions impose restrictions and determine the set of possible actions that can be performed over the system.

Entity-relationship model (ERM) of circular flow of waste and resources

The Conceptual model was then formalised using a ERM. Fig. 4 presents the proposed ERM of waste and resources management in city regions, focusing on the relationships between entities so that these can be described and visualised properly. The attributes of each entity will be detailed later, in the relational database schema.

The entities of the model are grouped into five categories. Actors and their roles in dark blue represent the stakeholders in the system. The second group of entities, in light blue, is related to waste and resources and captures information about how waste is generated, transported and transformed into resources. The places that hold waste are represented in black. Finally, in red are the entities related to waste transportation, and in green are institutional related entities, such as regulations and maintenance. Next, we describe the entities and their relations in more detail.

Actor is a parent entity with seven child entities that represent possible roles that an actor can have, the primary roles being: Generator, Recycling, Storage, CE Consumer and Transport. Two secondary roles, Public office and Maintenance, are incorporated to capture additional complexities of the system. The roles will hold specific data about the actors' activities. Since the same stakeholder can engage in different activities, any general information such as name or address are attributes of the parent entity Actor, to avoid repetition.

An Actor can have several instances of the Generation role for each waste stream that it produces. Data about the actual waste generated will be recorded in the Waste Generated entity. The Waste Generated entity has two connections, one to the Actor and another to Waste Place, where it is disposed of.

Waste Place has data about a general location where waste materials are kept, e.g. a disposal site or a street corner. It is a parent entity allowing for different child categories, and supports groups of containers as in a recycling collection point or hub. At present, only a general container is represented, but more categories could be created to define other types of waste container. Each Container can have several IoT Devices that generate different reports about the Container status, such as weight, temperature, gasses or an image.

Waste Transfers is an entity that registers waste movement, holding data about how the transfer was done, from where, to where, when the process occurred, and the type of waste and quantity that was moved. Waste Transfers has two pointers to Waste Place because waste is being transported from one place to another place. Waste Transfers has two additional relationships, one to Equipment, and another with Staff, in both cases entities related to the Transport role of an Actor. This role is linked to additional entities that store information about the Collection Route and Vehicle transporting waste and waste materials.

This model is relevant for tracking progress in closing material loops since it contemplates Actors that have other vital roles such as Recycling and CE Consumers. In this case, Recycling contains data about places where waste is transformed into a resource; CE Consumer is the final role that an actor can have in the circular supply chain and will have data about what is being used and for what purpose. Both roles are related to the entity Resource: on the one hand capturing information about the stock of material saved, and on the other, the amount that is ready to be used again.

The Actor entity can capture different relationships between stakeholders via Contract and Messages. Actors can establish formal relationships with other actors in a Contract, recording who is demanding a service, who is providing it, and who is controlling that the relationship is working accordingly. Contract can be used, for instance, to indicate that a municipal unit has a contract with a private firm that is responsible for the collection of waste. Furthermore, the model can store information transferred between actors in Messages, for instance, a waste management unit notifying its citizens of a change in collection times or a resident informing that a waste bin was vandalised. Finally, a Key Performance Indicators (KPI) entity related to Actor captures data on different KPIs, and will enable to track and analyse the performance of difference entities.

The ERM for Circular Waste and Resources Flows has been designed to incorporate spatial aspects of the system supporting spatial planning. Actors, Waste Places, GPS reading, Service Zone, and Collection Routes are spatial entities with location (i.e., geographic coordinates) in their attributes. This feature enables answering spatial planning related questions and, more importantly, it allows establishing links with other data sources or geographical models of the built environment.

Relational database schema

The final data modelling step was the translation of the Circular Flow of Waste and Resources ERM to a relational data model schema, containing a total of 27 tables and 281 fields. The following examples reinforce the understanding of the data model and illustrate the attributes that define a class in more detail. To improve the organisation and readability of the study, Appendix A (Fig 10-12)contains detailed figures of different parts of the relational database schema; only Fig. 5 has been included in this section.

Actor is a central class of this data model that can represent the household, productive, recreational or administrative units of a city. Actors (i) are of many types, (ii) can employ resources, (iii) must comply with regulations, (iv) communicate with other actors, (v) set objectives, and (vi) define operation details. Fig. 10 shows the attributes contained in the Actor class and its child classes (roles).

Waste generated holds a registry with information about who generated the waste (actor id), what type and how much was generated, and where it was placed (waste place id). Moreover, there is a relationship between Regulation and Waste generated that stipulates what regulations apply to a given waste type. The full details of the attributes and cardinality of these tables can be found in Fig. 11.

Containers are one of the most frequently addressed entities in waste related smart city applications. This class's attributes include location, colour, type of waste that it should contain or capacity, and identify a particular waste container in the system. Containers can also be embedded with IoT Devices that produce various readings on the status of the bin, its content (i.e., current capacity, temperature, humidity, open lid), and its surroundings (i.e., sun exposure, temperature, image). A single container can have multiple devices, and each of these devices generates readings with a specific frequency. Fig. 5 shows the cardinality and attributes of each of these tables.

Waste transfers has two Waste place ids indicating a starting and an ending container, and it has a timestamp that shows when the waste transfer job was performed, what waste types and amounts were transferred. Moreover, it is connected to Equipment and Staff to retrieve information from those tables. Details of these table's attributes can be seen in Fig. 12.

The complete data model schema can be found in an open source repository in dbml and SQL formats for PostgreSQL [17]. Also, an interactive version has been uploaded for visual exploration [18].

Validation of the data model of circular flow of waste and resources using case studies

The CFWR data model proposed in this study is aimed at supporting the modelling – for data management, description, analysis, simulation or visualisation - of the widest range of waste and resources management scenarios, while being flexible to represent the different local contexts. Four case studies were implemented to test to which extent the proposed data model can be applied to different contexts.

The first two cases are related to Municipal Solid Waste Management (MSWM): (i) Recycling: Material recovery in Buenos Aires City and (ii) Optimization: IoT in waste management operations in Helsingborg. Although, the topic in both cities is the same, the operations of waste management differ significantly. In Buenos Aires, urban pikers sort and

---

[17] https://github.com/Urban-JonathanCohen/GeneralWasteDataModel

[18] https://dbdocs.io/Urban-JonathanCohen/Waste2Resources

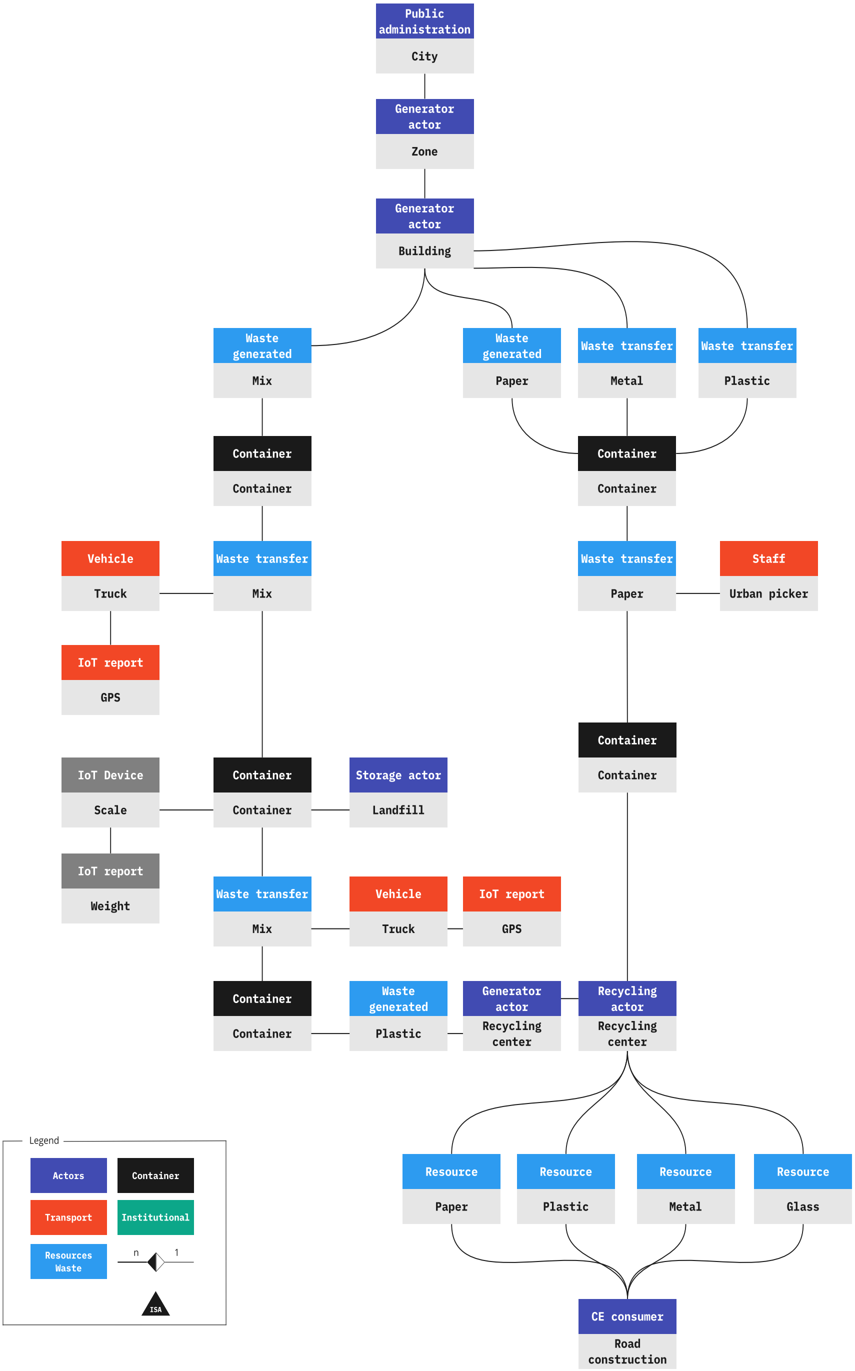


Fig. 6.. Recycling: Material recovery in Buenos Aires City.

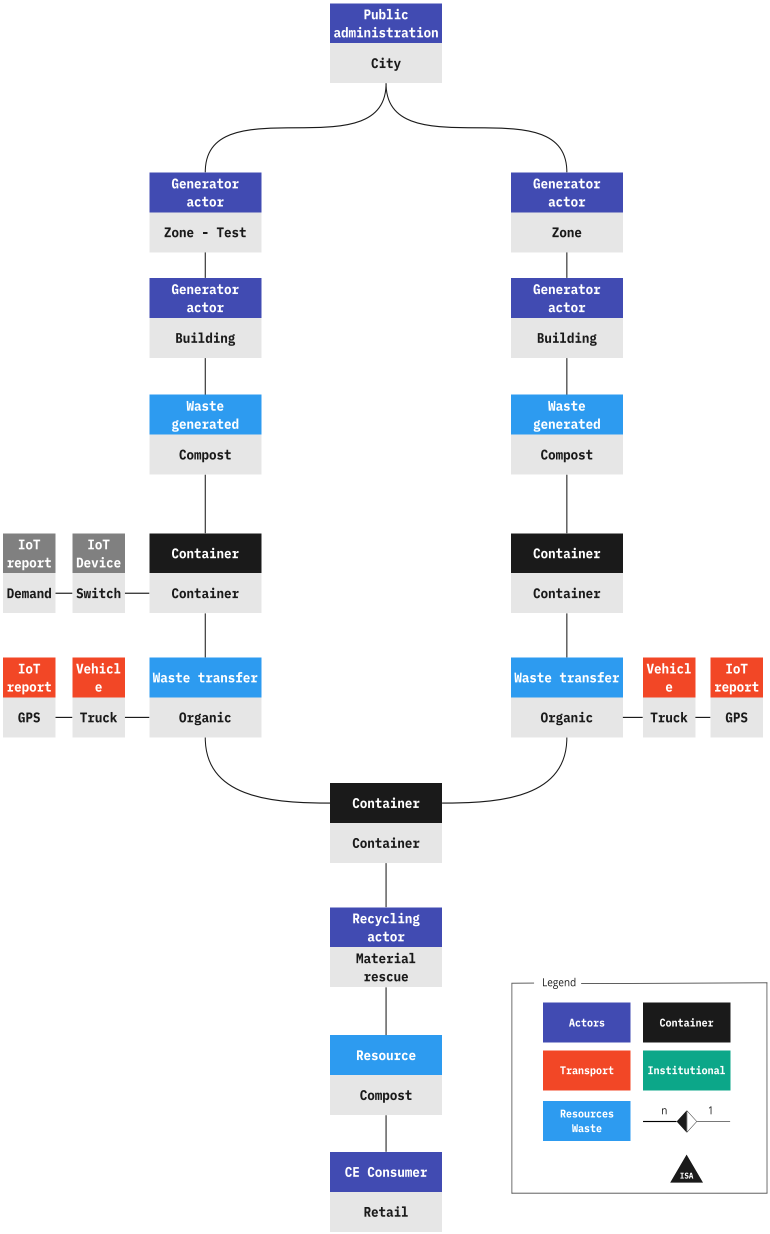


Fig. 7.. Optimization: IoT in waste management operations in Helsingborg.

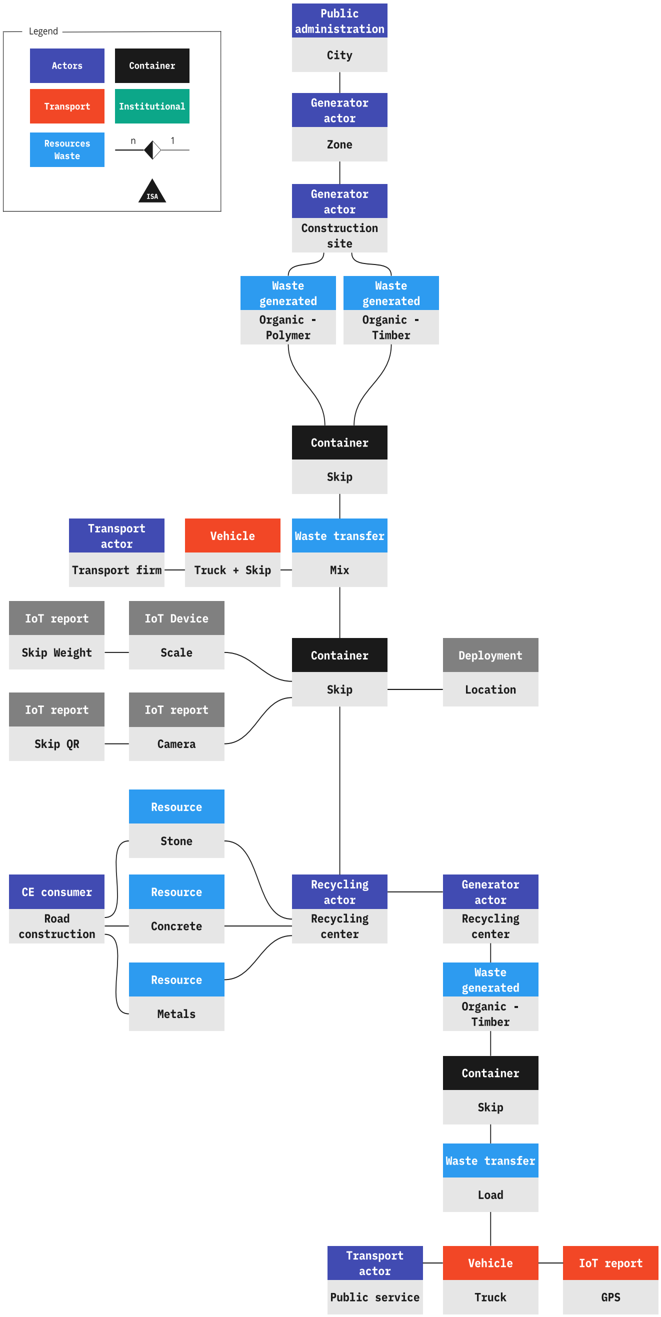


Fig. 8.. Reuse of materials: Construction and demolition sector in Buenos Aires City.

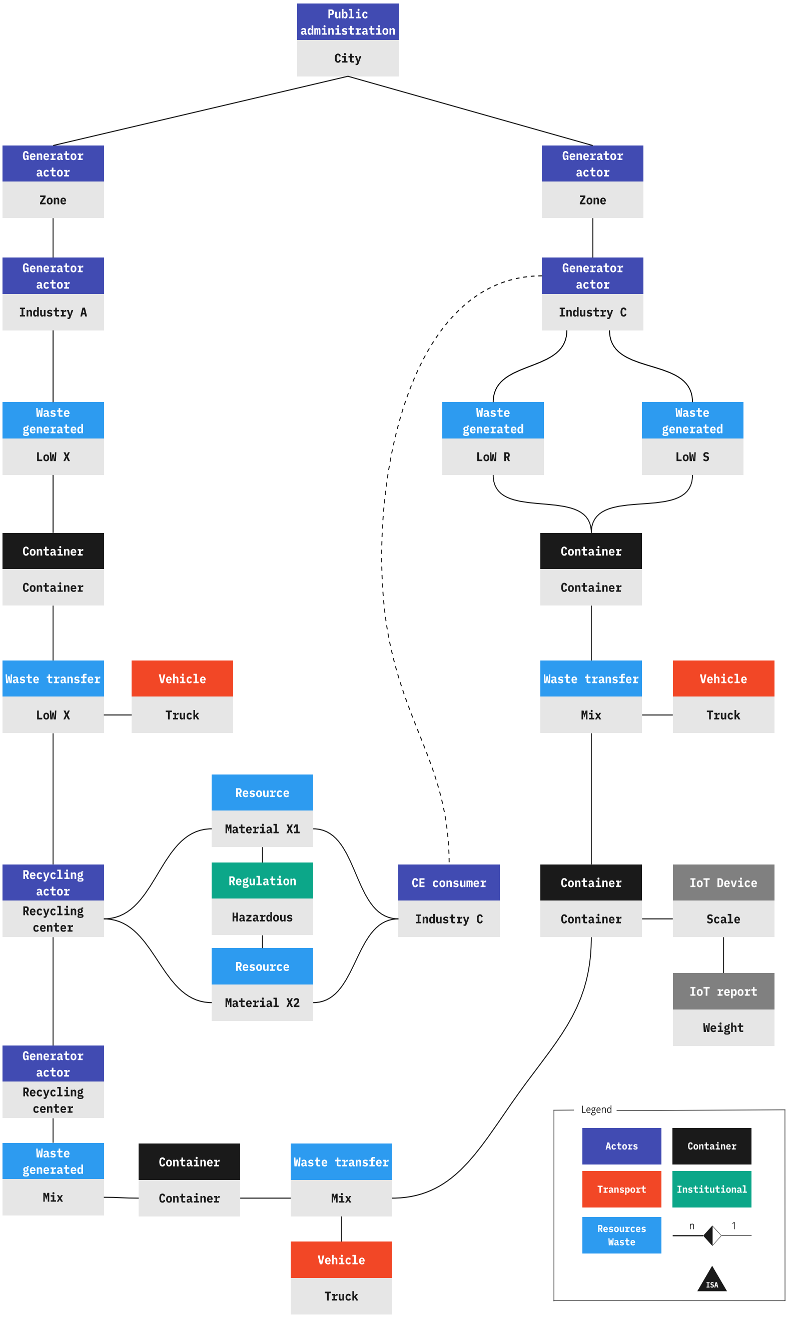


Fig. 9.. Regional waste exchanges: A general implementation.

collect recyclable materials on the street after the citizens have put them on the streets and in the case of Helsingborg, the sorting is done at origin and the municipality is testing an on-demand collection service.

The third and fourth cases are about Industrial Symbiosis (IS): (iii) Reuse of materials: Construction and demolition sector in Buenos Aires City and (iv) Regional waste exchanges: A general implementation. IS happens when two or more firms engage in cooperation by exchanging resources. This activity is of particular interest to the CE since it enables the reuse of waste materials, as waste resulting from a production process is treated as a potential input to another.

Each case study is presented by an instantiated diagram of the CFWR data model, and a set of three competency questions relevant to the specific case are used to test the logic of the data model. For each of the case, in Appendix B (Fig 13-16 & Table 2-5) we included a more detailed ERM and a longer list of competency questions is included.

Recycling: material recovery in Buenos Aires city

In Buenos Aires City, urban pickers play an essential role in recovering recyclable material. These workers are employed by the Municipality and belong to a set of self managed recycling cooperatives. Today, the Municipality of Buenos Aires works with six cooperatives and supports the work of approximate 6000 urban pickers. Each cooperative is assigned a zone and the Municipality assigns a specific area of 6 urban blocks to each worker, who collect paper, cardboard, glass, plastics and metals (dry waste). Waste is transported to facilities where the materials get sorted, cleaned, and readied to be sold to recycling firms that will transform it into a resource.

shows a sample of how the data model can be used for this specific case. Among the stakeholders of this case, we can find the municipality and its departments (hygiene, recycling or circular economy) and the cooperatives, residents, staff, and recycling firmsFig. 6.

The case shows how information at different scales can be organized using the data model. City-data such as population and boundaries can be found in the Public Office entity. Waste generation information can also be represented at different scales: zones or buildings. In this case, a single building is responsible for generating different Waste Generated streams such as mixed, paper, metal, or plastics. Waste generated is then disposed of in different containers. Containers holding recyclable materials are visited by municipal Staff, and they take the material to a Recycling facility where the material is treated for later reintroduction in the system as Resource. The other Containers are visited by Staff on Vehicles and taken to Storage in a landfill, where the waste is weighed and discarded. Note that the recycling facility also generates waste, and this is sent to the landfill in trucks.

The following Competency Questions could be answered: (i) How much material of a specific type was collected at a specific time and place? (ii) How much material and of what type arrives at the recycling facilities? (iii) Is there available capacity for recycling?

Optimization: IoT in waste management operations in Helsingborg

Helsingborg municipality, located in the southwest of Sweden, has a contract with a firm responsible for managing municipal waste (NSR AB). Currently, an on-demand system to collect waste generated by households is being tested with a set of 6000 units. Using an IoT device attached to the waste bins, the residents can demand a collection service. This test will allow NSR to re-evaluate their operations and improve its operations.

shows how the data from this case study could be captured using the data model. The implementation represents two processes: waste bins equipped with the IoT device; and the traditional system. Moreover, in this case, the trucks' position is currently being recorded, and such data can also be incorporated in the CFWR model. Finally, the model shows how data about the process of transforming organic material into composted soil ready for retail can be representedFig. 7.

The following Competency Questions could be answered using this database: (i) How long does it take to fill a waste container? (ii) What is the relationship between the property size and the waste generated? (iii) Which system generates the most pick-ups?

Reuse of materials: construction and demolition sector in Buenos Aires City

The construction and demolition (C&D) sector is vital for the CE of cities because of the number of resources handled. Depending on the location and other variables such as economics or regulations, the amount of C&D waste can reach between 20% and 40% of the total municipal waste [19]. Better management of the C&D sector will decrease not only the environmental pressure but also the financial costs of managing these materials.

Since 2013, Buenos Aires City has a recycling centre to recover materials from the C&D sector. Registered transport firms that comply with current regulations can access and dispose of materials for free. On arrival, transported containers, in this case skips, are weighed. More than 3000 tons of solid material gets into the facility per day and uses different technologies to reuse it by the construction sector.

demonstrates how the proposed data model can be used to manage information on C&D waste streams. The Actor construction site can be the source of different waste streams depending on the project's stage, and in this case, two waste typologies are presented, polymer and timber. These resources are disposed of in a skip, transported to a recycling centre, detached and left for later transportation. This status of the skip is captured in the table Deployment. Another construction project can use resources recovered at a recycling facility. As the recycle centre recovers different materials, some material is disposed of into another container and later transported to a landfill. The table Waste Transfer holds information about where the waste material is transportedFig. 8.

The following Competency Questions could be answered: (i) How much material is transported per skip? (ii) How much material is being reused and for what purpose? (iii) How much material is gathered per day?

Regional waste exchanges: a general implementation

Urban planning can promote IS processes by deliberate creation of Eco-Industrial Parks (EIPs). By fostering the co-location of different industries and businesses, barriers for exchange of knowledge and resources are eroded. These exchanges can also happen outside EIPs, and the data model can be used to manage information about actual and potential exchanges.

In this case, the CFWR model in Fig. 9 represents an exchange between two industries in different sectors and locations. Both industries are contained within a geographical boundary, in this case a city, but the model can be used to represent regions or country-level data. In this example, Industry A generates a waste categorized as LoW X and Industry C generates waste streams classified as LoW R and S. The application shows how a recycling centre transforms the residual material from Industry A into materials (X1 and X2) that can be used by Industry C.

The following Competency Questions could be answered: (i) What is the closest industrial facility where a waste could be used?, (ii) What is the contribution to GHGs of transporting the waste within a region? and (iii) What waste materials are being recycled the most and the least?

Discussion

Industry 4.0 can play a significant role in delivering sustainable urban futures. IoT and new computational methods are expanding how

---

[19] https://www.buenosaires.gob.ar/educacion/escuelas-verdes/conoce-las-plantas-de-tratamiento

we manage waste and resources in city regions. As the ecosystem of digital tools and techniques continues to grow, there is an increasing demand to manage and integrate these new data sources and tools. As identified in sections 1 and 2, effective KM and data standards are critical elements in the Industry 4.0 and data-driven paradigms. Knowledge silos and islands of IT are known factors that make the transition towards a Circular Economy difficult. Lack of compatibility between data formats and diverse definitions of the same concept reduces information exchange across different urban planning domains. This paper has addressed this challenge by proposing a data model to support information management for waste and resources in city-regions. Stakeholder engagement proved to be a critical part of the process, helping to incorporate different perspectives and correct modelling inconsistencies. This model can be used in various contexts, by different actors, and at various stages of the supply chain.

Despite the existence of different waste streams and that their management varies across local contexts, this paper has shown that municipalities worldwide face similar challenges. Information collected and used to address these challenges is also similar, if not the same. Namely, the operations of municipal waste services differ greatly from city to city, but the general components of the CFWR data model are sufficient to capture the specificity of the different cases. For example, in the cases of Buenos Aires City and Helsingborg, where waste is managed significantly different, it was shown that the data model can be used to describe both contexts. For instance, waste collection and transfers by urban pickers (actors) plays an important role in the Buenos Aires context, whereas in Helsingborg case study, the containers, the IoT devices and their reporting become central components of the system. Although both cases depart from the same general data model, it becomes clear that the instantiating of the data model acquired different forms. Although the resulting database implementations will differ from case to case, by using the same standard these two cases could be compared, or even digital tools developed for one case can be adopted in the other with relative ease. Finally, the same CFWR data model also managed to accommodate a generic industrial symbiosis case, where it can be noticed that the same actor is having different roles: a recycling centre is a recycling actor but also a waste generator.

Contributions of the CFWR data model as a standard

The primary contribution of this study is a general framework to integrate information about waste and resources management in city regions that conciliates perspectives from various actors. The proposed data model goes beyond traditional waste management tools by considering the circular economy and the spatial dimensions. On the one hand, the data model expands the traditional waste management perspective so that wastes are seen as potential resources. By including in the model recycling and how the materials are being re-used, the data model can support tracking progress on material circularity. On the other hand, the data model brings the ideas of CE closer to spatial planners' practice. By including geographical attributes in several classes, it allows to ground Circular Economy strategies and Key Performance Indicators on the territory. For example, by explicitly including the location of firms, it is possible to analyze resource efficiency in different territories. Moreover, this information can be used to prioritise locations for intervention, based on the results from predefined performance indicators. Finally, the more granular the information about waste and resources becomes (in spatial terms), the closer urban metabolism analyses get to urban planning practice. For instance, waste generation and product consumption patterns at the building level can provide useful insights to better plan neighbourhoods.

Besides managing knowledge about waste and resources, the proposed data model provides a framework for digital tools and methods to be validated, compared, replicated, inter-operated and extended. Adopting a data standard enables the creation of reproducible tools and analysis methods, which is of particular interest for small and medium-size municipalities without financial or technical resources to develop such tools. There is an untapped potential that by using a data standard and developing open-source tools, solutions built for one place can be reproduced in another with ease. Local action is needed to tackle global environmental challenges; therefore, data standards, more and better open data and processes, all contribute to enhancing waste and resources management.

Moreover, the proposed data model offers several data points of entry and exit that can be used to facilitate the interoperability between KM systems. The geographic location of objects stored in the model is a clear point of linkage to other data sources. For example, by including the geographic location of waste containers the model can be linked to other aspects of the built environment, namely incorporated in digital twins of cities for visualisation and analysis in impact assessment of traffic, noise or air pollution. Conversely, other data sets such as those from Litterati or Unwaste can be directly linked to the waste place class, feeding this crowd sourced data into a CFWR database to find where littered objects are typically found.

Finally, the methodology described in section 3 can guide future research pursuing a similar objective of Knowledge Management for CE. Other CE strategies, such as sharing economy, would require the development of new classes and relationships to fit specific analysis and objectives. Therefore, a new process going through the different stages, including a new conceptual model and engagement of different stakeholders and experts, would be required. And ultimately these models could be easily linked to provide a more integrated understanding of Circular Cities.

Limitations

This study's primary focus was to track objects from when they are disposed of until they are stored, processed or reused. As a result, the proposed data model falls short of managing knowledge regarding other CE strategies, such as sharing economy or design for circularity. For instance, to accommodate circular design, where material sourcing, modularity and working towards expanding the life span of products are key principles, new classes would be needed to capture production processes. In addition, the model would need some rethinking to include the sharing economy since there is no disposal of objects. In this case, the model should include a new class to represent shared objects and their users to show the availability and usage intensity, among other attributes. Nevertheless, it is possible to link related models, developed separately, to expand their individual capabilities.

In the development of the data model, even though the interviews were thorough, the number of stakeholders involved was limited. To fully understand to what extent the proposed model is more generally useful to manage knowledge about waste and resources in cities, more cases and interviews are needed. By interviewing new stakeholders, new perspectives and narratives will emerge to complement this study. The validation process will continue, as more applications and studies use the data model proposed here.

Beyond the list of stakeholders reported in section 3, many other engagements did not result in interviews or workshops, potentially limiting the scope of application of the data model. For different reasons meriting reflection, it was challenging to collaborate openly with some stakeholders, and as a result, those who shared their knowledge already understand the value of and need for digitalisation of their processes. The interviews fulfilled their purpose, but it would be worth investigating some institutions that are more reluctant towards digital transformation processes than others. Including their visions can be essential to address other challenges and dynamics not captured in the present CFWR model.

There are also possible uncertainties surrounding the general adoption of the data model, because the diversity of actors and political incentives around the waste and resources system are extensive. The multiplicity of actors translates into knowledge and data fragmentation, which the proposed model tries to address, but requires more than technological efforts to reconcile in one platform. Digitalisation processes can be perceived as a threat, and changing institutional, behavioural and corporate culture is a complex but worthy endeavour. In addition, business confidentiality and market competition erode potential collaborations that could improve how we allocate and consume resources, as documented by efforts to establish IS networks.

Finally, it is important to highlight that the data model proposed in this research is theoretical, and although it was validated to comply with the rules of DBML syntax and by showing its application in different contexts, a final validation with extensive data sets and a database implementation is needed. Until then, the model's usability and real capabilities remain uncertain.

Future work

As stated in the limitations, the CWRF model proposed here was developed based on knowledge derived from the stakeholders and almost no data was used during the process. Consequently, the next natural step is to acquire various data sets and implement databases for different case studies, in order to demonstrate application of the model in practice, and to confirm if the classes, attributes and relationships currently implemented are sufficient. Furthermore, one must continue to engage with additional stakeholders to identify new cases, available data sets, and to understand to what extent the proposed model can become a data standard for waste and resources management.

As reported in Section 2, several initiatives are generating information about waste an resources systems, and developing specific data standards. Future efforts should pursue how to integrate these new data sources and standards into a common framework, namely linking them to the proposed CFWR data model. By developing APIs, and defining clear data points of entry and exit, the proposed data model can be queried, populated and linked to other systems. Researching the interoperability of the proposed model with other data sources, standards and tools will be crucial to understand its usability in urban spatial planning.

In this paper we presented a translation of the ER representation to a relational database because of their simplicity and popularity. However, other database technologies are available, in particular ontologies and graph database technologies, more closely linked to the semantic web. It would be relevant to study possible benefits and limitations in data processing, integration, storage, analytic performance, and usability, to provide users with the adequate tool to tackle their challenges.

Finally, the proposed CFWR data model provides a stable information structure to develop different automated tools and methods, that can boost the municipal digitalisation process. For example, developing tools to extract information about waste treatment from municipal reports or from open-data web sites, and loading this information into a database so that is it more easily findable, queried and analysed. Or for instance, by adhering to the classes, attributes and relationships of the proposed model, the tools or methods developed for one place can be easily replicated in a different context. Future work can focus on developing these tools and methods and exploring how to integrate already existing DSS with the proposed CFWR data model. These studies are vital to increasing the DSS' transparency and unpack black-box analysis that only fit one problem.

Conclusion

This paper proposed a framework to improve KM for the waste and resources sector by developing a data model of Circular Flows of Waste and Resources (CFWR). The CFWR data model details how different components of the system of waste and resources are related and defines the characteristics that describe these components. As an intermediate step towards developing an ERM, the paper delivered a conceptual diagram that identifies the fundamental system components needed to manage waste and resources in city regions. The ERM representation expands this to captures the system's components, their attributes, and their relationships. Moreover, the paper provides a formal representation of the CFWR data model in the form of a relational database schema that should allow the sharing of information with ease. Although the conceptual diagram and the ERM were intermediate steps towards the relational database, these representations were extensively used to communicate with stakeholders and experts about how the urban waste and resources system operates, and to detail its various components. Finally, to validate the model and test its general applicability, it was used to represent different municipal waste management and industrial symbiosis cases. Instantiating the ERM into these specific use cases was helpful to discuss with stakeholders the functioning of the specific system, its components, and their relationships. The diagrams and the data schema are available online and freely accessible.

The outputs of this work represent a step forward in the digital agenda for waste and resources management. Using new digital technologies to measure, analyse or visualise information are relevant advances that illustrate some of the potential that Industry 4.0 has to offer. Additional (stronger and long term) benefits of digitising existing complex urban systems will materialise when the replication, expansion and integration of the different processes and systems is enabled. Specifications and protocols for handling data are a fundamental pre-requisite to unlock the potential of Industry 4.0, and to achieve more Circular Cities.

Acknowledgments

This work is part of the Digital Twin Cities Centre supported by Sweden's Innovation Agency Vinnova under Grant No. 2019-00041. The authors are grateful to all experts for their valuable time spent during the interviews and workshops. In particular, we thank Prof. Graham Kemp for his guidance in the development of the ERM; and Dr. Leonardo Rosado for his expertise on the challenges of the Circular Economy.

Appendix A: Relational database schema

Figure 10, 11 & 12 Should be here

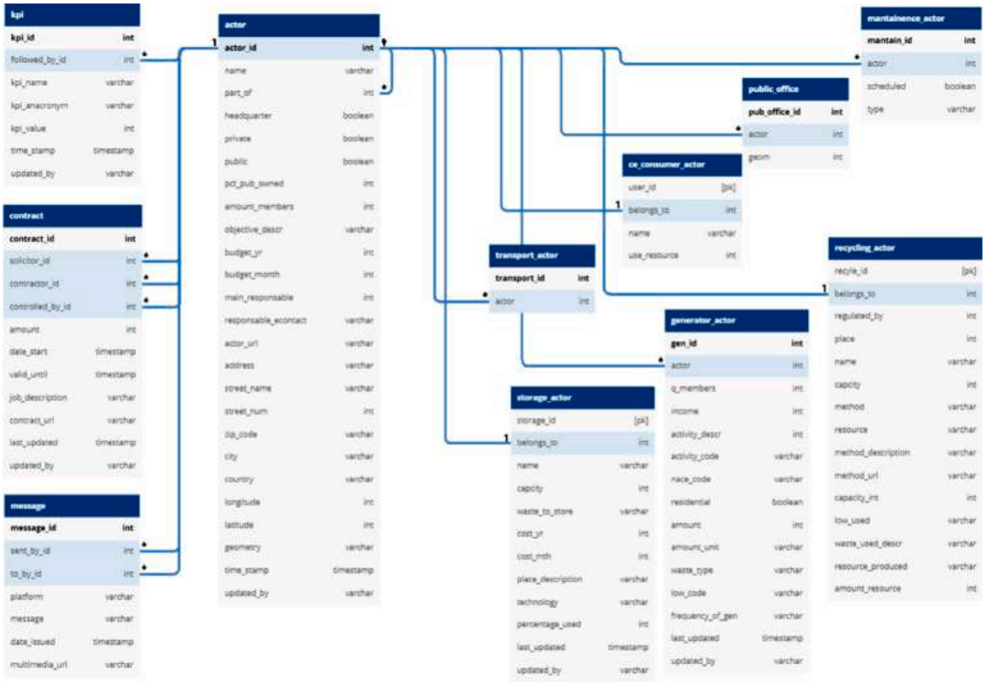


Fig. 10.. Relational data model schema of actors and roles.

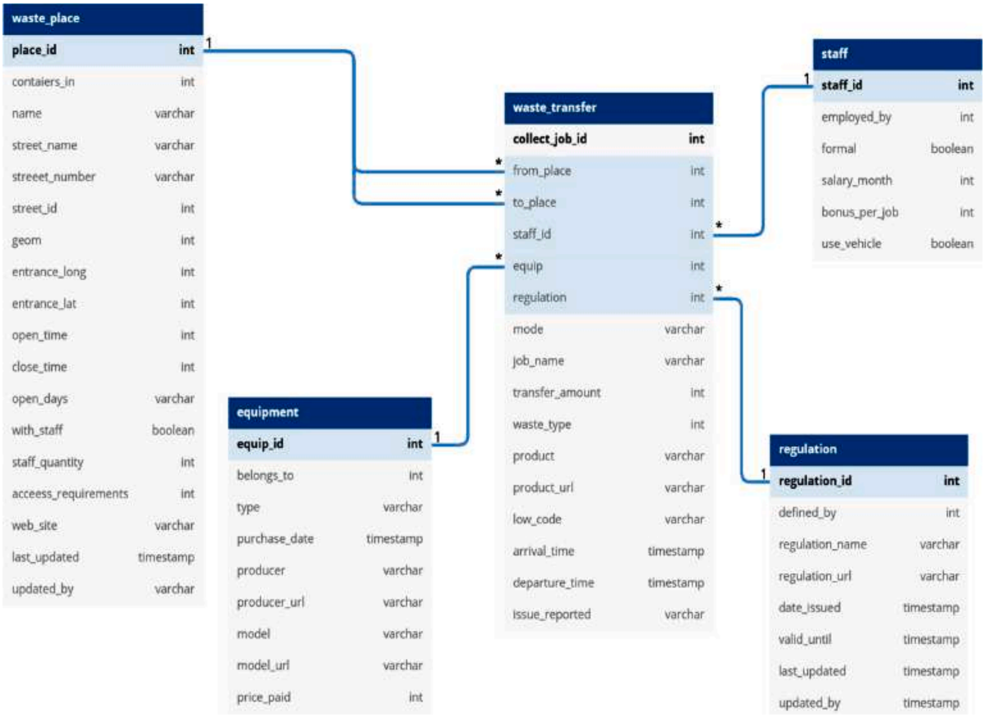
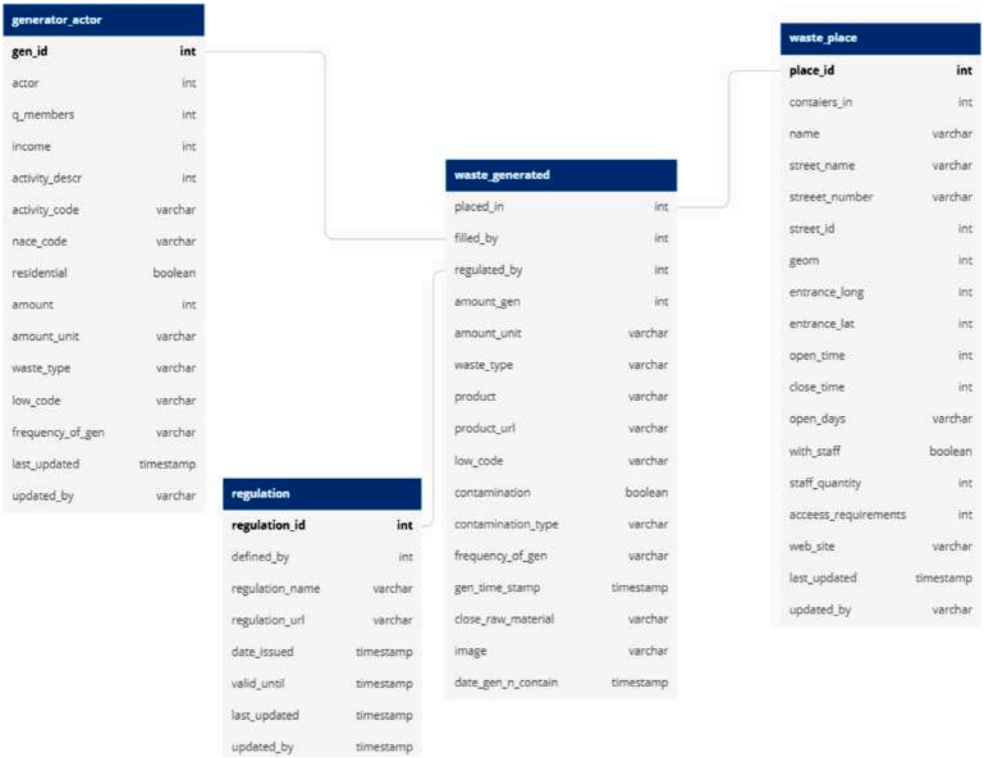


Fig. 11.. Relational data model schema of waste generated.



generator_actor	
gen_id	**int**
actor	int
q_members	int
income	int
activity_descr	int
activity_code	varchar
nace_code	varchar
residential	boolean
amount	int
amount_unit	varchar
waste_type	varchar
low_code	varchar
frequency_of_gen	varchar
last_updated	timestamp
updated_by	varchar

regulation	
regulation_id	**int**
defined_by	int
regulation_name	varchar
regulation_url	varchar
date_issued	timestamp
valid_until	timestamp
last_updated	timestamp
updated_by	timestamp

waste_generated	
placed_in	int
filled_by	int
regulated_by	int
amount_gen	int
amount_unit	varchar
waste_type	varchar
product	varchar
product_url	varchar
low_code	varchar
contamination	boolean
contamination_type	varchar
frequency_of_gen	varchar
gen_time_stamp	timestamp
close_raw_material	varchar
image	varchar
date_gen_n_contain	timestamp

waste_place	
place_id	**int**
contaiers_in	int
name	varchar
street_name	varchar
streeet_number	varchar
street_id	int
geom	int
entrance_long	int
entrance_lat	int
open_time	int
close_time	int
open_days	varchar
with_staff	boolean
staff_quantity	int
acceess_requirements	int
web_site	varchar
last_updated	timestamp
updated_by	varchar

Fig. 12.. Relational data model schema for waste transfers.

Appendix B: Case Studies implementation

Figures 13, 14, 15, 16 should be here and Table 2, 3, 4, 5. Moreover, the order should be: Figure 13, followed by Table 2.Figure 14, followed by Table 3.Figure 15, followed by Table 4. Finally, Figure 16, followed by Table 5

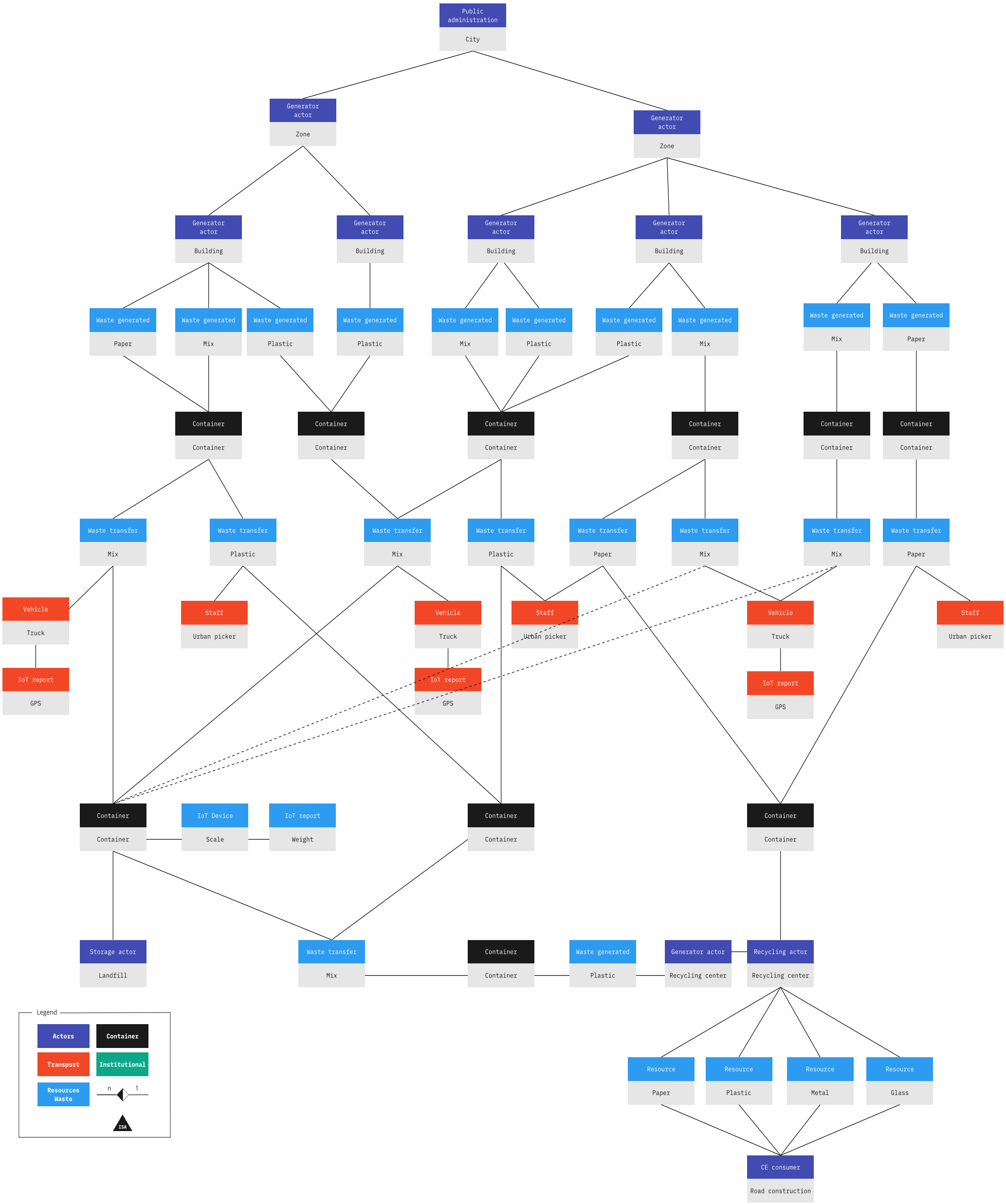


Fig. 13.. ERM for Recycling: Material recovery in Buenos Aires City.

Table 2
Competency questions for Material recovery in Buenos Aires City.

Recycling: Material recovery in Buenos Aires City
1. How many workers have been working at a specific time-place?
2. How much material of a specific type was collected at a specific time-place?
3. What distance do they travel every day?
4. What is the average distance between each container?
5. What is the time distribution of time spent sorting and collecting in each container?
6. How much material and of what type arrives at the recycling facilities?
7. Is there available capacity for recycling?
8. How much value is recovered by an employee?
9. How many cooperatives are working in the city?
10. What is the area covered by each cooperative?

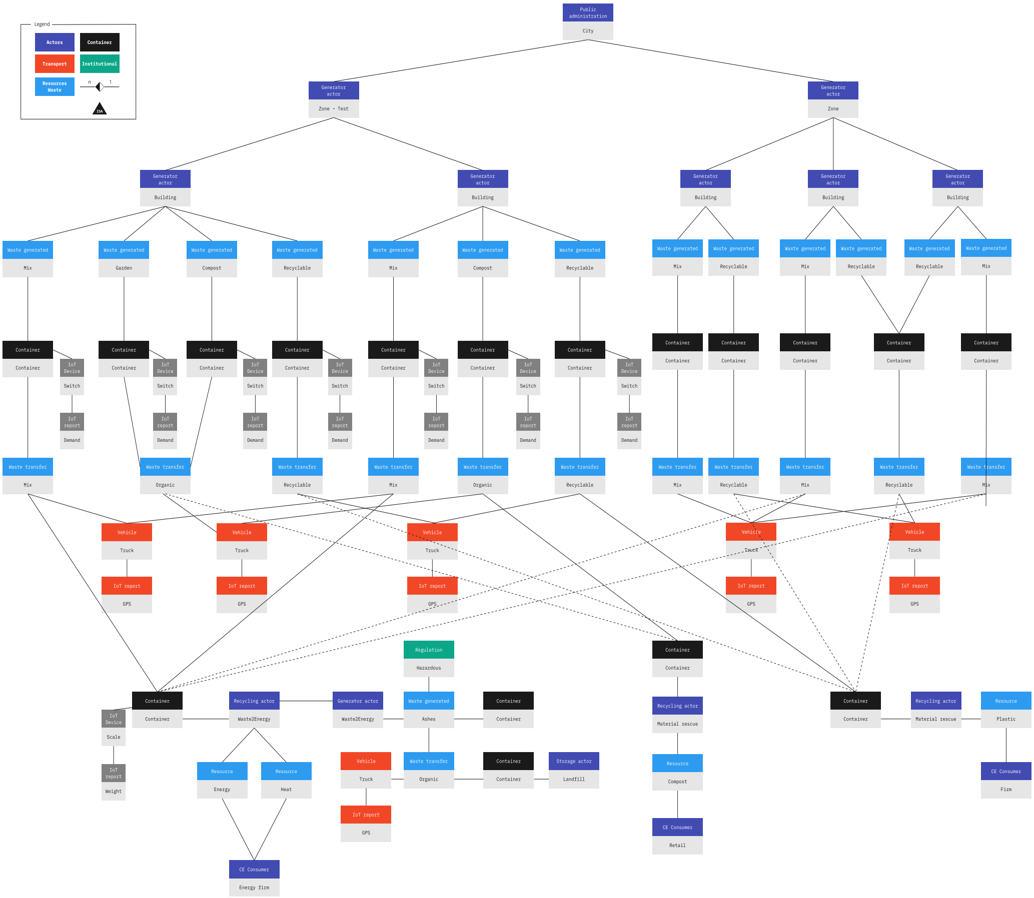


Fig. 14.. ERM for Optimization: IoT in waste management operations in Helsingborg.

Table 3
Competency questions for IoT in waste management operations in Helsingborg.

Optimization: IoT in waste management operations in Helsingborg
1. What is the most popular time to demand a pick-up service? 2. What areas demand the most pickups? 3. How long does it take to fill a waste container? 4. Does the on-demand service generate more demands than the non tested one? 5. What is the most collected waste stream? 6. What is the relationship between plot size and waste generated? 7. What is the average distance between one transfer waste place to another? 8. What is the difference in distance between containers in one system and the other one? 9. which system generates the most pickups?

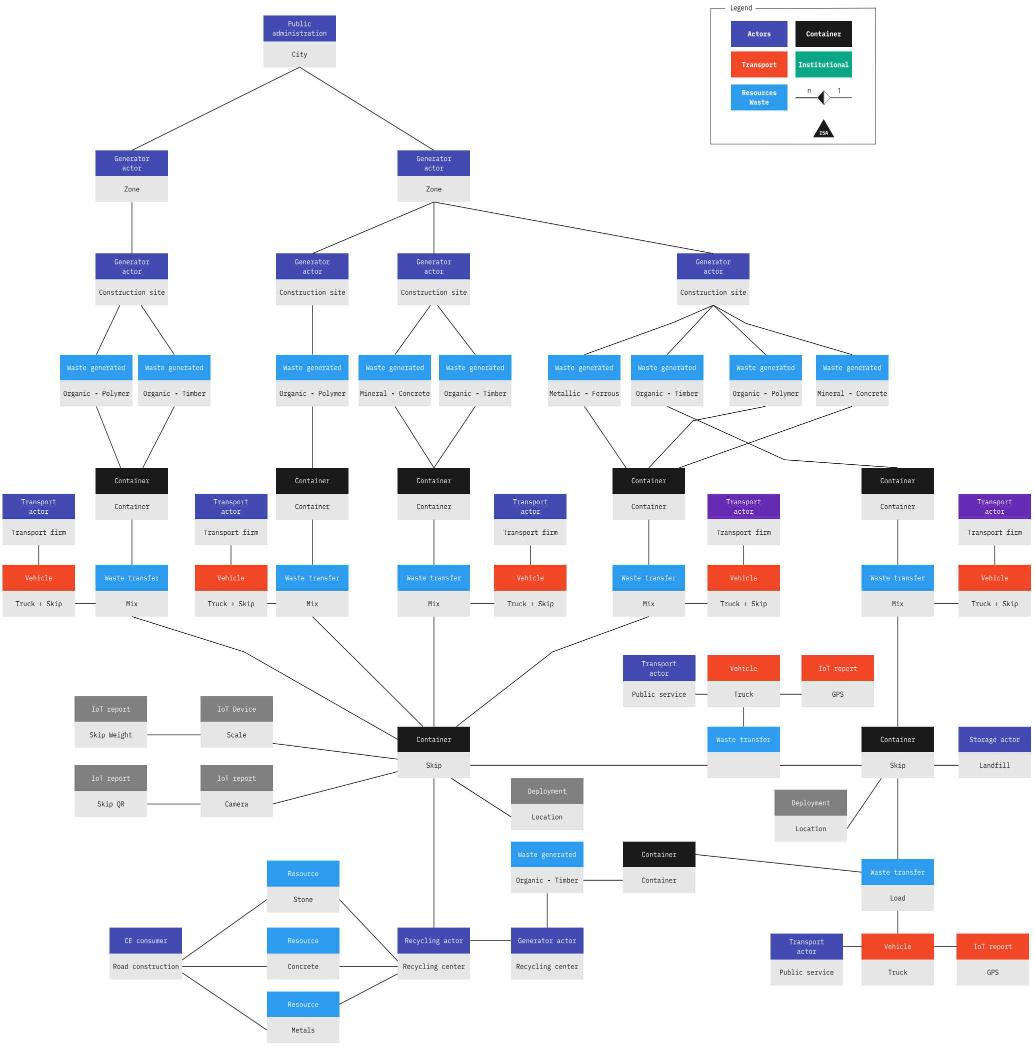


Fig. 15.. ERM for Re-use of materials: Construction and demolition sector in Buenos Aires City.

Table 4
Competency questions for re-use of materials in CnD in Buenos Aires.

Re-use of materials: Construction and demolition sector in Buenos Aires City
1. How much material is gathered per day?
2. How many skips are in use every day?
3. How many skips are available?
4. How much material is transported per skip?
5. How many construction sites are currently happening in the city?
6. What is the total distance travelled between construction sites and recycling facility?
7. How does the number of construction permits and waste received at the recycling facility correlate?
8. How many emissions are being produced due to the transportation of these materials?

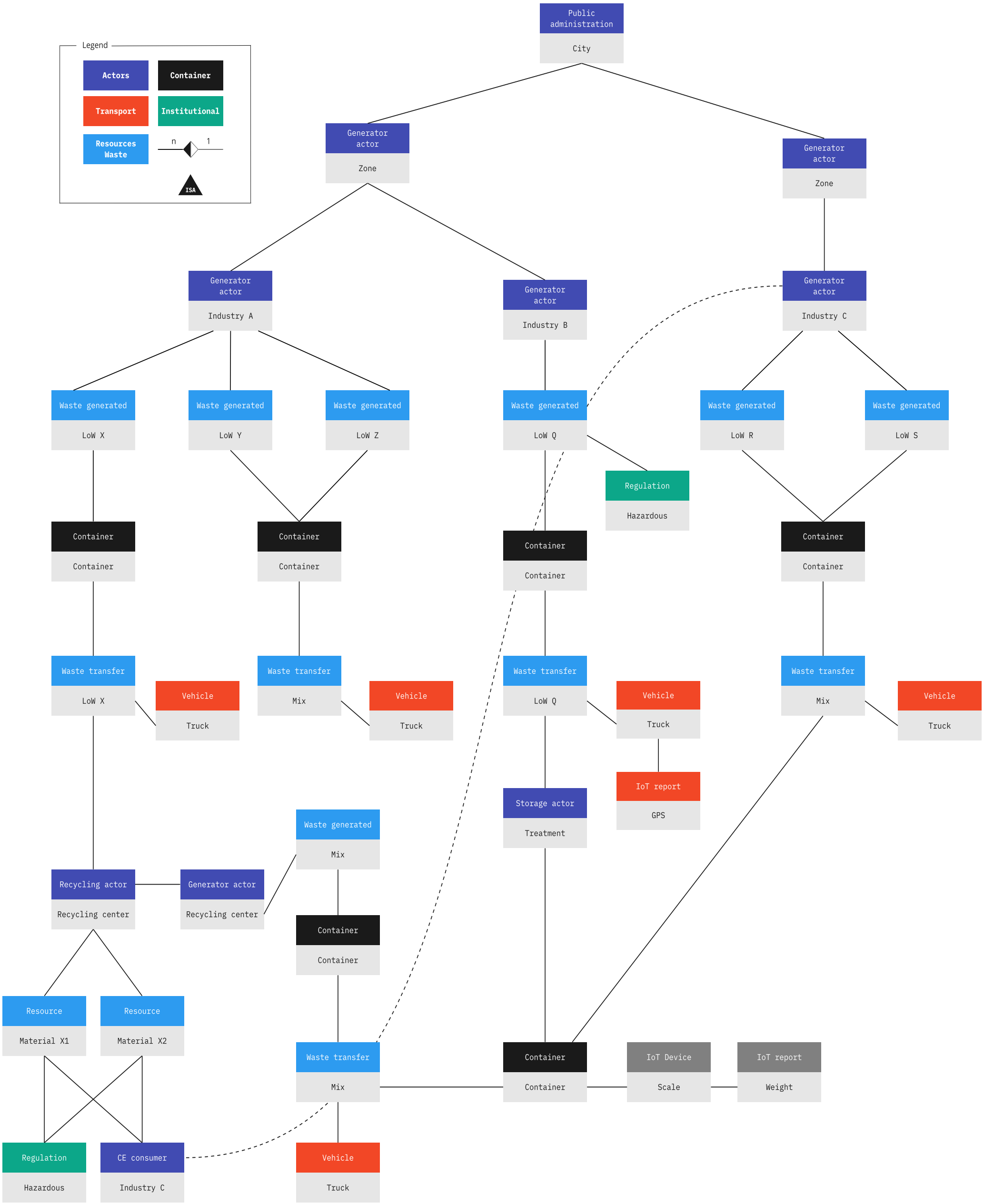


Fig. 16.. ERM for Regional waste exchanges: A general implementation.

Table 5
Competency questions for Regional waste exchanges.

Regional waste exchanges: A general implementation
1. How much waste is being produced by a specific sector?
2. How is industrial waste characterized in a specific area?
3. What is the closest destination that waste could be used?
4. What is the logistic cost of moving the waste from one place to another?
5. What is the capacity to recycle a specific waste stream?
6. What is the contribution of GHGs to move the waste in a region?
7. How much space is being used to store recyclable materials?
8. What is the capacity to store waste and of what type?
9. How many resources are being reused?
10 What materials are being recycled the most and the least?

References

Acheampong, Ran.sford A., Silva, Elisab.ete A., 2015. Land use–transport interaction modeling: a review of the literature and future research directions. J. Transp. Land Use 8 (3), 11–38. https://doi.org/10.5198/jtlu.2015.806.

Ahmad, Mo.hammad N.azir, Badr, Kam.al Bad.r Ab.dalla, Salwana, E.ly, Zakaria, No.r Hid.ayati, Tahar, Zulki.fli, Sattar, Ab.dul, 2018. An ontology for the waste management domain. In: Proceedings of the 22nd Pacific Asia Conference on Information Systems - Opportunities and Challenges for the Digitized Society: Are We Ready?, PACIS 2018. https://aisel.aisnet.org/pacis2018/12.

Alnajem, Mo.hamad, Mostafa, Moha.med M., ElMelegy, Ahme.d R., 2021. Mapping the first decade of circular economy research: a bibliometric network analysis. J. Ind. Prod. Eng. 38 (1), 29–50. https://doi.org/10.1080/21681015.2020.1838632.

Arciniegas, Gus.tavo, Šileryté, Rus.né, Dąbrowski, M.arcin, Wandl, Alexa.nder, Dukai, Bal.ázs, Bohnet, M.ax, Gutsche, Je.ns-Marti.n, 2019. A geodesign decision support environment for integrating management of resource flows in spatial planning. Urban Plan. 4 (3), 32. https://doi.org/10.17645/up.v4i3.2173.

Arribas, Claud.ia And.rea, Blazquez, Car.ola Alej.andra, Lamas, Ale.jandro, 2010. Urban solid waste collection system using mathematical modelling and tools of geographic information systems. Waste Manage. Res. 28 (4), 355–363. https://doi.org/10.1177/0734242X09353435.

Bacudio, Lind.ley R., Benjamin, Mic.hael Franc.is D., Eusebio, Ram.on Chr.istian P., Holaysan, Se.d Ande.rson K., Promentilla, Mic.hael Ang.elo B., Yu, Kr.ista Da.nielle S., Aviso, Kath.leen B., 2016. Analyzing barriers to implementing industrial symbiosis networks using DEMATEL. Sustain. Prod. Consump. 7, 57–65. https://doi.org/10.1016/j.spc.2016.03.001. March.

Baptista, A.J., Lourenço, E.J., Silva, E.J., Estrela, M.A., Peças, P., 2018. MAESTRI Efficiency Framework: The concept supporting the Total Efficiency Index . Application case study in the metalworking sector. Procedia CIRP 69, 318–323. https://doi.org/10.1016/j.procir.2017.11.119. May.

Batty, M., Axhausen, K.W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., Ouzounis, G., Portugali, Y., 2012. Smart cities of the future. Europ. Phys. J. 214 (1), 481–518. https://doi.org/10.1140/epjst/e2012-01703-3.

Bing, Xiao.yun, Keizer, Marl.ies de, Bloemhof-Ruwaard, Jac.queline M., Vorst, Jac.k G.A. J.v.an der, 2014. Vehicle routing for the eco-efficient collection of household plastic waste. Waste Manage. (Oxford) 34 (4), 719–729. https://doi.org/10.1016/j.wasman.2014.01.018.

Bob, C. 2000. Beyond Transparency. https://doi.org/10.1057/9780230107397_11.

Cecelja, F., Raafat, T., Trokanas, N., Innes, S., Smith, M., Yang, A., Zorgios, Y., Korkofygas, A., Kokossis, A., 2015. E-Symbiosis: technology-enabled support for industrial symbiosis targeting small and medium enterprises and innovation. J. Clean. Prod. 98, 336–352. https://doi.org/10.1016/j.jclepro.2014.08.051.

Chauhan, An.kur, Kumar Jakhar, Sur.esh, Chauhan, Ch.etna, 2021. The interplay of circular economy with industry 4.0 enabled smart city drivers of healthcare waste disposal. J. Clean. Prod. 279, 123854 https://doi.org/10.1016/j.jclepro.2020.123854.

Chen, Pet.er Pi.n Sha.n, 1976. The entity-relationship model—toward a unified view of data. ACM Trans. Database Syst. (TODS) 1 (1), 9–36. https://doi.org/10.1145/320434.320440.

Chou, I..Hs.in, Fan, Chin.Fen.g, 2010. An agent-based national radioactive waste management framework design. Prog. Nucl. Energy 52 (5), 470–480. https://doi.org/10.1016/j.pnucene.2009.10.003.

Circle Economy, 2020. Circularity Gap Report 2020. Circle Economy. https://www.circularity-gap.world/

Davis, Chris., Nikolic, Igo.r, Dijkema, Ger.ard P.J., 2010. Industrial ecology 2.0. J. Ind. Ecol. 14 (5), 707–726. https://doi.org/10.1111/j.1530-9290.2010.00281.x.

Domenech, Tere.sa, Bleischwitz, Rai.mund, Doranova, A.sel, Panayotopoulos, Dim.itris, 2019, Lau.ra Roman., 2018. Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy. Resour. Conserv. Recycl. 141, 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016. August.

Esmaeilian, Beh.zad, Wang, B.en, Lewis, Kem.per, Duarte, Fab.io, Ratti, Ca.rlo, Behdad, Sar.a, 2018. The future of waste management in smart and sustainable cities: a review and concept paper. Waste Manage. (Oxford) 81. https://doi.org/10.1016/j.wasman.2018.09.047, 177–95.

ESPON (European Spatial Planning Observation Network), 2019. CIRCTER - Circular Economy and Territorial Consequences - Draft Final Report. ESPON https://www.espon.eu/sites/default/files/attachments/CIRCTER Inception Report.pdf.

European Commission, 2018. Delivering the Sustainable Development Goals at local and regional level Recommendations to the European Commission by the subgroup on "SDGs at local and regional level" of the Multi-Stakeholder Platform on the Implementation of the Sustainable. Eur. Commision. http://unsdsn.org/wp-content/uploads/2016/07/9.1.8.-Cities-SDG-Guide.pdf.

Faccio, Mau.rizio, Persona, Alessan.dro, Zanin, Gio.rgia, 2011. Waste collection multi objective model with real time traceability data. Waste Manage. (Oxford) 31 (12), 2391–2405. https://doi.org/10.1016/j.wasman.2011.07.005.

Ferrera, E., R. Rossini, A.J. Baptista, and S. Evans. 2017. "Toward Industry 4 . 0: Efficient and Sustainable Manufacturing Leveraging MAESTRI Total Efficiency Framework" 1 (c). https://doi.org/10.1007/978-3-319-57078-5.

Ghali, Moham.ed Ra.ouf, Frayret, Jean.Ma.rc, 2019. Social Semantic Web Framework for Industrial Synergies Initiation. J. Ind. Ecol. 23 (3), 726–738. https://doi.org/10.1111/jiec.12814.

Gravagnuolo, Ant.onia, Angrisano, Mariaros.aria, Girard, Lui.gi Fus.co, 2019. Circular economy strategies in eight historic port cities: criteria and indicators towards a circular city assessment framework. Sustainability (Switzerland) (13), 11. https://doi.org/10.3390/su11133512.

Gupta, Shiv.am, Chen, Haoz.he, Hazen, Be.njamin T., Kaur, S.arabjot, Santibañez Gonzalez, Ern.esto D.R., 2019. Circular economy and big data analytics: a stakeholder perspective. Technol. Forecast. Soc. Change 144, 466–474. https://doi.org/10.1016/j.techfore.2018.06.030. June 2018.

Gutierrez, Jos.e M., Jensen, Mich.ael, Henius, Mor.ten, Riaz, Ta.hir, 2015. Smart waste collection system based on location intelligence. Procedia Comput. Sci. 61, 120–127. https://doi.org/10.1016/j.procs.2015.09.170.

Hall, P. 1992. Urban & Regional Planning.

Hannan, M..A., Mamun, Md.Abdu.lla Al A., Hussain, Ain.i, Basri, Hassa.n, Begum, R..A., 2015. A review on technologies and their usage in solid waste monitoring and management systems: issues and challenges. Waste Manage. (Oxford) 43, 509–523. https://doi.org/10.1016/j.wasman.2015.05.033.

Hannan, M.A., Zailah, W., 2012. Image extraction and data collection for solid waste bin monitoring system. J. Appl. Sci. Res. 8 (8), 3908–3913.

Holgado, Ma.ria, Evans, Ste.ve, Benedetti, M.iriam, Dubois, Mer.ane, Li, Ya.n, Morgan, Da.i, Ferrera, Enr.ico, 2019. MAESTRI Toolkit for Industrial Symbiosis: Overview. Lessons Learnt Implications 2, 51–60. https://doi.org/10.1007/978-3-030-04290-5.

Howell, Sha.un, Rezgui, Ya.cine, Beach, Thom.as, 2017. Integrating building and urban semantics to empower smart water solutions. Autom. Constr. 81, 434–448. https://doi.org/10.1016/j.autcon.2017.02.004.

Huang, Be.ijia, Wang, Xiangy.u, Kua, Ha.rnwei, Geng, Y.ong, Bleischwitz, Ra.imund, Ren, Jing.zheng, 2018. Construction and demolition waste management in China through the 3R principle. Resour. Conserv. Recycl. 129, 36–44. https://doi.org/10.1016/j.resconrec.2017.09.029. April 2017.

Israilidis, Jo.hn, Odusanya, Kay.ode, Mazhar, Muhamm.ad Usm.an, 2021. Exploring knowledge management perspectives in smart city research: A review and future research agenda. Int. J. Inf. Manage. 56, 101989 https://doi.org/10.1016/j.ijinfomgt.2019.07.015. July 2019.

Kalmykova, Yu.liya, Sadagopan, Madum.ita, Rosado, Leon.ardo, 2018. Circular economy - from review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 135, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034.

Kjaer, Louis.e Lau.mann, Pigosso, Dan.iela C.A., Niero, M.onia, Bech, Ny.nne Mar.ie, McAloone, Ti.m C., 2019. Product/Service-systems for a circular economy: the route to decoupling economic growth from resource consumption? J. Ind. Ecol. 23 (1), 22–35. https://doi.org/10.1111/jiec.12747.

Kontokosta, Constan.tine E., 2018. Urban Informatics in the Science and Practice of Planning. J. Plan. Educ. Res. https://doi.org/10.1177/0739456X18793716.

Kultsova, Mari.na, Rudnev, Ro.man, Anikin, Anton., Zhukova, Iri.na, 2016. An ontology-based approach to intelligent support of decision making in waste management. In: IISA 2016 - 7th International Conference on Information, Intelligence, Systems and Applications. https://doi.org/10.1109/IISA.2016.7785401 no. January 2018.

Lam, Wing., 2005. Barriers to e-government integration. J. Enterprise Inf. Manag. 18 (5), 511–530. https://doi.org/10.1108/17410390510623981.

Lin, Dav.id, Hanscom, Lau.rel, Murthy, Ade.line, Galli, Al.essandro, Evans, M.ikel, Neill, Eva.n, Mancini, Ma.ria Se.rena, et al., 2018. Ecological footprint accounting for countries: updates and results of the national footprint accounts, 2012-2018. Resources 7 (3). https://doi.org/10.3390/resources7030058, 2012–18.

Maksimovic, M. 2016. "Implementation of spatial smart waste management system in malaysia Implementation of spatial smart waste management system in." https://doi.org/10.1088/1755-1315/37/1/012059.

Medvedev, Alex.ey, Fedchenkov, Pe.tr, Zaslavsky, Ark.ady, Anagnostopoulos, The.odoros, Khoruzhnikov, Ser.gey, 2015. Waste Management as an IoT-Enabled Service in Smart Cities. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 9247, 104–115 https://doi.org/10.1007/978-3-319-23126-6.

OECD, 2020. A territorial approach to the Sustainable Development Goals. OECD Urban Policy Reviews https://doi.org/https://doi.org/10.1787/e86fa715-en.

Raul Neto, Oli.veira, Gastineau, Pa.scal, Cazacliu, Bog.dan Grigo.re, Guen, La.uredan Le L., Paranhos, Régi.s Sebb.en, Carlos Otávio, Pe.tter, 2017. An economic analysis of the processing technologies in CDW recycling platforms. Waste Manage. (Oxford) 60, 277–289, 2017https://doi.org/10.1016/j.wasman.2016.08.011.

Paquin, Ray.mond L., Howard-Grenville, Jennife.r, 2012. The Evolution of Facilitated Industrial Symbiosis. J. Ind. Ecol. 16 (1), 83–93. https://doi.org/10.1111/j.1530-9290.2011.00437.x.

Patricio, Jo.ao, Angelis-dimakis, Athan.asios, Castillo-castillo, Art.uro, Kalmykova, Yuliya., Rosado, Leon.ardo, 2017. Method to identify opportunities for CCU at regional level — Matching sources and receivers. J. Co2 Utilization 22, 330–345. https://doi.org/10.1016/j.jcou.2017.10.009. September.

Perkins, Devin .N., Noel Brune Drisse, Ma.rie, Nxele, Tapi.wa, Sly, Pet.er D., 2014. E-waste: a global hazard. Ann. Global Health 80 (4), 286–295. https://doi.org/10.1016/j.aogh.2014.10.001.

Policymakers, Summary., 2018. Summary for Policy. Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.7551/mitpress/1866.003.0006.

Rajput, S., and S.P. Singh. 2018. "Industry 4 . 0 – challenges to implement circular economy." https://doi.org/10.1108/BIJ-12-2018-0430.

Ravalde, To.m, Keirstead, Ja.mes, 2017. A Database to Facilitate a Process-Oriented Approach to Urban Metabolism. J. Ind. Ecol. 21 (2), 282–293. https://doi.org/10.1111/jiec.12429.

Reyes-Córdoba, A..P., Sharratt, P..N., Arizmendi-Sánchez, J.A., 2008. Contribution of knowledge management for the implementation of waste minimisation measures into process industries. Process Saf. Environ. Prot. 86 (5), 375–388. https://doi.org/10.1016/j.psep.2008.02.002.

Rubenstein-Montano, B., 2000. A survey of knowledge-based information systems for urban planning: moving towards knowledge management. Comput., Environ. Urban Syst. 24 (3), 155–172. https://doi.org/10.1016/S0198-9715(99)00055-1.

Sattar, Abdu.l, Ahmad, Moham.mad Nazi.r, Surin, El.y Salw.ana Ma.t, Mahmood, Ahm.ad Ka.mil, 2021. An improved methodology for collaborative construction of reusable, localized, and shareable ontology. IEEE Access 9, 17463–17484. https://doi.org/10.1109/ACCESS.2021.3054412.

Shahrokni, Hos.sein, Lazarevic, Da.vid, Brandt, Nil.s, 2015. Smart urban metabolism: towards a real-time understanding of the energy and material flows of a city and its citizens smart urban metabolism: towards a real-time. J. Urban Technol. 0 (0), 1–22. https://doi.org/10.1080/10630732.2014.954899.

Sharma, Ma.nu, Joshi, Sud.hanshu, Kannan, Dev.ika, Govindan, Kann.an, Singh, Ro.hit, Purohit, H.C., 2020. Internet of Things (IoT) adoption barriers of smart cities' waste management: an Indian context. J. Clean. Prod. 270, 122047 https://doi.org/10.1016/j.jclepro.2020.122047.

Song, Bi.n, Yeo, Zhi.quan, Kohls, Pa.ul, Herrmann, Christ.oph, 2017. Industrial symbiosis: exploring big-data approach for waste stream discovery. Procedia CIRP 61, 353–358. https://doi.org/10.1016/j.procir.2016.11.245.

Steffen, W.ill, Richardson, Kat.herine, Rockström, Jo.han, Cornell, Sa.rah E., Fetzer, Ingo, Bennett, El.ena M., Biggs, Rei.nette, et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347. https://doi.org/10.1126/science.1259855, 6223.

Storey, Ve.da C., 1991. Relational database design based on the entity-relationship model. Data Knowl. Eng. 7 (1), 47–83. https://doi.org/10.1016/0169-023X(91)90033-T.

Themelis, Nick.olas J., 2019. Recovery of Materials and Energy from Urban Waste. Introduction. https://doi.org/10.1007/978-1-4939-7850-2_394. Vol. i.

Tolle, K.M. 2021. Fourth Paradigm. https://doi.org/10.1007/978-3-319-32001-4_354-1.

Toxopeus, M.E., De Koeijer, B.L.A., Meij, A.G.G.H., 2015. Cradle to cradle: Effective vision vs. Efficient practice? Procedia CIRP 29, 384–389. https://doi.org/10.1016/j.procir.2015.02.068.

Lang, Tse.ng Mi.ng, Tan, Ray.mond R., Chiu, Ant.hony S..F., Chien, Che.n Fu F., Kuo, Ts.ai Ch.i, 2018. Circular economy meets industry 4.0: Can big data drive industrial symbiosis? Resour. Conserv. Recycl. 131, 146–147. https://doi.org/10.1016/j.resconrec.2017.12.028. December 2017.

Lang, Tse.ng Mi.ng, Phuong, Th.i, Tran, Thu.y, Ha, Hie.n Mi.nh, Bui, Tat.Da.t, Lim, Ming.K., 2021. Sustainable industrial and operation engineering trends and challenges toward Industry 4.0: a data driven analysis. J. Ind. Prod. Eng. 00 (00), 1–18. https://doi.org/10.1080/21681015.2021.1950227.

United Nations Conference of Housing and Sustainable Urban Development. 2016. "Habitat III, New Urban Agenda," no. October: 24.

Uran, Odd.run, Janssen, R.on, 2003. Why are spatial decision support systems not used? Some experiences from the Netherlands. Comput., Environ. Urban Syst. 27 (5), 511–526. https://doi.org/10.1016/S0198-9715(02)00064-9.

Vitorino de Souza Melaré, An.gelina, Montenegro González, Sa.hudy, Faceli, Ka.tti, Casadei, Vit.or, 2017. Technologies and decision support systems to aid solid-waste management: a systematic review. Waste Manage. (Oxford) 59, 567–584. https://doi.org/10.1016/j.wasman.2016.10.045.

Paper II

Method for identifying industrial symbiosis opportunities

J.Patricio1, Y. Kalmykova1, L. Rosado1, **J. Cohen**, A. Westin & J. Gil

Resources, Conservation Recycling
185 (2022)

Resources, Conservation & Recycling 185 (2022) 106437

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Full length article

Method for identifying industrial symbiosis opportunities

Joao Patricio, Yuliya Kalmykova, Leonardo Rosado *, Jonathan Cohen, Alexandra Westin, Jorge Gil

Department of Architecture and Civil Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden

ARTICLE INFO

Keywords:
Industrial symbiosis
Circular economy
Industrial waste
Industrial symbiosis database
Input output matching

ABSTRACT

Industrial Symbiosis (IS) can reduce industrial waste and the need for virgin material extraction by utilizing waste generated by one industry as a raw material for another. Input-output matching is a commonly used approach for identifying potential IS partnerships. Usually, to collect necessary data for input-output matching, companies are asked to participate in workshops or surveys. However, such activities can be costly and time consuming. Additionally, companies may be unwilling to participate due to issues around data confidentiality. This article aims to show how these barriers can be overcome by a new method for identification of IS opportunities, which does not require companies to be surveyed. The developed matching approach uses statistical datasets and IS databases. The underlying principle is to use known IS partnerships and databases developed by the authors containing data on typical waste generation and resource use by industries, to expand and link other potential donors and receivers. This allows the expansion of one IS example into multiple potential relationships. The method promotes Circular Economy development by identifying more opportunities to utilize more secondary resources through connecting previously unrelated industry sectors. The method has been tested in Sweden, where the goal was to identify potential partnerships between industries that generate sawdust as a waste product and companies that could utilize sawdust in their industrial processes. Out of 6,726,534 potential symbiotic links identified by the method, 159,630 were shortlisted using prioritization criteria reflecting an increased likelihood of symbiosis.

1. Introduction

Industrial Symbiosis (IS) involves collaboration between companies, in which they exchange materials, energy, water and/or by-products (Chertow, 2007). Together with eco-industrial parks and supply chains, IS is one of the three main fields supporting sustainable industrialization within the Circular Economy arena (Homrich et al., 2018). In recent decades, IS has gained much attention among policy makers, businesses, and academia, as a means to support the transition to a circular model (Gregson et al., 2015). In the European Union (EU), IS has been recognized as a tool that can be used to promote sustainable growth and resource efficiency in industrial systems. In 2012, IS was defined as one of the top seven priority areas by the European Resource Efficiency Platform (Johnsen et al., 2015).

A number of different methods can be used to identify potential IS partnerships, including New Process Discovery, Relationship Mimicking, Material Budgeting, and Input-Output Matching (Grant et al., 2010; Holgado et al., 2018). Input-Output Matching is perhaps the most commonly used method, and involves finding potential IS matches by analyzing characteristics of output streams (i.e. wastes and by-products) from industries and the material inputs they require, before matching one to the other (Bin et al., 2015; Hein et al., 2016; Low et al., 2018; Yeo et al., 2019). This method can be used to achieve higher efficiency in industrial parks (Holgado et al., 2018), via IT-enabled identification using semantic matching (Trokanas et al., 2014) or expert-facilitated workshops (Maqbool et al., 2019). The most widely known program using Input-Output Matching is the National Industrial Symbiosis Program (NISP), which uses bottom-up approaches to facilitate IS in a given region. Using a cross-sectoral and supply chain approach, NISP is able to identify opportunities among stakeholders participating in workshops (NISP Canada, 2017).

Although bottom-up approaches have been shown to be successful in identifying opportunities for IS partnerships, they have some limitations. In order to obtain the necessary data, companies must take part in certain activities, such as registering resources or wastes on web platforms, or sharing information by participating in workshops or meetings

---

* Corresponding author at: Leonardo Rosado, Department of Architecture and Civil Engineering, Chalmers University of Technology, 412 96, Gothenburg, Sweden.
E-mail address: rosado@chalmers.se (L. Rosado).

https://doi.org/10.1016/j.resconrec.2022.106437
Received 10 March 2022; Received in revised form 25 May 2022; Accepted 31 May 2022

(Alvarez and Ruiz-Puente, 2017). However, certain factors can limit the necessary data acquisition, including: 1) data confidentiality, 2) time constraints, and 3) high costs. There are multiple examples of companies being reluctant to share confidential information, e.g. on raw material consumption or waste generation (Bacudio et al., 2016). Additionally, companies hesitate to share information if they do not see clear value gains (Patala et al., 2020) and in many cases companies do not have time to engage in these types of activities (Patricio et al., 2018). Conducting audits and interviews to collect information about inputs and outputs is associated with high costs and may be very time consuming (Hein et al., 2016). Sometimes companies may simply not have been considered for a workshop, forgotten to register their wastes on an online platform, or to fill in a questionnaire.

At the same time, we are facing the Fourth Industrial Revolution (Industry 4.0) which among other things, relies on the availability of large amounts of data. Data-driven analysis can now be used to optimize sustainable solutions, including the efficient use of resources and energy (Reis and Kenett, 2018; Tseng et al., 2018). The results and methods developed as part of Industry 4.0 may help decision-making processes and identify approaches that effectively promote waste circularity (Winans et al., 2017). As a result, it may be possible to employ top-down approaches that utilize available datasets, and to develop tools with the ability to identify IS opportunities. However there are still some challenges relating to data availability that have been identified. Chen and Ma (2015) have pointed out the lack of comprehensive and standardized databases for material streams. This is even more evident for waste generation datasets, which are usually only available with very high aggregation (Reynolds et al., 2016).

It is also known that considering different industries at the same time improves the chances of finding potential applications for waste reuse in a particular geographical area. According to Jensen (2016), diversity within industrial ecosystems promotes resource reuse and, potentially, increased system production. However, there is a lack of tools that allow identification of potential relations between multiple sectors and industries (European Commission, 2018). One explanation for this may be the lack of comprehensive and standardized databases for material flows (Chen and Ma 2015). In particular, waste generation datasets are usually only available with very high aggregation (Reynolds et al., 2016). If this data was available, input-output matching could rely on information about stream characteristics and technological capability, rather than the willingness and ability of individual companies to share data (Yeo et al., 2019).

The aim of this article is to introduce a method for identification of potential IS partnerships that makes use of available detailed datasets. This has been achieved by coupling a top-down approach with input-output matching. The developed method intends to: 1) use available data to avoid direct involvement of companies in the preliminary phase of IS, overcome common issues, including confidentiality problems and the use of time-consuming tools such as surveys or interviews, and to 2) employ comprehensive tools to consider potential relationships between companies from different sectors operating within the same spatial area. To achieve this, the method considers 103 industries, 1,264 material input types, and 816 waste types. The method has been tested in a spatial application on the Västra Götaland region.

2. Method

The method developed in this study identifies potential matches for IS using a top-down approach. A schematic diagram of the method is presented in Figure 1. The method consists of three steps: 1) identification of industrial wastes generated by industries, 2) identification of material inputs needed by industries, and 3) matching industrial wastes to material inputs. It has been developed using Eurostat standard nomenclatures, which correspond to similar nomenclatures used in other regions of the world. The method has been tested in a spatial application that involved analysis of potential IS opportunities considering distances between companies. In this study, the method was applied to wood wastes generated in the Västra Götaland region in Sweden. The methodology is explained in detail in Section 2.2.

2.1. Nomenclatures and Data Collection

In this article, industries, material inputs and wastes have been classified using Eurostat standard nomenclatures, which correspond to similar nomenclatures used in other regions of the world (Ramon, 2020).

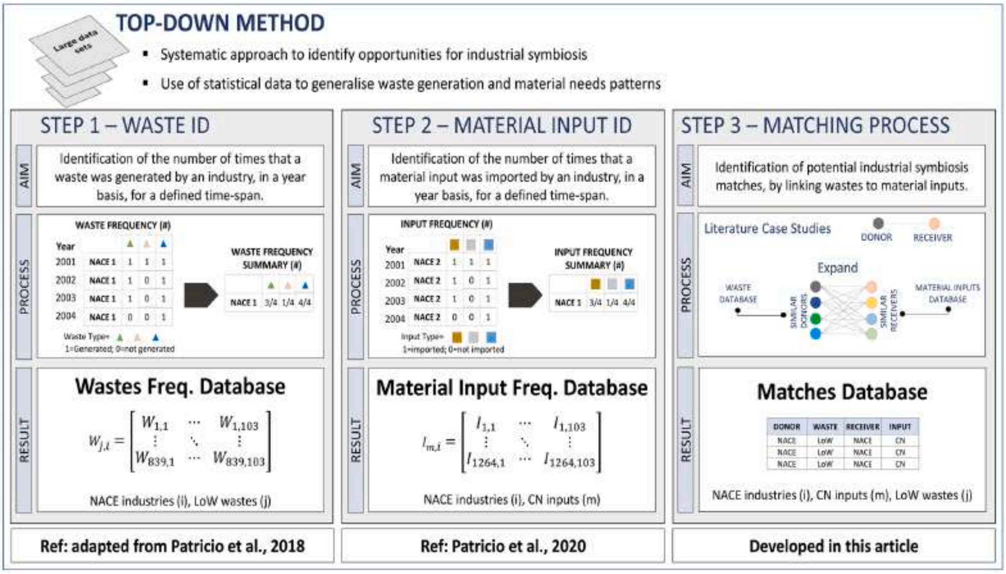


Figure 1. - Top-down Method for Identifying Industrial Symbiosis Opportunities

- Industries are classified using the Statistical classification of economic activities in the European Community nomenclature, abbreviated as NACE. More specifically, the NACE rev. 2 nomenclature at 3 Digits is used. This study includes companies from agriculture, mining and manufacturing sector, corresponding to NACE 011 up to NACE 380, a total of 103 activities, referred henceforth as 'industries'. For example, NACE code 310 stands for "Manufacture of Furniture". The entire list of NACE codes can be found in Table 1 in Supplementary Information. There is a correspondence between NACE and United Nations' International Standard Industrial Classification of all economic activities (ISIC).
- Products or material inputs are used interchangeably in this article and represent all the goods used by industries. This includes structural products, auxiliary products and investment goods (see Patricio et al (2020) for more details). They are classified according to the Combined Nomenclature (CN), the classification used in the European Commission for collecting and processing data on foreign trade. The four-digit disaggregation (CN4) is used (Table 2 in Supplementary Information), which includes 1,264 different products. As an example, CN4 code 4407 stands for "Wood sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, of a thickness of $>$ 6 mm" (Eurostat, 2020). The CN codes correspond to the Harmonized System (HS) which is the internationally standardized system of names and numbers to classify traded products.
- Industrial wastes are classified according to the European List of Wastes (LoW) nomenclature, developed by the European Commission. This waste nomenclature encompasses 839 wastes types. As an example, LoW code 30101 stands for "Waste bark and cork (Eurostat, 2010). The LoW codes can also be aggregated into European Waste Classification for Statistics (EWC-stat) waste categories. Following the same example, LoW code 30101 (waste bark and cork) belongs to the EWC-stat 07.5 "Wood wastes".

The method employs three databases that were developed using existing datasets: 1) Material Input Data contains detailed international trade data on products (8-digit CN codes) imported in a specific year, at country level and by industry (NACE codes). The International Trade dataset is a detailed database that measures value and quantity of goods traded both between EU Member States and between EU Member States and non-EU countries on a product basis (Eurostat, 2016). Data for Portugal for the years 2000 through 2012 was used; 2) Industrial Waste contains detailed data on wastes (LoW codes) generated by industries (NACE code). This data is collected by APA under the Portuguese regulation Decree-Law no 73/2011, which makes it mandatory for companies and operators to disclose information regarding waste generation and transfers on a yearly basis. Data for Portugal for the period from 2010 until 2014 was used; 3) Industrial Symbiosis Case Studies, developed using published literature, contains IS case studies with information on waste donor, waste receiver, and type of exchanged waste (See Table 3 in Supplementary Information for more detailed information on the databases). Due to difficulties in acquiring the first two datasets for Sweden, data for Portugal was used. As shown in Patricio et al. (2021), material inputs to industries in Portugal and Sweden are 60-80% similar, which makes use of developed databases suitable for Swedish conditions as well. The use of the datasets is limited to identifying the frequencies of production of waste and the frequency of use in industries since some products with high dependence on domestic input sources will not be captured with the International Trade datasets and therefore skew the quantification of the inputs amounts in weight.

2.2. Top-Down Methodology

2.2.1. Typical Waste Identification (Step 1)

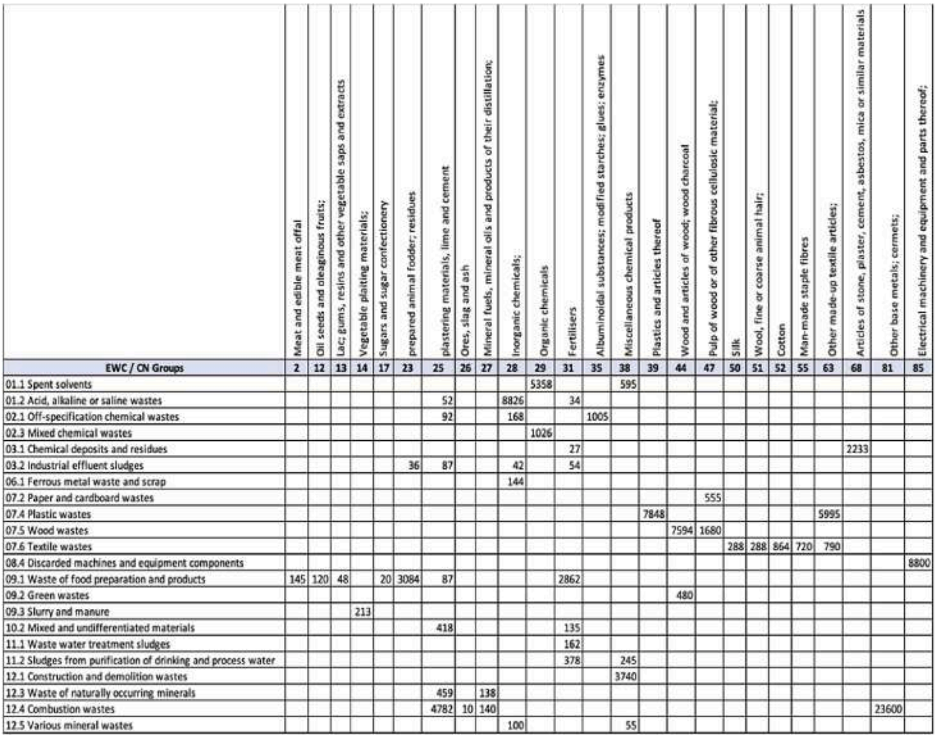
The first step identifies the types of wastes generated by different industries (by NACE codes). This is based on the assumption that companies within the same industry generally generate similar types of waste. Based on the previous work by Patricio et al. (2020), a matrix of typical wastes generated within each industry was developed. The Waste Frequency database has also been created based on the Industrial Waste dataset described in section 2.1 Nomenclatures and Data Collection. The frequency value indicates the number of years in which at least one company within a particular industry (k) generated a specific waste type (j) within a given time span. This means that if only one company within a particular industry generated a specific waste type in a given year, the frequency value is 1, regardless of the amount of waste generated. The time span used in this study was four years (2012 to 2015), and the frequency values therefore vary from 0 to 4. As an example, a frequency value of 2 means that at least one company within a particular industry generated a specified waste in two of the four years. This does not necessarily have to be the same company. Following the same example, a frequency value of 2 can also mean that two companies within the same industry each generated the same waste type once in two different years. A frequency value of 4 represents a waste that is highly likely to be generated by a certain industry, and 0 represents a waste that is unlikely to be generated within a given industry.

$$\mathrm{W}_{j,k} = \begin{bmatrix} W_{1,1} & \cdots & W_{1,103} \\ \vdots & \ddots & \vdots \\ W_{839,1} & \cdots & W_{839,103} \end{bmatrix} W = \ \mathit{Waste\ Outputs\ frequency},\ j = 1,2\ ..\ 839\ \mathit{classes\ of wastes}\ (\mathit{LoW\ codes})\ \mathit{and}\ k = 1,2..103\ \mathit{industries}\ (\mathit{NACE\ codes}) \tag{1}$$

2.2.2. Typical Material Inputs Identification (Step 2)

Typical inputs used by industries were identified using the method developed by Patricio et al (2021), which assumes that companies belonging to the same industry (NACE codes) typically use the same types of material inputs. Using international trade statistics, a Material Inputs Frequency database was developed for all industries and all CN codes. This database is the equivalent of the Waste Frequency database, but for material inputs. It contains information on the frequency for each CN product (i) used by each industry (k) during a fourteen year-period (2000 to 2013). The frequency value indicates the number of times a given product was imported by an industry, and the values therefore vary between 0 and 14. The value 0 corresponds to a product that was never imported by an industry, and the value 14 a product that was imported in all the years. Any product with a value of 14 in the Material Input Frequency database is highly likely to be used by companies operating in that industry.

Table 1
- Summary of Potential Matches between Wastes and Material Inputs



	Meat and edible meat offal	Oil seeds and oleaginous fruits;	Lac; gums, resins and other vegetable saps and extracts	Vegetable plaiting materials;	Sugars and sugar confectionery	prepared animal fodder; residues	plastering materials, lime and cement	Ores, slag and ash	Mineral fuels, mineral oils and products of their distillation;	Inorganic chemicals;	Organic chemicals	Fertilisers	Albuminoidal substances; modified starches; glues; enzymes	Miscellaneous chemical products	Plastics and articles thereof	Wood and articles of wood; wood charcoal	Pulp of wood or of other fibrous cellulosic material;	Silk	Wool, fine or coarse animal hair;	Cotton	Man-made staple fibres	Other made-up textile articles;	Articles of stone, plaster, cement, asbestos, mica or similar materials	Other base metals; cermets;	Electrical machinery and equipment and parts thereof;
EWC / CN Groups	**2**	**12**	**13**	**14**	**17**	**23**	**25**	**26**	**27**	**28**	**29**	**31**	**35**	**38**	**39**	**44**	**47**	**50**	**51**	**52**	**55**	**63**	**68**	**81**	**85**
01.1 Spent solvents											5358			595											
01.2 Acid, alkaline or saline wastes							52			8826		34													
02.1 Off-specification chemical wastes							92			168			1005												
02.3 Mixed chemical wastes											1026														
03.1 Chemical deposits and residues												27											2233		
03.2 Industrial effluent sludges						36	87			42		54													
06.1 Ferrous metal waste and scrap										144															
07.2 Paper and cardboard wastes																	555								
07.4 Plastic wastes															7848							5995			
07.5 Wood wastes																7594	1680								
07.6 Textile wastes																		288	288	864	720	790			
08.4 Discarded machines and equipment components																									8800
09.1 Waste of food preparation and products	145	120	48		20	3084	87					2862													
09.2 Green wastes																480									
09.3 Slurry and manure				213																					
10.2 Mixed and undifferentiated materials							418					135													
11.1 Waste water treatment sludges												162													
11.2 Sludges from purification of drinking and process water												378		245											
12.1 Construction and demolition wastes														3740											
12.3 Waste of naturally occurring minerals							459		138																
12.4 Combustion wastes							4782	10	140															23600	
12.5 Various mineral wastes										100				55											

$$\mathrm{I}_{i,k} = \begin{bmatrix} I_{1,1} & \cdots & I_{1,103} \\ \vdots & \ddots & \vdots \\ I_{1264,1} & \cdots & I_{1264,103} \end{bmatrix} I = \mathit{Material\ Inputs\ frequency},\ i = 1, 2\ ..\ 1, 264\ \mathit{classes\ of\ products}\ (\mathit{CN\ codes})\ \mathit{and}\ k = 1, 2..103\ \mathit{industries}\ (\mathit{NACE\ codes}) \tag{2}$$

2.2.3. Matching Process (Step 3)

In this step, potential IS partnerships between NACE industries are identified. IS case studies found in the literature and the frequency databases developed in Section 2.2.1 and Section 2.2.2 were used to identify other industries that generate similar wastes (Donors) and need similar material inputs (Receivers). The core idea is to expand one single IS case study into multiple potential IS matches, defined in this study as the Matching process. The Matching process is divided into 4 stages: 1) Industrial Symbiosis case study details; 2) Expansion; 3) Matching, and; 4) Results printing. The Matching process is explained in detail below and in Figure 2.

In Stage 1 (utilization of IS case studies), the tasks done involved the identification of proven links between wastes and material inputs from IS case studies found in the literature. Existing databases are preferred sources of data, as they include multiple IS partnerships in a summarized format, and some are compiled using standard nomenclatures. The MAESTRI (MAESTRI project, 2020) and IS Data (IS Data, 2020) are examples of such IS databases. For illustration purposes, this article uses the MAESTRI database.

The MAESTRI database is a list of IS examples assembled by an EU-funded research project (MAESTRI Project, 2020). For each IS case study, the MAESTRI database contains information on: the NACE code of both industry Donor (i.e., waste provider) and Receiver (i.e., material inputs user); LoW code for the exchanged waste; and the CPA (Classification of Products by Activity) code of the material input. To use the MAESTRI database, certain data treatment was required. First, some missing nomenclature codes were added to the MAESTRI database, based on descriptions available in the database. Second, nomenclatures were converted into the ones used in this method. The CPA codes for material inputs in the MAESTRI database were converted to CN codes using a correspondence table, available in Eurostat (Ramon, 2020).

In total, the MAESTRI database contains 425 IS case studies. Non-applicable case studies were excluded as part of the data treatment performed in Stage 1. The removed case studies included: symbioses not related to materials, for example, heat, electricity, water, or vapor (72 cases); and lacking fundamental information, such as LoW or CPA codes (155 cases). Additionally, some of the case studies were duplicates. Each of the remaining 158 case studies in the MAESTRI database were used to create a match between a waste (LoW code) and material input (CN code). The relations between wastes and material inputs were then used in Stage 2, Expansion.

Stage 2 (Expansion) tasks, involved identification of potential Donors and Receivers for each relationship identified in Stage 1. Starting with the first relationship, the Waste database (section 2.2.1) was used to identify all industries that may generate the waste in question, by selecting those with frequency values higher than 1. Frequencies with a value of 1 are not considered because they may relate to sporadic events or measurement errors, for which the nomenclature was not correctly assigned. In this article, these industries are defined as potential Donors. The same process was applied for the material inputs, i.e. all industries which may use the relevant material inputs in their industrial processes and had a frequency value above 1 in the Material Input database (Section 2.2.2) were identified. These industries are defined in this article as potential Receivers. The frequency value for each material was extracted from the Waste and Material Input databases.

Stage 3 is defined as the Matching process. In this step, the relationships found in the MAESTRI database were expanded to match more potential Donors and Receivers. All potential Donors were matched to potential Receivers, as identified and selected in Stage 2. These expanded matches of potential IS partnerships are here defined as Potential Matches. They are represented with arrows in Figure 2.

The final stage, Stage 4 (Results printing), consisted of registering all obtained Potential Matches into a final database, defined as the Matches database. All four stages were repeated for all the 158 IS case studies selected from the MAESTRI database, and the resulting pairs were entered into the Matches database.

2.2.4. *Cross-Comparison Analysis for Method Validation*

To validate the method, the Matches database was crosschecked against the existing MAESTRI database. The cross-comparison process consisted of verifying whether, for each case study, the actual industry Donors and Receivers from the MAESTRI database were captured in Stage 2 (Expansion). If they were captured, they would also be identified in Stage 3 (Matching process). These are represented with blue arrows in Figure 2. For a blue arrow, the Donor industry, represented with a grey circle, is the same as the Donor industry in the case study from Stage 1 – IS Case Study details. The Receiver industry is represented with a black circle and is also the same industry as in Stage 1. This shows that both the Input Frequency and the Waste Frequency database were able to capture the industries identified in the original case study.

Only complete case studies in the MAESTRI database were considered in the validation process, i.e., cases where Donor, Receiver, LoW code, and CN code of the Material Input data were present. For each MAESTRI case study, the validation process included three checks: 1) whether the Donor of the waste in the MAESTRI case study was also found in the Matches database; 2) whether the Receiver of the material input in the MAESTRI case study was also found in the Matches database; and, 3) whether both the Donor and the Receiver from the MAESTRI case study were found in the Matches database. Additionally, an analysis of the obtained Waste frequencies and Material Input frequencies for both Donors and Receivers was performed. The aim of this final analysis was to verify whether the frequency databases returned high values for the wastes and input materials considered.

3. Results and Discussion

3.1. *Waste and Material Input Frequency Databases – Step 1 and 2*

The Waste Frequency database provides information on the types of wastes generated by different industries. The heat map presented in Figure 3 relates to the Waste database compiled in this study. Waste types (LoW) are presented in rows, while the industries that generate them, along with the corresponding industry sectors, are found in the columns. The heat map shows which industries can be expected to produce a given waste. As an example, Box 1 shows that animal and vegetable wastes are mainly expected to be generated within the food processing and agricultural sectors. It would also be possible to identify the types of wastes expected to be generated by a given industry. Box 2 shows that companies within the Manufacture of musical instruments (NACE 322) sector produce mostly wastes belonging to the metallic waste group.

The Material Inputs typically needed by each industry have been visualized using a heat map (Figure 4). The rows contain the types of input materials, according to CN4 code. The columns show the industry types as well as the sectors they belong to. As an example, Box 1 shows that base metals are widely used within the Manufacture of electrical equipment, with frequency values very close to the maximum of 14. Box 2 shows that food related products are generally not used in industries belonging to the Textile, Wood, or Transport sectors. Finally, Box 3 represents all the material inputs needed by an individual industry within the Agriculture sector.

3.2. *Matches Database – Step 3*

The matching process developed in this article aims to identify potential IS relationships between two industries, using their NACE classification codes. Using the developed methodology, 158 IS cases from the MAESTRI database were expanded to a total of 211,114 potential IS matches, which were stored in the Matches database. Records with a frequency value of 1 were removed from the Waste and Material Input databases, which reduced the number of matches to 96,622. Additional exclusions are possible, such as removing industries with low values for Waste or Material Input frequency. Table 4 in Supplementary Information shows the number of matches between Wastes and Material Inputs for each frequency value (excluding those with a frequency value of 1). There were 6,707 matches between industries with a frequency value of 2 (out of maximum 4) for generation of a particular Waste and industries with a frequency value of 2 (out of maximum 14) for requiring a particular Material Input. Theoretically, matches become stronger with increasing frequency values, as both supply and demand for the waste become more reliable. The strongest possible matches, with values of 4/4 and 14/14 for Waste and Material Input frequency, respectively, comprised 10% (9,709) of the total number of obtained matches. However, all the frequencies could be considered, as the reliability of individual matches may also depend on other factors in addition to supply and demand.

Table 1 presents a summary of the obtained 96,622 matches. It shows the relations between Waste and Material Inputs, aggregated by waste and material input groups. These represent unique matches between two industries. Note that a cell may contain a repeated Waste – Material Input relation, however the industries will be different. Wastes are presented in rows, the columns contain the Material Inputs they may be able to replace. Both wastes and material inputs have been aggregated into European Waste Classification for Statistics (EWC-stat)[1] and CN 2 categories[2], respectively. In the Matches database, 67 different potential wastes (LoW codes) were matched with 80 material inputs (CN codes). As an example, Spent solvent wastes, in row number one, can be used to replace two material inputs, namely Organic Chemicals and Miscellaneous Chemical products. Cement-related inputs could be replaced by Combustion waste materials. The most representative waste group in numbers is Combustion wastes. These wastes have been identified as potential replacements for material inputs used in the production of Cement and concrete products. A total of 115 unique potential Donor industries were found, and 112 industries were identified as potential Receivers. Although, approximately 100,000 possible IS matches are

---

[1] The European Waste Classification for Statistics (EWC-stat) covers 12 waste groups and further subcategories. Each LoW code is assigned an EWC category

[2] The Combined nomenclature 2 digits, includes 99 groups of goods.

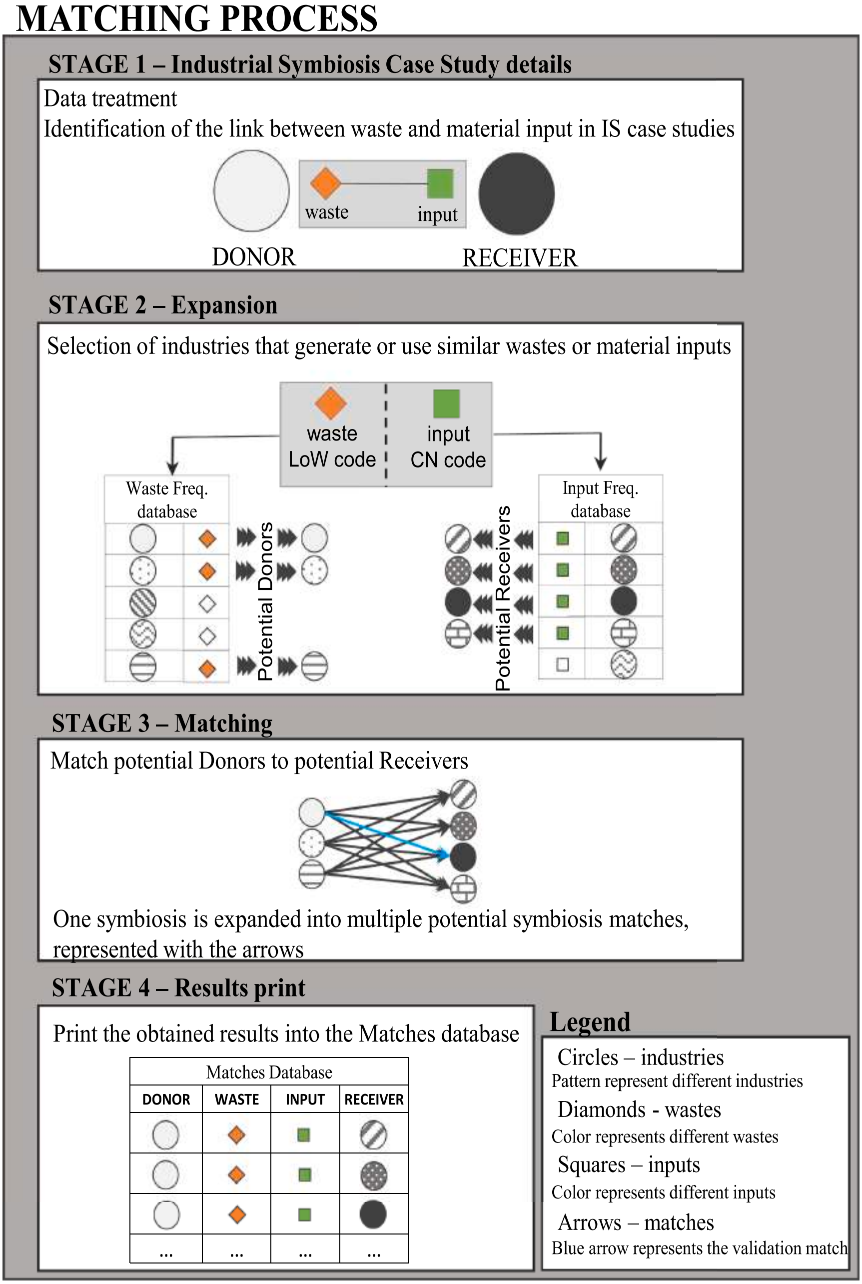


Figure 2. – Schematic diagram of the matching process

identified with the MAESTRI database, the same process could be applied to the IS Data dataset and to other cases found in the literature to enrich the database and update with new possibilities that arise from technological development. Recent developments in data mining could also be employed to further the possible IS matches, such as, applying a big-data approach to discover Industrial Symbiosis using standard nomenclatures (Song et al. 2017).

3.3. *Matching Validation*

The validation process included verification of whether the industries from the MAESTRI database case studies used were also present in the Matches database. For the cross-comparison, all MAESTRI case studies containing complete information on Donor, Receiver, exchanged waste, and material input were used; 146 cases in total. With respect to the Donors, 98 of the 146 industries in the MAESTRI database were also

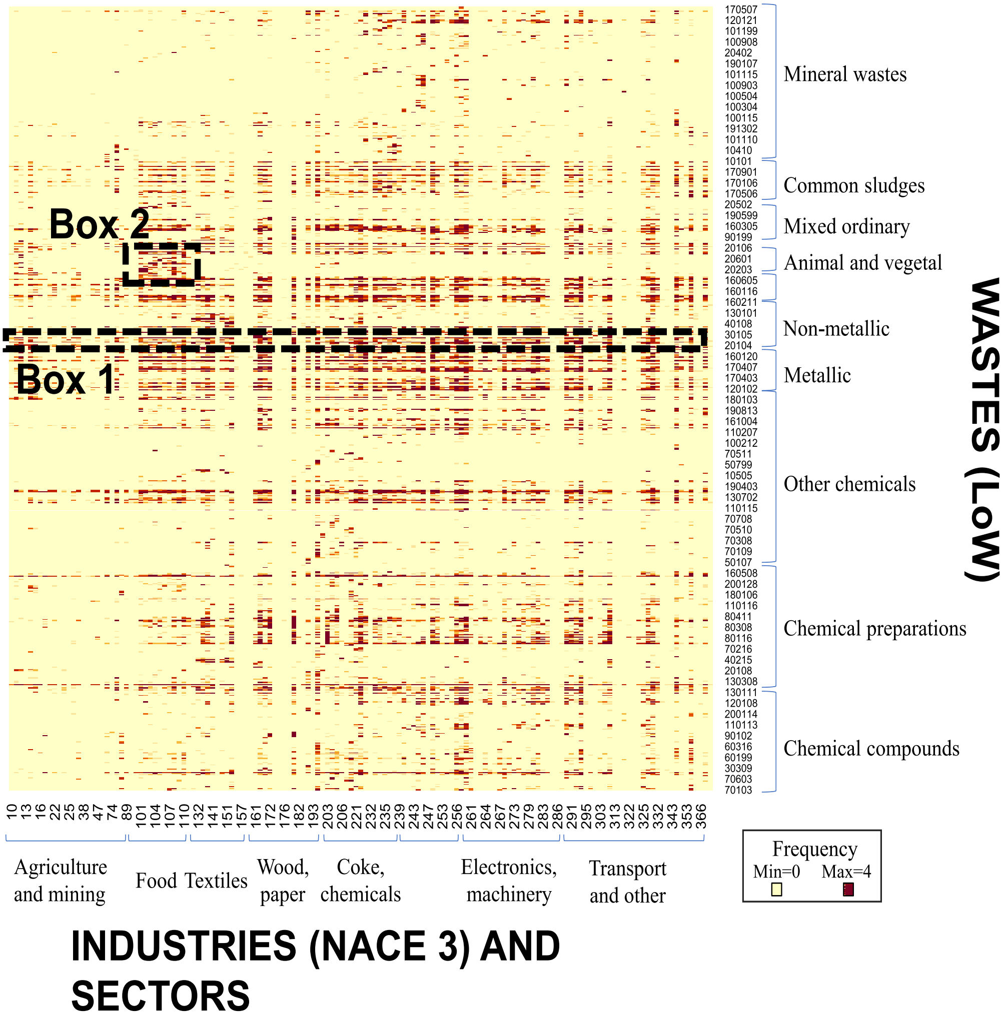


Figure 3. – Heat map for the Waste Frequency database

found in the Matches database. More than 75% of these 98 Donors had the maximum Waste frequency value of 4 out of 4. Therefore, these industries were considered high probability waste generators. In the case of the Receivers, 119 of the 146 industries present in the MAESTRI database were also found in the Matches database. Here, 50% of the industries had a frequency value of at least 10 for Material Inputs, and more than 25% registered a value of 14. In 77 out of the 146 cases, both Donor and Receiver were found in the Matches database. There are a few reasons why more Receivers than Donors were found. In a review of the European list of waste classification, some difficulties were mentioned by the Member States, including: Problems resulting from the lack of suitable waste codes; Ambiguous classification on account of two or more possible codes; Problems resulting from unclear or imprecise definitions (Ökopol GmbH, 2008). Therefore, in some particular cases, the LoW codes may not have the adequate level of detail for IS exploration.

3.4. Application of the Matching Process

In this section, an example from the MAESTRI database is used to illustrate the Matching process. In the MAESTRI case study, the Donor is a plywood manufacturing company (NACE 162) that generates sawdust (LoW 30105), which is then used as fuel wood (CN 4401) by a chemical production company (NACE 205) (Receiver). Applying the developed methodology, the waste type (LoW 30105) and the input type (CN code 4401) are the only fixed variables.

All industries (NACE codes) that may generate waste type LoW 30105 were identified using the Waste database. In total, 44 industries were identified as potential Donors; 11 industries with frequency value 1; 4 with frequency value 2; 5 with frequency value 3, and; 24 with frequency value 4. Some of the industries identified as potential Donors were expected, including Manufacture of products of wood, cork, straw and plaiting materials (NACE 162), Manufacture of furniture (NACE 310) and Manufacture of cutlery, tools and general hardware (NACE 257). One of the industries identified as a producer of waste type LoW 30105 was Plywood manufacturing (NACE 162), which shows that the model also captures the industry that generates the waste in the MAESTRI case study example.

The identification of industries that use similar material inputs to the one identified in the case study (potential Receivers) is performed in

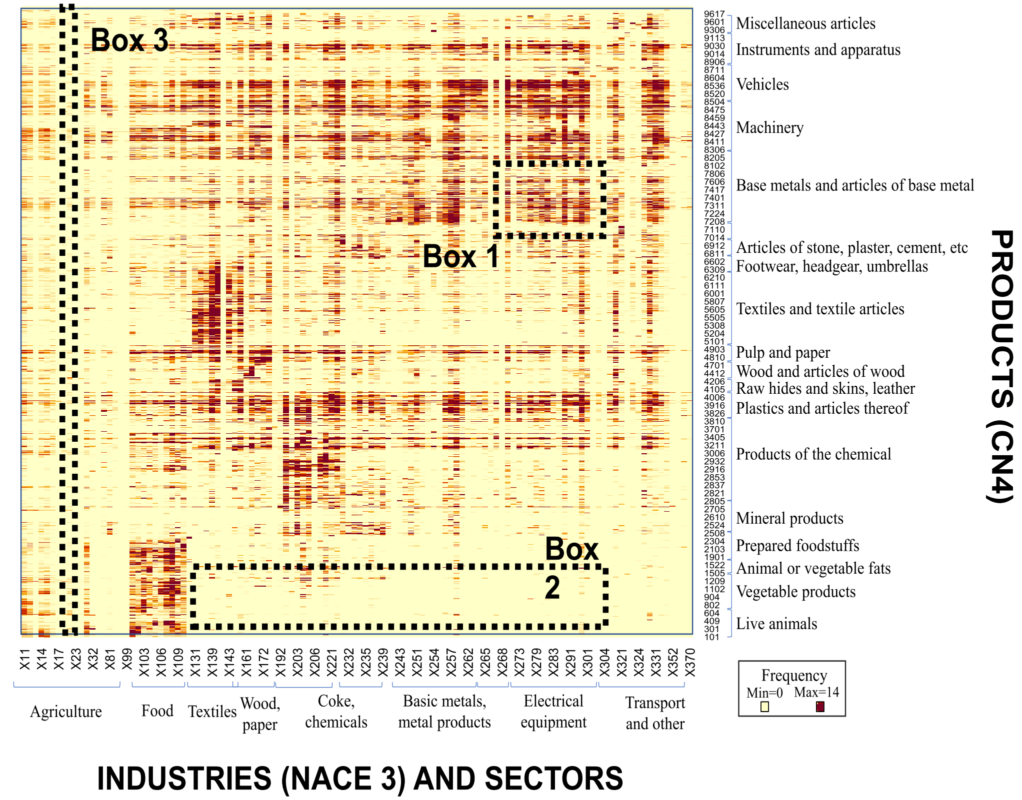


Figure 4. –Heat map of Material Input Frequency database

Stage 2 – Expansion. In the CN nomenclature, fuel wood has the code 4401 (Fuel wood, in logs, billets, twigs, faggots or similar forms; wood in chips or particles; sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar). Table 5 in the Supplementary Information shows the industries identified as currently using this product as a material input, as well as the corresponding Material Inputs Frequency, extracted from the Material Input database.

The identified uses are not limited to the original usage from the MAESTRI database. In the MAESTRI database, sawdust was used as an energy source. However, with the applied method, many other potential uses were identified; a selection of potential uses is available in Table 5 in the Supplementary Information. Each possibility identified through the Material Input Frequency database was cross-checked through a literature review. In the case of this particular waste being used as material input, the cross-check confirmed that the method correctly identified potential users. For example, high frequency values, of 12 and 14 respectively, were found for sawdust being used for animal bedding in NACE 14 (Animal production), or to produce wood boards such as fiberboards or oriented strand board in NACE162 (Manufacture of products of wood, cork, straw and plaiting materials).

The final step included matching all companies that may generate sawdust with all potential sawdust users. In this process, a single IS case study from the MAESTRI database was expanded into 910 different matches.

3.5. Spatial Application

In this section, the matching method presented above is applied to industries working with wood resources in the Västra Götaland region, Sweden. This example analyzes residual sawdust, shavings, cuttings, wood, particle board, and veneer (LoW 30105). Based on the geographical location of the companies, the linear distances between potential Donors and Receivers were calculated. This section demonstrates how spatial proximity can be used to identify realistic IS opportunities by applying different filters to the Matches database.

A total of 2,520 companies located in the region, and potential Donors or Receivers of LoW 30105, were analyzed. Each company was classified by NACE code in the dataset used. In total, 6,726,534 potential IS links were identified. These links did not take into account in-house reuse, i.e. companies that reuse their own waste. First, a set of three restrictions was applied to select the most promising links: 1) Waste generation frequency; 3) Material Input frequency; and 3) distance between companies, where distances above 48km were excluded. This distance was selected based on results obtained by (Jensen et al.,2011), where typical resource movement distances for different waste types were calculated based on actual IS partnerships in the UK. The summary of results of this analysis is provided in Table 6 in the Supplementary Information. With the unrestricted dataset (R0) as a starting point, the distance restriction of 48km was introduced, along with frequencies for Waste and Material Input (R1). The latter restriction led to a significant reduction in the number of potential Donors and Receivers.

Application of the most restrictive filters (R2) reduced the number of potential IS relationships to 159,630 links, which is only 2.3% of the initial number. By applying restrictions relating to distance and possibility that a given waste will be produced (Waste Frequency), and used (Input Frequency), the number of potential opportunities can be reduced to more feasible cases, which can then be used to stimulate policies, business opportunities, and ultimately reduce the requirement for

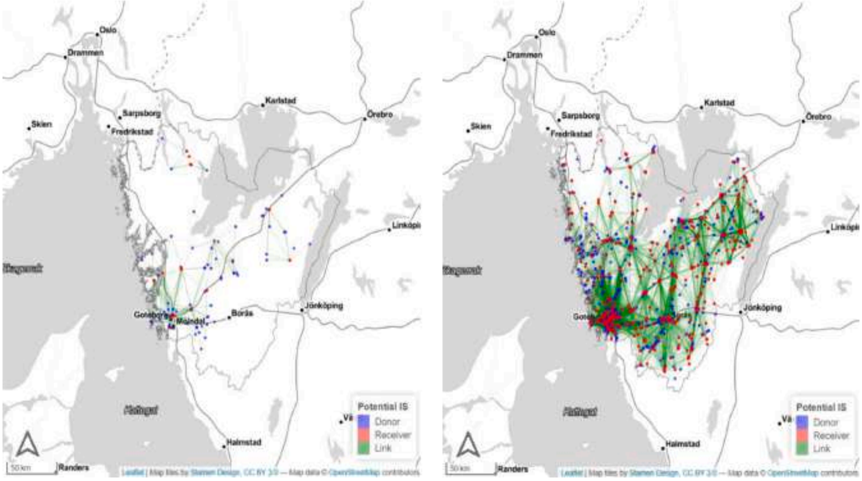


Figure 5. – Map of obtained potential IS links for LoW 30105. Left map (A) using the MAESTRI case study; Right map (B) using the matchmaking process presented in this article

natural resource usage. Among the Potential Donors, NACE 256 and NACE 331 (Machining manufacture and Repair of fabricated metal products, machinery and equipment, respectively) were among the most representative Donors in terms of number of companies (17% and 11%, respectively). Of the potential Receivers, companies with NACE code 162 (Manufacture of products of wood, cork, straw and plaiting materials) accounted for 29% of the database, followed by those with NACE codes 259 (Manufacture of plastics products), 310 (Manufacture of other fabricated metal products), and 293 (14%, 11%, and 10% respectively).

Two maps were produced to spatially locate the Donors and Receivers, and the corresponding links (Figure 5). Map A shows potential IS relationships by mimicking the original case study from the MAESTRI database. In this example, LoW 30105 generated by a plywood manufacturing company (NACE 162) is burned to produce energy by a chemical production company (NACE 205). Once the 48km restriction had been applied, 19 similar opportunities were identified in the region. Following the methodology developed in this article, Donors and Receivers of the same waste type were mapped and linked. MAP B shows the obtained results, with 159,630 potential symbiotic links mapped.

3.6. Discussion

The method presented in this article identifies potential IS partnerships in a given spatial area. The results show that the databases developed by the authors can be used to identify potential partnerships without the need to survey companies. This overcomes some of the challenges of the bottom-up approaches, such as the dependence on the willingness of companies to share input and output data, confidentiality issues, and time constraints. However, the reliability of the obtained results would be greater if more datasets were available. For example, there is a very limited number of detailed datasets on industrial waste generation. Still, the available datasets can be used to give an indication of potential IS partnerships.

A comprehensive approach is applied that considers all businesses, wastes, and material inputs, and uses data to identify companies from different sectors with the potential to engage in IS. This has been demonstrated in the spatial application, according to which it would be possible to share sawdust between companies from a multiple number of different sectors operating in the studied region (see Table 5 in the Supplementary Information for different application examples). This shows that the ability to evaluate several sectors simultaneously opens opportunities for innovative resource management.

The spatial analysis shows that the method can be easily applied to any given situation, and that the number of identified potential IS links can be very high. On one hand, having many links increases the probability of finding a promising IS relationship. On the other hand, having many links can also be overwhelming and make it difficult to prioritize potential IS partnerships. In fact, this is one of the drawbacks of using a top-down approach (Jiang et al., 2014). Nevertheless, techniques can be applied to aid the selection of the most promising IS partnerships. In this context, frequency values and distances between potential Donors and Receivers have been shown to be easily available criteria for filtering of potential IS partnerships. Additional criteria can be applied, depending on the aim of the analysis and the type of stakeholder that is analysing the possibilities. For example, available quantities and Technology Readiness Level information for the IS could be used to identify the most likely options for companies interested in sharing their waste or substituting their raw materials, or specific benefits such as CO2 mitigation potential (Patricio et al. 2017) or Biogas production potential of each different process (Patricio et al. 2020) could be relevant for regional planners to understand the impact of their choices.

The developed top-down method provides a starting point for identification of potential IS relationships. However, there are some limitations in the obtained results. One is the level of uncertainty. Unlike bottom up approaches, this method is based on statistical data and the usage of standard nomenclatures, which in some cases may be too broad. For example, within the Waste nomenclature, LoW code 30105 includes a wide range of wastes, including sawdust, shavings, cuttings, wood, and particle boards. In another example, facilities with the same NACE code are assumed to use similar technologies in their industrial processes but some NACE codes are broad and include more than one type of manufacturing process or final product. NACE code 241, relates to all industries that manufacture basic chemicals, including the production of plastics in primary forms and manufacture of industrial gasses. Therefore, potential IS partnerships should be selected for more detailed studies.

The analysis performed in this study was based on datasets collected for one country. It may be worth performing the Material Inputs and Waste frequency analysis for more countries, to evaluate if there are major differences in the types of materials needed and wastes generated. Additionally, the Waste frequency analysis was performed for a time span of 4 years. The analysis could be optimized if the database covered more years, however, detailed information on the wastes generated by companies is very limited and difficult to obtain (Salhofer, 2000).

This method does not provide any information about the expected mass. Accounting for mass may be a way to make the matching process significantly more accurate. Additionally, the Material Inputs database has been populated with international trade data. Although some of the domestic material inputs are also expected to be captured in this database (see Patricio et al., 2021 for further explanations), some products may be missed.

Technologies in the initial development phase, or emerging technologies, may have a very low frequency value or may not be captured by the Material Input database. Therefore, low frequency material inputs should not be ignored, as they may contain valuable information. In some cases, it may be useful to cross-check the potential uses of different types of input materials, using for instance literature review.

4. Conclusions

This study is a contribution towards promoting IS development. A top-down method that identifies potential IS partnerships without any need to survey companies has been developed and presented. Instead of contacting companies, the method uses available statistical datasets. The method consists of three main steps: 1) Identification of Waste generated by companies; 2) Identification of Material Inputs used by companies, and; 3) Matching of Waste to Material Inputs, in a so-called Matching process. The final result is a Matches database, containing potential relationships between industries. The database is comprehensive, considering 123 industries, 839 waste types and 1,264 material input types. The method can be applied at different scales, from single facilities to industrial parks, regions, and entire countries.

The Matching process identified 96,622 potential matches between Waste generators and potential Material Input receivers, after applying filters reflecting the probability of waste generation or material input needs, based on frequency values relating to production and use in the datasets. This process was performed using 158 IS case studies from the MAESTRI database. Of the 96,622 matches, 10% corresponded to relationships with the maximum values for Waste or Material Inputs Frequency.

In this article, the Matches database was further expanded in a spatial example, used to identify potential IS partnerships for wood wastes generated in the Västra Götaland region. Based on known IS partnerships, available in the MAESTRI database, multiple similar Donors and potential Waste Receivers were mapped using the matching process developed in this study. The spatial application identified 159,630 potential symbiotic links between companies that generate sawdust and companies with the potential to use this waste as raw material.

In the future, this top-down method can be applied to additional waste and material input datasets. Regarding the Västra Götaland example, future work includes adding more features in order to prioritize and select links with higher implementation potential, considering different types of stakeholders and their specific needs. Additionally, there is room for methodological improvements. First, the number of matches identified in the Matches database can be expanded. In this article, only one database of IS case studies was used, namely the MAESTRI database. To systematically increase the number of links in the Matches database, other IS databases should be used.

Declaration of Competing Interest

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

Acknowledgements

The presented work is a result of the research project “Regional Industrial Symbiosis”, funded by Västra Götaland Regional Government in Sweden. The authors would like to express their gratitude to the Swedish Statistical Office (SCB) and Statistics Portugal (INE) for making available their International Trade and the Portuguese Environment Agency (APA) waste statistics.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106437.

References

Alvarez, R., Ruiz-Puente, C., 2017. Development of the tool symbiosys to support the transition towards a circular economy based on industrial symbiosis strategies. Waste and biomass valorization 8, 1521–1530.

Bacudio, L.R., Benjamin, M.F.D., Eusebio, R.C.P., Holaysan, S.A.K., Promentilla, M.A.B., Yu, K.D.S., Aviso, K.B., 2016. Analyzing barriers to implementing industrial symbiosis networks using DEMATEL. Sustain. Prod. Consum. 7, 57–65.

Bin, S., Zhiquan, Y., Jonathan, L.S.C., Jiewei, D.K., Kurle, D., Cerdas, F., Herrmann, C., 2015. A big data analytics approach to develop industrial symbioses in large cities. Procedia CIRP 29, 450–455.

Chen, P., Ma, H., 2015. Using an industrial waste account to facilitate national level industrial symbioses by uncovering the waste exchange potential. J. Ind. Ecol. 19, 950–962.

Chertow, M.R., 2007. Uncovering” industrial symbiosis. J. Ind. Ecol. 11, 11–30.

European Commission, 2018. Cooperation fostering industrial symbiosis market potential, good practice and policy actions. https://doi.org/10.2873/346873.

Eurostat, 2010. Guidance on classification of waste according to EWC-Stat categories. https://ec.europa.eu/eurostat/documents/342366/351806/Guidance-on-EWCStat-categories-2010.pdf/0e7cd3fc-c05c-47a7-818f-1c2421e55604. (Accessed January 2019).

Eurostat, 2016, User guide on European statistics on international trade in goods 2016. Available at:https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/KS-GQ-16-009 [Accessed 2022-05].

Eurostat, 2020. Combined Nomenclature, 2020. https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL&StrNom=CN_2020&StrLanguageCode=EN&IntPcKey=&StrLayoutCode=HIERARCHIC Accessed January 2019).

Grant, G.B., Seager, T.P., Massard, G., Nies, L., 2010. Information and communication technology for industrial symbiosis. J. Ind. Ecol. 14, 740–753.

Gregson, N., Crang, M., Fuller, S., Holmes, H., 2015. Interrogating the circular economy: the moral economy of resource recovery in the EU. Econ. Soc. 44, 218–243.

Hein, A.M., Jankovic, M., Farel, R., Yannou, B., 2016. A Data-and Knowledge-Driven Methodology for Generating Eco-Industrial Park Architectures. In: ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers p. V004T05A002-V004T05A002.

Holgado, M., Benedetti, M., Evans, S., Baptista, A.J., Lourenço, E.J., 2018. Industrial symbiosis implementation by leveraging on process efficiency methodologies. Procedia CIRP 69, 872–877.

Homrich, A.S., Galvao, G., Abadia, L.G., Carvalho, M.M., 2018. The circular economy umbrella: Trends and gaps on integrating pathways. J. Clean. Prod. 175, 525–543.

IS DATA, 2020. Industrial Symbiosis Data Repository. Available online: http://isdata.org/(Accessed December 2019).

Jensen, P.D., 2016. The role of geospatial industrial diversity in the facilitation of regional industrial symbiosis. Resour. Conserv. Recycl. 107, 92–103.

Jensen, P.D., Basson, L., Hellawell, E.E., Bailey, M.R., Leach, M., 2011. Quantifying ‘geographic proximity’: experiences from the United Kingdom’s national industrial symbiosis programme. Resources, Conservation and Recycling 55, 703–712.

Jiang, Q., Liu, Z., Li, T., Zhang, H., Iqbal, A., 2014. Life cycle assessment of a diesel engine based on an integrated hybrid inventory analysis model. Procedia CIRP 15, 496–501. https://doi.org/10.1016/j.procir.2014.06.091.

Johnsen, I.H.G., Berlina, A., Lindberg, G., Teräs, J., Smed Olsen, L., Mikkola, N., 2015. The potential of industrial symbiosis as a key driver of green growth in Nordic regions.

Low, J.S.C., Tjandra, T.B., Yunus, F., Chung, S.Y., Tan, D.Z.L., Raabe, B., Ting, N.Y., Yeo, Z., Bressan, S., Ramakrishna, S., 2018. A collaboration platform for enabling industrial symbiosis: application of the database engine for waste-to-Resource matching. Procedia CIRP 69, 849–854.

MAESTRI project, 2020. MAESTRI—A H2020-Project under the SPIRE-PPP Initiative. Available at: https: //maestri-spire.eu/. Accessed November 2019.

Maqbool, A., Mendez Alva, F., Van Eetvelde, G., 2019. An Assessment of European Information Technology Tools to Support Industrial Symbiosis. Sustainability 11, 131.

NISP Canada, 2017. Available at: https://nispcanada.files.wordpress.com/2016/06/nispcanadafeasibilitystudy20160725.pdf (Accessed February 2020).

Ökopol GmbH, 2008. Review of the European List of Wastes. Available at: https://ec.europa.eu/environment/waste/pdf/low_review_oekopol.pdf. (Accessed January 2020).

Patala, S., Salmi, A., Bocken, N., 2020. Intermediation dilemmas in facilitated industrial symbiosis. J. Clean. Prod. 121-093.

Patricio, J., Angelis-Dimakis, A., Castillo-Castillo, A., Kalmykova, Y., Rosado, L., 2017. Region prioritization for the development of carbon capture and utilization technologies. Journal of CO2 Utilization 17, 50–59.

Patricio, J., Axelsson, L., Blomé, S., Rosado, L., 2018. Enabling industrial symbiosis collaborations between SMEs from a regional perspective. J. Clean. Prod. 202, 1120–1130.

Patricio, J., Kalmykova, Y., Rosado, L., 2020. A method and databases for estimating detailed industrial waste generation at different scales–with application to biogas industry development. J. Clean. Prod. 246, 118–959.

Patricio, J., Jimenez Encarnacion, D., Kalmykova, Y., Rosado, L., 2021. Top-down method and databases for typical product demands of 103 manufacturing industries. Resour. Conserv. Recycl. 164, 105–165.

Ramon, 2020. Reference And Management Of Nomenclatures. Available at https://ec.europa.eu/eurostat/ramon/index.cfm?TargetUrl=DSP_PUB_WELC (Accessed February 2020).

Reis, M.S., Kenett, R., 2018. Assessing the value of information of data-centric activities in the chemical processing industry 4.0. AIChE J 64, 3868–3881.

Reynolds, C., Geschke, A., Piantadosi, J., Boland, J., 2016. Estimating industrial solid waste and municipal solid waste data at high resolution using economic accounts: An input–output approach with australian case study. J. Mater. Cycles Waste Manag. 18, 677–686.

Salhofer, S., 2000. Modelling commercial/industrial waste generation: a Vienna, Austria case study. Waste Manag. Res. 18, 269–282.

Song, B., Yeo, Z., Kohls, P., Herrmann, C., 2017. Industrial symbiosis: Exploring big-data approach for waste stream discovery. Procedia CIRP 61, 353–358.

Trokanas, N., Cecelja, F., Raafat, T., 2014. Semantic input/output matching for waste processing in industrial symbiosis. Comput. Chem. Eng. 66, 259–268.

Tseng, M.-L., Tan, R.R., Chiu, A.S.F., Chien, C.-F., Kuo, T.C., 2018. Circular economy meets industry 4.0: can big data drive industrial symbiosis? Resour. Conserv. Recycl. 131, 146–147.

Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renew. Sustain. Energy Rev. 68, 825–833.

Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., Barnes, S., 2019. Tools for promoting industrial symbiosis: A systematic review. J. Ind. Ecol. 23, 1087–1108. https://doi.org/10.1111/jiec.12846.

Paper III

Exploring urban scenarios with an agent-based model to assess residential waste sorting

J. Cohen, J. Gil & L.Rosado

Submitted to Waste Management
Under review

Exploring urban scenarios with an agent-based model to assess residential waste sorting

Jonathan Cohen[1*]; Jorge Gil[1]; Leonardo Rosado[1]

[1] Department of Architecture and Civil Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden

[*]Corresponding author, Department of Architecture and Civil Engineering, Chalmers University of Technology, 412 96, Gothenburg, Sweden; E-mail: *jonathan.cohen@chalmers.se*

Abstract

Efficient waste management is vital for sustainable urban development, reducing emissions, and increasing recycling. Waste separation at the source relies on citizens' behaviour. The theory of planned behaviour (TPB) can explain waste sorting behaviour, but factors like bin distance, recycling facilities' characteristics, and information campaigns need more research. This study explores the relationship between the built environment and residential waste sorting using a spatially explicit agent-based model (ABM) with TPB. The article details how TPB was exploited to model the behaviour of waste sorting. The ABM was implemented in two urban areas with low and high population densities, showing that changing bin placement affects sorting and proximity to recycling bins influences adequately sorted residual waste. This article demonstrates how to model and study the link between urban planning and waste sorting performance, revealing the impact of individual residents' behaviour on sorting percentages.

Keywords:

Agent-based model; Theory of Planned Behaviour; Waste sorting; Waste Management; Urban planning

1. Introduction

Under the current linear economic system, waste materials are an unavoidable and undesirable by-product of daily activities that need adequate management. Globally, it is estimated that by 2050, waste generation will grow to 3.4 billion tons, and municipal waste management (MWM) related emissions will grow to 2.6 billion tons of CO2e (i.e. 5% of global emissions) (Kaza et al., 2018). As environmental concern continues to increase, waste-related issues are gaining attention and ranking high in priority worldwide (Matiiuk & Liobikienė, 2021).

The activity of MWM involves collecting, transporting, disposing, and recycling waste materials generated by households, and municipalities dedicate between 4% to 20% (high-income and low-income countries) of their budgets to managing waste (Kaza et al., 2018. p102). Despite being often overlooked (Ewijk & Stegemann, 2020), improvements in MWM systems contribute to moving forward several Sustainable Development Goals (SDGs) (Elsheekh et al., 2021; Roy et al., 2023). Environmentally, efficient waste management provides a healthy and clean environment, reduces greenhouse gases (GHGs), and reduces resource depletion by recycling and reusing strategies.

Waste separation at source is perceived as an effective MWM strategy. This strategy depends on citizens' behaviour in separating their waste into different fractions, and it is adopted or implemented in many cities. However, the success of such a strategy relies on an adequate understanding of the drivers of waste-sorting behaviour (Kaplan Mintz et al., 2019; Matiiuk & Liobikienė, 2021) and how different aspects of the system interact.

The behaviour of waste sorting and recycling has been extensively studied in various contexts and analysed through different theoretical frameworks. The Theory of Planned Behaviour

(TPB) (Ajzen, 1991) stands out as the most widely used and validated theory for understanding the drivers behind individual waste sorting (Phulwani et al., 2020; Raghu & Rodrigues, 2020). Besides internal factors determining the behaviour of residents, such as environmental knowledge or attitudes, the urban environment also plays a role in determining the behaviour towards waste separation (Cohen et al., 2024; Rousta et al., 2020; Struk, 2017a). Moreover, few studies have focused on linking the behaviour of individual residents with the actual amounts disposed of (Perrin, D; Barton, 2000). Research on this gap is relevant to determine how much and how well waste is being sorted at neighbourhood and city levels.

To tackle these issues, waste sorting and waste management can be studied and understood as Complex Adaptive Systems (CAS) (Chen & Gao, 2021; G. Luo et al., 2016; H. Luo et al., 2020). This perspective allows research to include multiple agents with microscopic behaviours that interact with each other and their environment. Within CAS, Agent-Based Models (ABMs) are computational tools for developing simulations that incorporate these agents and their interactions. ABMs are an adequate methodological approach to addressing the complexity of waste sorting because they include rich decision-making and bottom-up processes that allow for the emergence of system properties (Ceschi et al., 2021; Tong et al., 2018). As a result, ABMs can contribute to answering questions that would otherwise be difficult to assess, such as "How would the recycling rate of a neighbourhood change if there were twice as many waste bins?".

Several studies advocate the integration of TPB and ABMs (Jager, 2017; Muelder & Filatova, 2018; Scalco et al., 2018) since TPB offers a behavioural model for the agents. However, more applications for residential waste sorting and recycling are needed. First, we need to understand how individual behaviours result at a household or city level. Moreover, simulations are often non-spatial(Chen & Gao, 2022; Meng et al., 2018; Tucker & Smith, 1999), or space and location of different urban elements related to waste sorting are abstracted (Tong et al., 2018), making the models unsuitable for urban planning.

This study aims to explore the relationship between the built environment and residential waste sorting through individual behaviour. To accomplish this, this paper describes an ABM that incorporates the TPB to model how residents sort their waste. The model is spatially explicit by incorporating relevant characteristics of the built environment and allows for the assessment of urban scenarios. By simulating the interactions between the built environment and the residents' behaviour in different hypothetical scenarios, the research offers a tool to quantify and visualise the quality of residential waste sorting.

The remainder of this paper is structured as follows. Section 2 introduces the state of the art on TPB and ABM for waste sorting. Section 3 describes the methodology and the proposed ABM. Section 4 describes the data and case study of Gothenburg. Section 5 presents the application of the ABM to different urban scenarios, which is discussed in Section 5. Section 6 concludes by highlighting the main findings.

2. Models for studying waste sorting: state-of-the-art

This study builds on two research streams: Theory of Planned Behaviour (TPB) and Agent-Based Models (ABM). Firstly, the TPB has been extensively applied to study waste-sorting behaviour (Phulwani et al., 2020), and it offers a valuable understanding of the various factors affecting waste sorting. Secondly, ABM provides an adequate (bottom-up) approach to analysing a system with many agents and their interactions. The TPB fits this approach by informing how the ABM agents behave, and the integration of ABM with TPB has been used as a framework for studying waste sorting outcomes.

2.1. Waste Sorting and Theory of Planned Behaviour

According to the TPB, people's behaviour (BEH) is determined by four primary constructs: intention (INT), social norm (SN), attitude (ATT), and perceived behavioural control (PBC) (Ajzen, 1991). ATT refers to an individual's evaluation of performing a particular behaviour. It encompasses beliefs, knowledge, and a subjective valuation of performance. SN refers to the perceived social pressure or influence by other individuals to perform a behaviour. Finally, PBC refers to the perceived ease or difficulty of performing the behaviour. It encompasses internal and external factors such as skills, resources, opportunities, and barriers. Combined, ATT, SN and PBC are used to determine the INT that (with PCB) leads to a specific BEH. Figure 1 presents the original conceptualisation proposed by Ajzen. It can be noted that the constructs are determined using observable variables (att1, att2, att3, sn1 …, beh3).

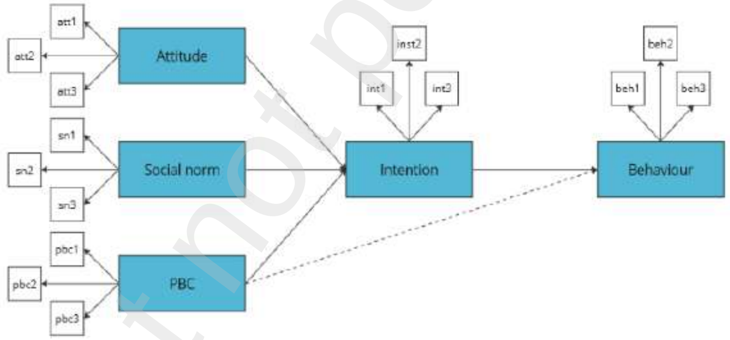


Figure 1 Conceptualisation of the Theory of Planned Behaviour (Ajzen, 1991).

TPB allows the inclusion of other constructs in addition to these primary constructs, and previous research has shown evidence that awareness of consequences (Hu et al., 2021; Tonglet et al., 2004; Wang et al., 2020), situational factors (Azlina et al., 2013; Govindan et al., 2022; Tonglet et al., 2004; Zhang et al., 2019), self-identification (Issock Issock et al., 2020; Knussen et al., 2004) or past behaviour (Knussen et al., 2004; Lakhan, 2018) are relevant constructs in specific contexts. Empirically, to evaluate the validity of a TPB model, researchers design a survey that captures various aspects of each construct.

Existing studies usually consider the behaviour of individual waste sorting or recycling as a single phenomenon. For instance, specific studies have focused on food waste (Abdelradi, 2018; Azlina et al., 2013) and the return of packaging (Struk, 2017b). Moreover, research shows that perceived increased distance towards waste bins can reduce how residents sort their waste. Li, et al. (2020) provide evidence that distance does not play a significant role in participation in recycling, while other studies found that shorter distances to bins are associated with more involvement in recycling and pro-environmental attitudes (Cohen et al., 2024; Ibrahim, 2020; Lange et al., 2014; Rousta et al., 2020; Struk, 2017a).

Despite these advancements, linking the individual behaviour of residents with the actual amounts disposed of needs to be further researched (Perrin, D; Barton, 2000). Research on this gap is relevant to determining how much and how well waste is sorted at neighbourhood and city levels. Moreover, studies have yet to address the temporal aspect of behaviour. For instance, Hu et al. (2021) follow a community for three months and show evidence that environmental knowledge and guidelines can induce behavioural changes over time.

2.2. Waste sorting and Agent-Based Models

Tucker et al. provided the first example of an ABM simulation for waste and resources (Tucker & Fletcher, 2000; Tucker & Smith, 1999) to study how waste sorting changes over time by introducing different disturbances to the system. Although their early conceptualisation does not explicitly incorporate TPB, the authors include Attitudes, Norms and Conditions in their model to determine the behavioural aspects of the simulation.

Other studies have used or proposed using TPB with ABM to explore waste sorting outcomes. TPB is beneficial in an ABM context because it enriches the behavioural mechanism that determines the agent's actions with an established model, bringing realism to the simulations. The integration of TPB within an ABM framework is represented in Figure 2.

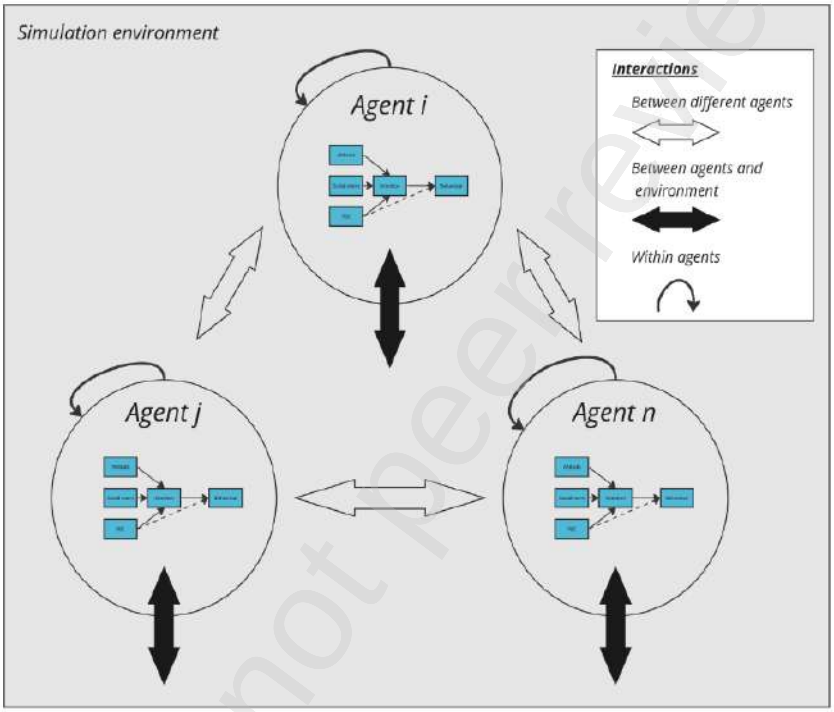


Figure 2 Integration of TPB and Agent-Based Models.

Researchers have approached the topic of waste recycling using ABM to explore the role of the informal waste system (Chen & Gao, 2021) and the introduction of taxes (Meng et al., 2018). In both ABMs, the agents include psychological variables and a utility function is used to determine their behaviour. Tong et al. (2018) ran a social experiment using technology to affect residents' incentives for waste recycling, and TPB was used as a baseline mechanism to represent their behaviour. Results showed that Social Norms played a crucial role in their context. An ABM was then developed to explore different waste disposal possibilities and study the level of recycling participation, using an abstract representation of the town divided into zones with other demographics. Finally, Ceschi et al. (2021) developed an ABM incorporating the TPB primary constructs for waste recycling to evaluate norm-nudging policies. Although the ABM was able to reproduce historical data and provide evidence of how TPB can be used in an ABM setting, the model takes advantage of two simplifications: first, it is spatially abstract by representing households as grid cells, and second, the TPB individual behaviour is applied at the household level.

To sum up, three gaps have been identified in the literature: (1) Empirical studies that estimate TPB mainly focus on intentions or self-reported behaviour, leaving a need to establish a link between internal perception of behaviour and the actual action; (2) Simulations are spatially abstract or do not take into consideration environmental determinants such as the location or status of waste bins; (3) The unit of analysis at which TPB has been integrated into ABM has been the household, despite empirical data being collected at the level of residents.

3. Methodology

This section describes the proposed ABM for simulating waste sorting in urban scenarios, including how waste sorting behaviour was calculated and integrated into the ABM framework "Residents planned behaviour of waste sorting to explore urban situations

(1.4.0)."[1]. First, following the TPB, a set of equations is described to estimate the behaviour of waste sorting. Second, the agents and the heuristics of the ABM are presented.

3.1. Determining the behaviour of waste sorting

The coefficients of the TPB model were specified based on empirical observations by extracting the mean values of the path coefficients from a Structural Equation Model (Cohen et al., 2024). The values in Figure 3 correspond to the estimated coefficients and offer a visual representation of how the waste sorting behaviour of an agent in the ABM is calculated. Following the estimation methods used to determine the behaviour, each of the TPB constructs were computed using linear equations (Eq 1 to Eq 6). All these equations include a constant, and the estimated coefficients are in italics with a sub-index representing the dependent variable, while upper-case refers to factors. For more details on the mean value and standard deviation of these coefficients, see the appendix **Error! Reference source not found.**.

---

[1] Update and extensions of the model are available at https://www.comses.net/codebases/592f0caf-8a02-48f5-bb73-b6fdc969982f/.

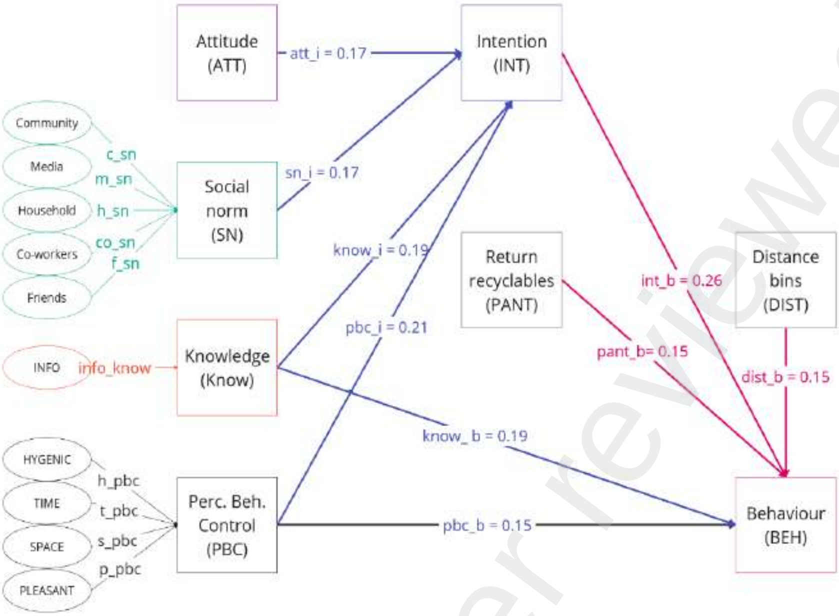


Figure 3 Path analysis of TPB coefficients. Source: adapted from (Cohen et al., 2024).

INT, PBC, KNOW, DIST and PANT determine the calculation of behaviour (BEH). Each of these factors have an associated estimated coefficient (int_b, pbc_b, $know_b dist_b$, ret_b) as presented in Eq 1.

$$BEH = constant_b + int_b \times INT + pbc_b \times PBC + know_b \times KNOW + dist_b \times I \times PANT \qquad Eq\ 1$$

In the equation above, DIST accounts for the average distance (meters) that a resident travels to dispose of organics, residuals, and recyclable waste. PANT is a dummy variable that identifies whether a resident exchanges packages for their economic value at supermarkets.

Also, following the path analysis, intention (INT) is estimated using Eq 4 and includes SN, ATT, PBC and KNOW, with their associated estimated coefficients (att_i, sn_i, pcb_i, $know_i$).

$$INT = constant_i + att_i \times ATT + sn_i \times SN + pbc_i \times PBC + know_i \times KNOW \qquad Eq\ 2$$

The value of Attitude (ATT) is assumed to be a normally distributed variable with a mean value of $\bar{x}$ and δ^2 as its standard deviation. Each resident is assigned a value because it represents internal valuations and preferences (Eq 3). There is no interaction with the environment, and it is an internal characteristic of the agents.

$$ATT \sim N(\bar{x},\ \delta^2) \qquad \text{Eq 3}$$

Social Norm (SN) represents the waste-sorting behaviour of the residents' social context. It is calculated using the average behaviour of each resident’s friends, co-workers, household, and community. Moreover, SN also includes the effect of social media (MEDIA). The estimated coefficients in Eq 4 are $friend_{sn}$, $media_{sn}$, $work_{sn}$, hh_{sn}, $bins_{sn}$.

$$\begin{aligned} SN & \\ &= constant_{sn} + friend_{sn} \times FRIEND + media_{sn} \times MEDIA \cdot \\ &\times HOUSEHOLD + bins_{sn} \times COMMUNITY \end{aligned} \qquad \text{Eq 4}$$

Perceived Behavioural Control (PBC) represents how much a resident believes that it can sort waste. It is calculated using a linear combination of a variable of the status of the waste bin and another of how much waste sorting space agents have at home. The estimated coefficients in Eq 5 h_{pbc}, t_{pbc}, p_{pbc}, s_{pbc}.

$$\begin{aligned} PBC = constant_{pbc} &+ h_{pbc} \times HYGENIC + t_{pbc} \times TIME + p_{pbc} \times PLEAS \\ &\times SPACE \end{aligned} \qquad \text{Eq 5}$$

Knowledge (KNOW) represents the resident's knowledge level. It is assumed to be a function of the information displayed in the public waste bins. The estimated coefficient in Eq 6 is $info_{know}$.

$$KNOW = constant_{know} + info_{know} \times INFO \qquad Eq\ 6$$

The values of the TPB constructs range between 0 and 100, with 0 being the lowest possible score. More information in the Supplementary Materials describes the estimation process of PBC, SN, KNOW and ATT.

3.2. The ABM of residential waste sorting

The developed ABM is a micro-simulation of residential waste sorting at the individual level, where residents of a neighbourhood decide how to sort their waste according to TPB. This individual level is consistent with the TPB framework used to determine individual behaviour. It avoids assumptions on how a household (integrated by a set of individuals) solves its waste-sorting problems based on individual preferences.

The ABM simulates the behaviour and interactions between various agents, namely residents, buildings, households, workplaces, waste bins and bin collectors. The model was developed to represent an entire year, and every step in the simulation represents a third of a day. The agent classes and their attributes are based on the entities presented in Cohen & Gil (2021). Each of the agents represented in the model is described below.

3.2.1. Residential buildings

Residential buildings are spatially explicit agents represented by polygons, and their primary function is to create the households and the total population of residents. Each building has information about the number of households and the total population living in each building.

3.2.2. Households

The households are an abstract agent in the ABM to determine which residents share the same housing unit, and the average behaviour of these residents is used to determine SN.

Moreover, the households have attributes that represent the private waste bins for organic, residual, and recyclable waste at residents' homes. Because the model aims to trace how residents dispose of waste, a set of variables tracks how much waste of each type is placed in an organics, residuals, and recyclables bin.

Every time the sum of waste in a private waste bin is greater than zero, a counter for every time step starts. This mechanism reflects the effect of waste decomposition so that after a specific count, waste needs to be transported to the designated public waste bins (the closest) outside the building.

3.2.3. Public waste bins

The public waste bins hold waste outside the households of the residents. These bins can be used for organic, residual, or recyclable waste. As the waste bins of each household reach their limit (a random value between 1 and 2 kg), waste is transferred to public waste bins. The waste bins have specific attributes to trace how much waste of a particular type is being placed in each bin. Moreover, the public waste bins have an attribute to indicate the level of information displayed in each bin, which is used for the calculation of knowledge.

1.1.1. Workplaces

The workplaces are spatially explicit agents represented by polygons and have two functions. Firstly, they hold all the waste material that needs to be disposed of outside of the home. The model does not focus on how waste is disposed of outside the home because the waste sorting behaviour may be different (Greaves et al., 2013a). Specific literature has focused on waste sorting behaviour in working environments, and the determinants of such behaviour may vary (Greaves et al., 2013b). Secondly, this agent represents the various working groups.

Each resident is randomly assigned to a workplace, forming groups of residents that are co-workers. The average behaviour of a group is used to determine the SN (Eq 2) of a resident.

1.1.2. Residents

Each resident agent belongs to a household with designated public waste bins for organic, residual, and recyclable waste and a workplace. Resident agents also belong to different social groups that impact SN: friend groups are a random set of resident agents; co-worker groups are resident agents that share the same workplace; household groups are resident agents that share the same household; and community groups are resident agents that share the same public waste bin.

During each step of the model, the residents follow a daily routine that includes commuting to work, generating waste, assessing its behaviour, disposing of waste at home, and later transferring it to waste bins. Based on their behaviour, the residents make different decisions on how to sort their waste.

Figure 4 presents the sequence of actions followed by the residents during every step of the simulation. First, the residents' TPB constructs are updated, and their behaviour is calculated. Second, based on the probability of heading to work, the agents commute. The waste generated away from home is outside the scope of the model. The agents staying at home receive a sum of organic, residual, and recyclable waste that they dispose of in their private waste bins. The amount of waste assigned varies across residents.

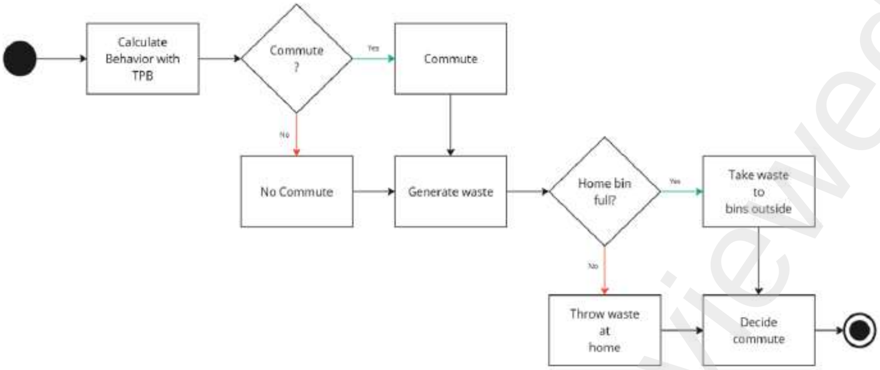


Figure 4 Routine of residents

At this stage, the residents' behaviour score determines how they dispose of their home waste based on a set of probabilities presented in

If the waste bins at home are found to be full, or the waste has been standing for a certain number of days, one resident of the household proceeds to empty the household waste bins and the waste amount is transferred to the public waste bins. For instance, when a resident has a positive amount of organic waste, it accesses the behaviour score. Let us imagine this is 65, which, according to the model, represents "Good" behaviour. The agent is assigned an 80% to 95% probability of throwing the organic waste into the organic waste bin and a 10% to 30% probability of throwing the organic waste into the residual waste bin. The cut-off values of what defines very bad, bad, or good behaviour are based on the results presented in the appendix **Error! Reference source not found.**.

Table 1 Probability distribution of disposal of various waste streams, depending on the averaged behaviour of residents.

	Behaviour			
	0-30 Very bad	30-55 Bad	55-75 Good	75-100 Very good
Disposal of organic				

Prob(… in organic)	0-50	50-80	80-95	95-100
Prob(… in residual)	60-100	30-60	10-30	0-10
Disposal of residual				
Prob(… in residual)	0-65	65-75	75-80	80-100
Prob(… in organic)	0-0	0-5	2-5	0-2
Disposal of recyclable				
Prob(… in recyclable)	0-75	75-80	80-85	85-100
Prob(… in residual)	80-100	50-80	25-50	0-25

If the waste bins at home are found to be full, or the waste has been standing for a certain number of days, one resident of the household proceeds to empty the household waste bins and the waste amount is transferred to the public waste bins.

2. Simulation of residential waste sorting in Gothenburg

The ABM developed for this research has been applied to two distinct neighbourhoods in the city of Gothenburg, Sweden. The model parameters, the location of buildings, households, and public waste bins, are specific to these selected locations. Here, we present the data inputs and the urban scenarios used in the simulations, which further elucidate the ABM simulation requirements.

2.1. Data inputs

The ABM requires three data sets as input to the simulation: (i) the amounts of waste generated per day for each waste stream, (ii) the value of the coefficients to specify the TPB for waste sorting, (iii) and a set of geodata files that determine the spatial context.

First, the amount of waste generated per individual resident is determined by a set of values taken from the Annual Swedish Waste Management Report (Avfall Sverige, 2022), which reports that residents generate approximately 42 kg/year of organic waste, 157 kg/year of residual waste, and 65 kg/year of recyclable waste (glass, paper, metal, and so forth).

The second input needed by the ABM, the parameters to specify the residential waste sorting behaviour, were derived from the data collected and the analysis developed in a study of waste sorting behaviour in Gothenburg (Cohen et al., 2024)Table A 1 in the appendix contains the values of the estimated coefficients used in the TPB model.

To determine the four types of behaviour (very bad to very good) and the probabilities of how to dispose of waste, empirical data from the survey was used. In this case, the respondents indicated a percentage of properly sorted waste for organic, residual, and recyclable waste. These three values were averaged, and the calculation of quartiles of the averaged behaviour gave the ranges of four distinguishable groups, which are presented in the appendix in **Error! Reference source not found.**.

Finally, a set of 3 geographic data files are required to define the spatial context of the simulation: (i) polygons representing residential buildings' footprints, (ii) polygons representing workplace locations and (iii) points representing public waste bins. The data files defining the building footprints were obtained from Lantmäteriet (Swedish cadastre agency). The point data set of waste bins has information about the designated type of waste of each bin: residual for mixed and burnable waste; organics for food scraps and other forms of degradable material; and recyclable bin stations.

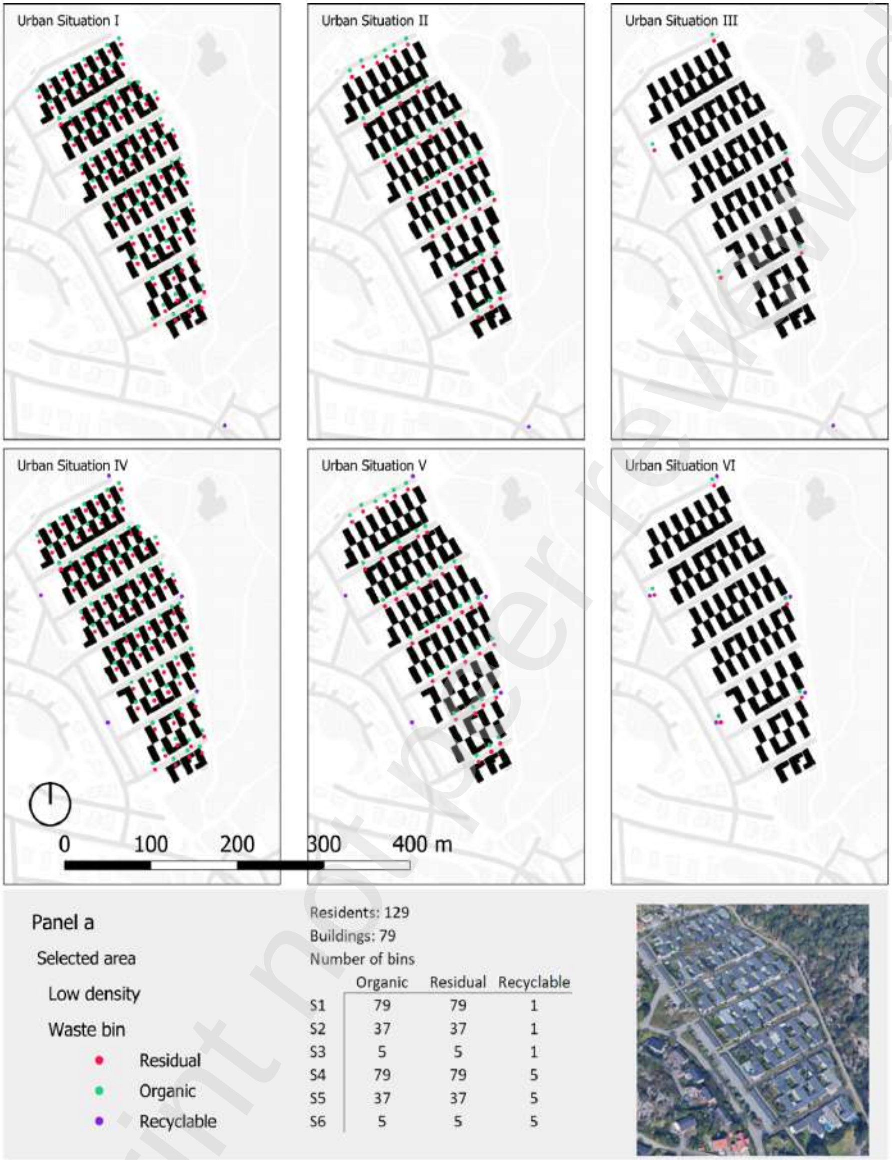
In Sweden, residents are expected to dispose of plastics, metals, glass, papers, and other recyclable materials in recycling stations. The location of these recycling stations was used to identify two distinct urban areas in terms of population density. Google Street View was used to determine the location of residual and organic bins. Usually, low-density areas have waste bins next to each house, while in higher-density areas, households share bins with others from the same building.

2.2. Urban scenarios

In this study, we simulate two urban areas: a low-population housing area and a high-density population area. Figure 5 presents the low-population density (Panel 5a) and high-population density (Panel 5b) urban areas. For each urban area, six urban scenarios were created using different numbers and locations of public waste bins.

Scenario 1 (S1) represents the current situation. In the low-density area, each household owns a pair of waste bins for residual and organic waste and uses one shared recycling station for recyclable materials located outside the neighbourhood. In the high-density area, each building has its bins for residual and organic waste, and all buildings use the same recycling station outside the neighbourhood. In scenarios 2 and 3 (S2 & S3), the recycling station is kept in the exact location as in S1. However, the number of residual and organic waste bins is reduced so that the distance to the bins increases, and the interaction between residential agents also increases. In scenarios 4, 5, and 6 (S4 – S6), the number of recycling stations increases, and they are located in the neighbourhood, close to the buildings, while the location and number of the residual and organic waste bins are the same as in scenarios S1, S2, and S3.

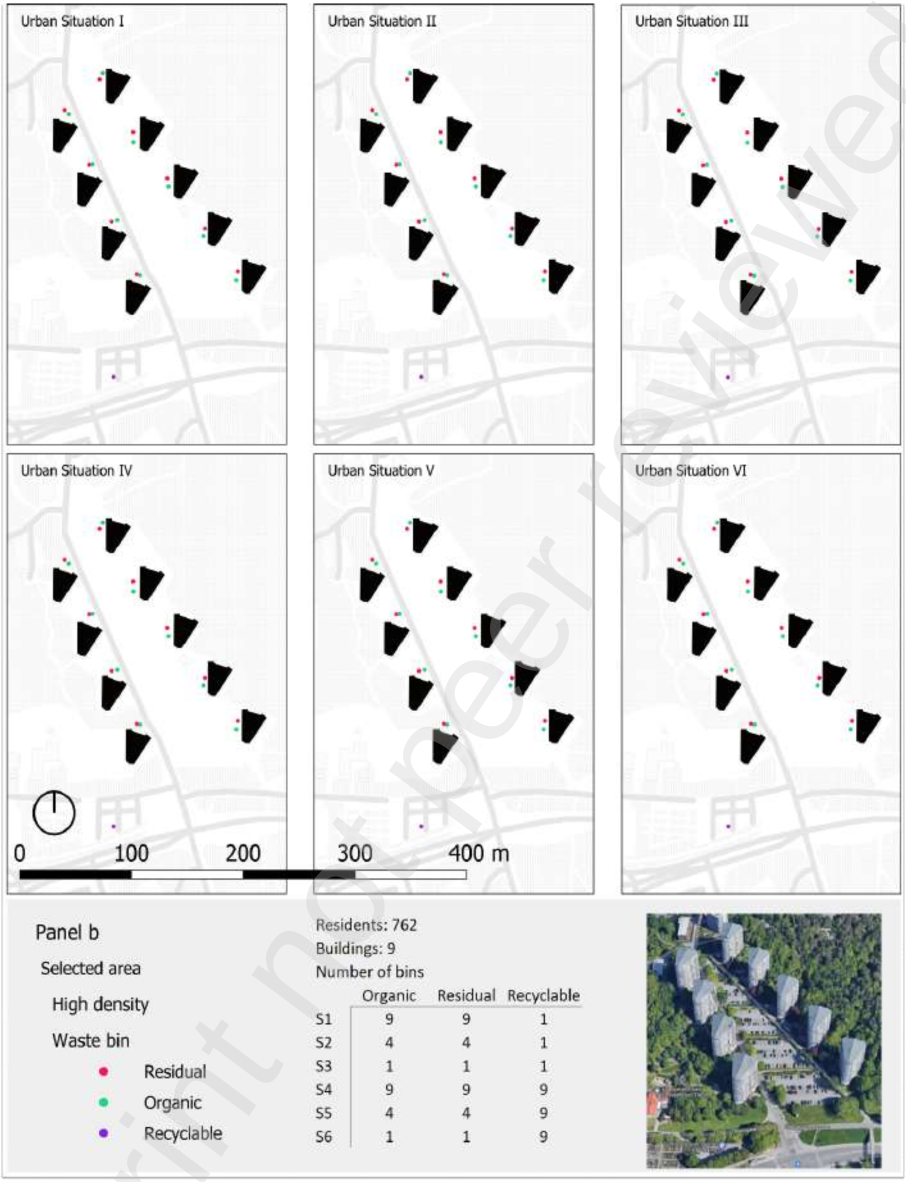
Combined, the geographic data files representing residential buildings, work areas, and waste bins are used to define a single urban scenario. In this study, the model was implemented in two urban areas by changing the location within the city and providing data files on different residential buildings and workplaces. This enables the simulation of how the behaviour of waste sorting is affected by these changes.



Residents: 129
Buildings: 79
Number of bins

	Organic	Residual	Recyclable
S1	79	79	1
S2	37	37	1
S3	5	5	1
S4	79	79	5
S5	37	37	5
S6	5	5	5

Panel 5a



Residents: 762
Buildings: 9
Number of bins

	Organic	Residual	Recyclable
S1	9	9	1
S2	4	4	1
S3	1	1	1
S4	9	9	9
S5	4	4	9
S6	1	1	9

Panel 5b

Figure 5 Urban scenarios created for the ABM simulations: panel 5a) low population density scenarios; panel 5b) high population density scenarios.

2.3. Simulation and analysis

To explore the relationship between behaviour and waste sorting, each urban scenario was simulated 200 times. The ABM was programmed to retrieve the percentages of properly sorted waste of each waste stream and the behaviour of the residents. More specifically, the results will be assessed by looking at the average value of behaviour and the percentages of properly sorted waste (i.e. organic, residual, and packaging) across the population at the end of one year.

3. Results

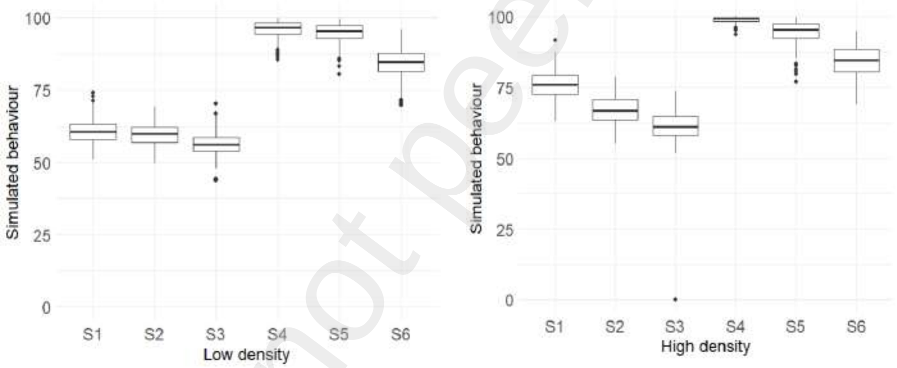
In this section, we present a summary of the results obtained from the simulation runs of the ABM on the different urban scenarios. For each urban area (i.e. low and high density), six urban scenarios are evaluated (S1 to S6), where scenarios S1 – S3 explore the impact of reducing the number of organic and mixed waste bins, and scenarios S4 – S6 explore the effect of increasing the number of recycling stations. Specific details of the results of the simulations are provided in the Supplementary material.

3.1. Residents' waste sorting behaviour

The waste sorting behaviour of the residents is presented in Figure 6. Panel 6a presents the results for the low-density single-family housing urban area, and Panel 6b presents the results for the high-density multifamily housing urban area. Comparable results can be appreciated across both urban areas. In both cases, S1, S2, and S3 have lower average behaviour than S4, S5, and S6. Recall that more waste bins for recyclable materials were placed in the latter scenarios.

In the low-density area, the initial scenario (S1) produced an average behaviour of 60 with a standard deviation of 4. As expected, the simulated behaviour decreases when residual and organic bins decrease in S2 and S3 to an average of 59 and 56, respectively. S4, the scenario with the most waste bins, presents the best-behaved simulated agents with a score of 96. Again, moving to scenarios S5 and S6, where the number of residual and organic bins decreases, so does the average waste sorting behaviour, to 94 and 84, respectively.

In the high-density area, S1 has an average behaviour of 76 with a standard deviation of 5. As residual and organic bins decrease in S2 and S3, the average behaviour decreases to 67 and 59. Urban scenario S4 presents an average behaviour of 98 and a standard deviation of 1. As the number of residual and organic bins decreases, the average behaviour drops to 94 in S5 and 84 in S6.



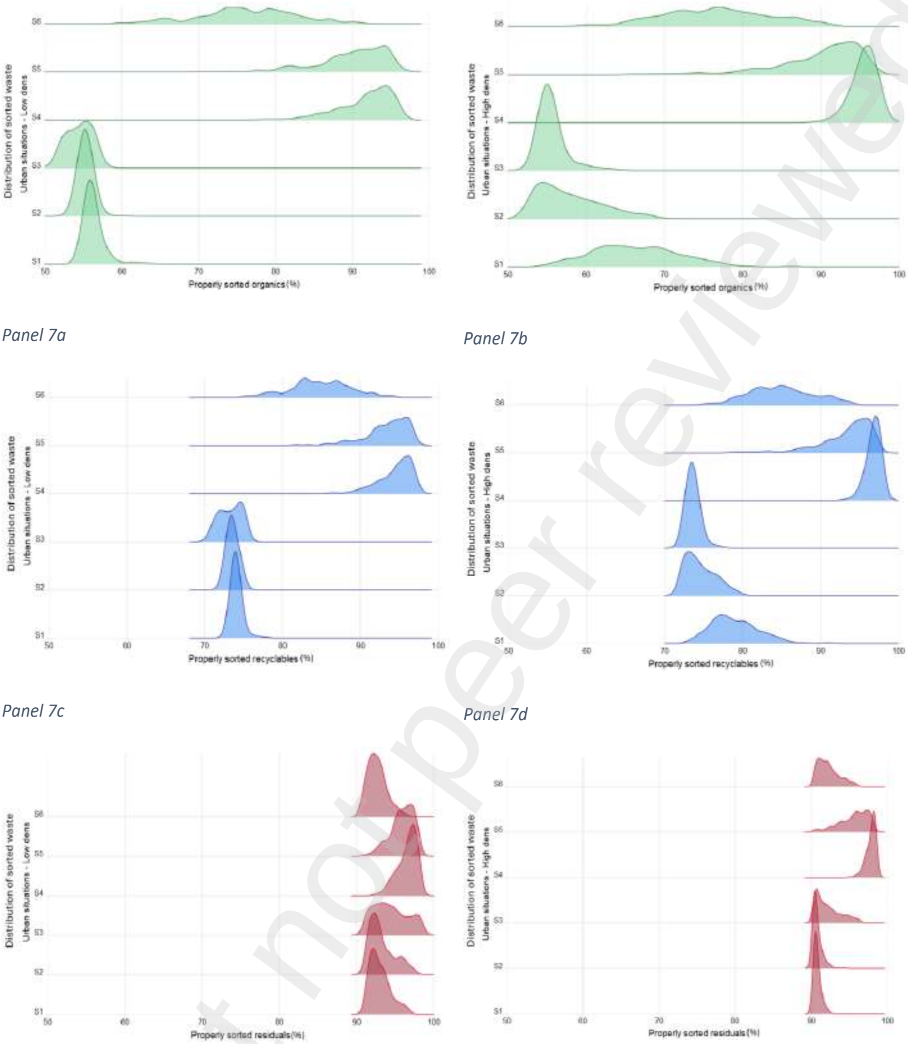
Panel 6a

Panel 6b

Figure 6 Average waste sorting behaviour under different urban scenarios: a) low population density scenarios; b) high population density scenarios.

3.2. Properly sorted waste percentages

Besides tracking the residents' waste sorting behaviour, the model follows the amounts of adequately sorted waste. Figure 7 shows plots of the distribution of the percentage of adequately sorted waste for three waste streams (i.e., organic, residual, and recyclable) in each urban area (i.e., low-density and high-density) for the different simulated urban scenarios. In each plot, one can find six distributions, one for each scenario (S1 to S6).



Panel 7a

Panel 7b

Panel 7c

Panel 7d

Panel 7e

Panel 7f

Figure 7 shows the Density distribution of the percentage of adequately sorted waste in low and high-population density scenarios. Panels 7a, 7c, and 7e present results of low-density scenarios for organic (green), recyclable (blue), and residual (red) waste streams, respectively. Panels 7b, 7d, and 7f present results of high-density scenarios for the same waste streams.

The results presented in Panel 7a and Panel 7b show that in all urban scenarios, at least 50% of organic waste is correctly sorted. However, scenarios S4 to S6 (top) perform better than scenarios S1 to S3 (bottom). In high-density scenarios (Panel 7b), there is more variability than in low-density scenarios (Panel 7a).

S1 has an average of 56% properly sorted organic waste in the low-density area. As the number of waste bins decreases in S2 and S3, the average of properly sorted waste increases, but the standard deviation slightly worsens. In the high-density area, the current situation S1 exhibits higher variability and a higher average than S2 and S3.

S4 has the highest number of bins, and as a result, the percentage of adequately sorted organics increases to 92% on average. In S5, the tail of the distribution shifts to the left, indicating less properly sorted waste. Finally, S6 demonstrates the highest volatility across the population, and by increasing the number of recyclable bins, the average of organic sorting increases along with the variability.

When it comes to recyclable waste (as shown in Panel 7c and Panel 7d), every scenario (S1 to S6) has an average of over 70% of adequately sorted waste. Even in low-density scenarios (Panel 7c), sorting accuracy ranges from 70% to 78% in S1 to S3. However, when the bins for organic and residual waste are reduced (S2 and S3), the percentage of correctly sorted recyclables decreases slightly. Equivalent results were observed in high-density areas (Panel 7d), where S1 had an average of 79%. However, reducing the number of bins (S2 and S3) led to a decrease in the percentage to 71%. In both urban areas, placing more accessible bins for recyclable materials increased the percentage of waste that was sorted correctly, specifically in S4, to 94% in low-density areas and 97% in high-population-density areas. In the low-density area, as waste bins were located further away from residential units, the average percentage of properly sorted waste decreased. S5 has, on average, 93% of correctly sorted recyclable waste, while S6 has only 84%. The high-density scenario produced comparable results.

Proper waste sorting is highest with residual waste (Panel 7e and Panel 7f), with more than 90% properly sorted in all urban scenarios. The distributions follow a similar trend to the previous waste types, with scenario S4 performing the best. However, the changes observed between scenarios are small, and introducing more recyclable bins may not necessarily increase the proper waste sorting of residual waste.

In summary, the results indicate that waste is being appropriately sorted by more than 50% in all scenarios and that there are significant differences across waste streams and scenarios. The percentage of properly sorted residual waste has minor variability, ranging from 90% to 100% in all scenarios; recyclable waste varies from 70% to 100% depending on the urban scenario, and organic waste displays the most variability across all scenarios. Lastly, the baseline scenario (S1) presents more significant variability in the high-density urban area when it comes to organic and recyclables.

4. Discussion

The behaviour of waste sorting is usually considered dichotomous: individuals recycle or do not sort (or recycle) their waste. The ABM simulations in this work, incorporating a TPB model of waste sorting, have shown that residents behave differently for different waste streams. Improvements in how the waste sorting behaviour is measured are critical to understanding how municipalities can increase the amount of waste purity or material circularity. The relationship between individual behaviour and waste streams is not independent of the built environment or each other. After 200 simulations in each urban scenario, it was possible to extract the effect of different waste bin scenarios. The results seem to indicate that improvements in the spatial distribution and number of recyclable material collection points can also yield improvements in properly sorted residuals and organics.

4.1. Contributions

Firstly, the present study has developed an ABM that researchers and city planners can use to analyse how different urban scenarios might affect residential waste sorting. Users can change the parameters in the model, such as the level of information available in the bins or how often they are cleaned. Additionally, they can provide alternative initialisation files, such as geodata on the location of waste bins or the buildings and population distribution. This will allow users to explore different what-if scenarios. The ABM of waste sorting behaviour is available online as an open-source resource with an ODD protocol that can help users adapt the model to fit other contexts or TPB formalisations. Future research will be able to look at the programmed functions in detail, allowing for discussion, improvement, and expansion of the model.

Secondly, the ABM advances agent-based modelling for waste sorting by explicitly modelling space and by introducing a direct connection between the built environment, individual behaviour, and waste sorting quantities. By being spatially explicit, the ABM enables city planners to evaluate how different what-if scenarios perform in relation to waste sorting. Moreover, agents in the model are individual residents instead of households, harmonising the unit of analysis between TPB and its implementation in an ABM setting. In addition, the model formalises the relationship between behaviour and percentages of properly sorted waste, demonstrating a direct relationship between TPB and waste sorting.

Finally, the simulations reveal the effect of various waste bin quantities and locations on waste sorting quality. Since the model was calibrated using results from a survey study, the simulation results follow the main trends from the statistical model. The results show that although placing more bins leads to better waste sorting, there is room for planners to make decisions regarding how many waste bins, of what kind, and where they should be placed. A critical outcome of the study is showing the relationship between organic, residual, and recycling waste bins. More recyclable bins increase the proportion of adequately sorted waste for recyclables and for residual waste. The results show that high-density urban areas perform better than low-density ones, reflecting the fact that bins are positioned closer to the residents. However, these results require further research as socio-demographics and population density are not independent.

4.2. Limitations and future research

In the ABM, the relationships between the items used to calculate the TPB constructs and the objects in the model are not validated. For instance, from the empirical model, it is possible to know that the distance to waste bins is a factor that hinders the probability of adequately sorting waste. However, since the distance to bins is a variable outside the scope of the TPB, the coefficient linking both was assumed. This is also the case for other items and constructs of TPB. How a resident's perceived peer pressure relates to the peers' actual behaviour still needs to be researched. To summarise this point, previous research has found TPB to be a practical framework to map individual behaviours. However, for TPB and other psychological theories to become relevant for models supporting public policy, future research must address the connection between perceptions and quantifiable variables of the objective realm.

Another aspect of the study that needs to be further developed is the dynamic aspects of TPB. While the behaviour of individual agents can change during the simulation, given the interactions with the environment, the coefficients of TPB used in the ABM stay constant over time, and this assumption can be challenged. Future research involving longitudinal surveys would make it possible to assess changes in behaviour and TPB constructs, addressing this knowledge gap.

Although the residents in the ABM are heterogeneous, these differences are driven by stochastic processes rather than socio-demographics or lifestyles. The earlier survey did not collect information about the respondents' personal characteristics or living environments. Therefore, the outputs in this study used the same distribution of perceived home space in all the simulations, regardless of housing typology. Future models could use synthetic populations to explore this heterogeneity.

This study evaluated specific urban scenarios; however, other relevant variables not considered here can positively affect waste sorting. The information available at waste bins, how clean the waste bins are, and the amount of household space are variables encoded in the proposed ABM and can be set as parameters for different scenarios. Further exploration of such determinants of waste sorting can be used to guide urban policy (Bernstad, 2014).

In this study, the ABM operationalised TPB to model waste sorting behaviour. While this theory is widely used in waste sorting research, future studies should explore how to incorporate other relevant behavioural models, such as social contagion theory. (Griliches, 1957; Mansfield, 1961).

A stochastic process in the global section of the ABM defines the amount of waste generated by residents. As a result, waste reduction strategies relevant to the Circular Economy and environmental sustainability in general are beyond the scope of this model. This aspect of waste management is essential, and future studies should also focus on researching how effective waste reduction strategies are.

5. Conclusion

This study implements an Agent-Based Model (ABM) to investigate how changing the spatial distribution and quantity of waste bins of diverse types affects recycling rates. The research is based on previous studies that support the use of TPB as a framework for modelling waste sorting behaviour. The ABM was applied to two urban areas with different building typologies and population densities, and various scenarios were simulated to assess how changes in waste bin location affect waste sorting rates. The results of the study show that reducing the distance to recycling bins has a significant and positive impact on waste sorting rates. Additionally, the simulation results indicate that the number of bins for residual and organic waste could be reduced without significantly affecting how people sort waste.

This model allows other researchers and urban planners to explore waste management scenarios. The model is based on empirical data derived from surveys, and the residential agents' behaviour is based on a behavioural theory that allows for complex decision-making by residents. The ABM developed for this study advances previous efforts by creating a spatially explicit model, modelling individuals as agents instead of households, and establishing a direct link between behaviour and the percentage of adequately sorted waste for different waste streams. Finally, the study's model is open source, which enables future research to investigate how waste sorting might change under various conditions and to improve the details of the model.

Acknowledgements

This work is part of the Digital Twin Cities Centre, which Sweden's Innovation Agency Vinnova supports under Grant No. 2019-00041.

6. References

Abdelradi, F. (2018). Food waste behaviour at the household level: A conceptual framework. *Waste Management*, *71*, 485–493. https://doi.org/10.1016/j.wasman.2017.10.001

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Avfall Sverige. (2022). *Swedish Waste Management* (Swedish Waste Management). Avfall Sverige. https://www.avfallsverige.se/in-english/

Azlina, W., Ab, W., Ghani, K., Rusli, I. F., Radiah, D., Biak, A., & Idris, A. (2013). An application of the theory of planned behaviour to study the influencing factors of participation in source separation of food waste. *Waste Management*, *33*(5), 1276–1281. https://doi.org/10.1016/j.wasman.2012.09.019

Bernstad, A. (2014). Household food waste separation behavior and the importance of convenience. *Waste Management*, *34*(7), 1317–1323. https://doi.org/10.1016/j.wasman.2014.03.013

Ceschi, A., Sartori, R., Dickert, S., Scalco, A., Tur, E. M., Tommasi, F., & Delfini, K. (2021). Testing a norm-based policy for waste management: An agent-based modeling simulation on nudging recycling behavior. *Journal of Environmental Management*, *294*(February). https://doi.org/10.1016/j.jenvman.2021.112938

Chen, L., & Gao, M. (2021). Formal or informal recycling sectors? Household solid waste recycling behavior based on multi-agent simulation. *Journal of Environmental Management*, *294*, 113006. https://doi.org/10.1016/j.jenvman.2021.113006

Chen, L., & Gao, M. (2022). Predictive modeling for behavioral evolution of municipal household waste classification and recycling. *Sustainable Cities and Society*, *78*, 103659. https://doi.org/10.1016/j.scs.2021.103659

Cohen, J., & Gil, J. (2021). An entity-relationship model of the flow of waste and resources in city-regions: Improving knowledge management for the circular economy. *Resources, Conservation & Recycling Advances*, *12*, 200058. https://doi.org/10.1016/j.rcradv.2021.200058

Cohen, J., Gil, J., & Rosado, L. (2024). *Understanding residential waste sorting behaviour with situational factors: A data-driven approach* (SSRN Scholarly Paper 4751831). https://papers.ssrn.com/abstract=4751831

Elsheekh, K. M., Kamel, R. R., Elsherif, D. M., & Shalaby, A. M. (2021). Achieving sustainable development goals from the perspective of solid waste management plans. *Journal of Engineering and Applied Science*, *68*(1), 9. https://doi.org/10.1186/s44147-021-00009-9

Ewijk, S. V., & Stegemann, J. A. (2020). Recognising waste use potential to achieve a circular economy. *Waste Management*, *105*, 1–7. https://doi.org/10.1016/j.wasman.2020.01.019

Govindan, K., Zhuang, Y., & Chen, G. (2022). Analysis of factors influencing residents' waste sorting behavior: A case study of Shanghai. *Journal of Cleaner Production*, *349*, 131126. https://doi.org/10.1016/j.jclepro.2022.131126

Greaves, M., Zibarras, L. D., & Stride, C. (2013a). Using the theory of planned behavior to explore environmental behavioral intentions in the workplace. *Journal of Environmental Psychology*, *34*, 109–120. https://doi.org/10.1016/j.jenvp.2013.02.003

Greaves, M., Zibarras, L. D., & Stride, C. (2013b). Using the theory of planned behavior to explore environmental behavioral intentions in the workplace. *Journal of Environmental Psychology*, *34*, 109–120. https://doi.org/10.1016/j.jenvp.2013.02.003

Griliches, Z. (1957). Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica*, *25*(4), 501. https://doi.org/10.2307/1905380

Hu, J., Tang, K., Qian, X., Sun, F., & Zhou, W. (2021). Behavioral change in waste separation at source in an international community: An application of the theory of planned behavior. *Waste Management*, *135*(June), 397–408. https://doi.org/10.1016/j.wasman.2021.09.028

Ibrahim, M. A. (2020). Modeling of risk for improper sorting of waste at Recycling Centers. *Waste Management*, *102*, 550–560. https://doi.org/10.1016/j.wasman.2019.11.017

Issock Issock, P. B., Roberts-Lombard, M., & Mpinganjira, M. (2020). *Understanding household waste separation in South Africa: An empirical study based on an extended theory of interpersonal behaviour*. *31*(3), 530–547. https://doi.org/10.1108/MEQ-08-2019-0181

Jager, W. (2017). Enhancing the realism of simulation (EROS): On implementing and developing psychological theory in social simulation. *Jasss*, *20*(3). https://doi.org/10.18564/jasss.3522

Kaplan Mintz, K., Henn, L., Park, J., & Kurman, J. (2019). What predicts household waste management behaviors? Culture and type of behavior as moderators. *Resources, Conservation and Recycling*, *145*, 11–18. https://doi.org/10.1016/j.resconrec.2019.01.045

Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1329-0

Knussen, C., Yule, F., MacKenzie, J., & Wells, M. (2004). *An analysis of intentions to recycle household waste: The roles of past behaviour, perceived habit, and perceived lack of facilities*. *24*(2), 237–246. https://doi.org/10.1016/j.jenvp.2003.12.001

Lakhan, C. (2018). *The garbage gospel: Using the theory of planned behavior to explain the role of religious institutions in affecting pro-environmental behavior among ethnic minorities*. *49*(1), 43–58. https://doi.org/10.1080/00958964.2017.1337701

Lange, F., Brückner, C., Kröger, B., Beller, J., & Eggert, F. (2014). Wasting ways: Perceived distance to the recycling facilities predicts pro-environmental behavior. *Resources, Conservation and Recycling*, *92*, 246–254. https://doi.org/10.1016/j.resconrec.2014.07.008

Li, C., Zhang, Y., Nouvellet, P., Okoro, J. O., Xiao, W., & Harder, M. K. (2020). Distance is a barrier to recycling – or is it? Surprises from a clean test. *Waste Management*, *108*, 183–188. https://doi.org/10.1016/j.wasman.2020.04.022

Luo, G., Song, X., Yang, X., Thulasiraman, K., Monin, J. F., & Yang, G. (2016). Modeling, optimization, and verification for complex systems. *Mathematical Problems in Engineering*, *2016*. https://doi.org/10.1155/2016/2458369

Luo, H., Zhao, L., & Zhang, Z. (2020). The impacts of social interaction-based factors on household waste-related behaviors. *Waste Management*, *118*, 270–280. https://doi.org/10.1016/j.wasman.2020.08.046

Mansfield, E. (1961). Technical Change and the Rate of Imitation. *Econometrica*, *29*(4), 741. https://doi.org/10.2307/1911817

Matiiuk, Y., & Liobikienė, G. (2021). The impact of informational, social, convenience and financial tools on waste sorting behavior: Assumptions and reflections of the real situation. *Journal of Environmental Management*, *297*, 113323. https://doi.org/10.1016/j.jenvman.2021.113323

Meng, X., Wen, Z., & Qian, Y. (2018). Multi-agent based simulation for household solid waste recycling behavior. *Resources, Conservation and Recycling*, *128*, 535–545. https://doi.org/10.1016/j.resconrec.2016.09.033

Muelder, H., & Filatova, T. (2018). One Theory - Many Formalizations: Testing Different Code Implementations of the Theory of Planned Behaviour in Energy Agent-Based Models. *Journal of Artificial Societies and Social Simulation*, *21*(4), 5. https://doi.org/10.18564/jasss.3855

Perrin, D; Barton, J. R. (2000). If only households recycled what and when they said they would! *ISWA World Congress*.

Phulwani, P. R., Kumar, D., & Goyal, P. (2020). A Systematic Literature Review and Bibliometric Analysis of Recycling Behavior A Systematic Literature Review and Bibliometric Analysis of Recycling Behavior. *Journal of Global Marketing*, *33*(5), 354–376. https://doi.org/10.1080/08911762.2020.1765444

Raghu, S. J., & Rodrigues, L. L. R. (2020). Behavioral aspects of solid waste management: A systematic review. *Journal of the Air and Waste Management Association*, *70*(12), 1268–1302. https://doi.org/10.1080/10962247.2020.1823524

Rousta, K., Bolton, K., Lundin, M., & Dahlén, L. (2020). Quantitative assessment of distance to collection point and improved sorting information on source separation of household waste. *Waste Management*, *40*(2015), 22–30. https://doi.org/10.1016/j.wasman.2015.03.005

Roy, S., Rautela, R., & Kumar, S. (2023). Towards a sustainable future: Nexus between the sustainable development goals and waste management in the built environment. *Journal of Cleaner Production*, *415*, 137865. https://doi.org/10.1016/j.jclepro.2023.137865

Scalco, A., Ceschi, A., & Sartori, R. (2018). Application of psychological theories in agent-based modeling: The case of the theory of planned behavior. *Nonlinear Dynamics, Psychology, and Life Sciences*, *22*(1), 15–33.

Struk, M. (2017a). Distance and incentives matter: The separation of recyclable municipal waste. *Resources, Conservation & Recycling*, *122*, 155–162. https://doi.org/10.1016/j.resconrec.2017.01.023

Struk, M. (2017b). Distance and incentives matter: The separation of recyclable municipal waste. *Resources, Conservation and Recycling*, *122*, 155–162. https://doi.org/10.1016/j.resconrec.2017.01.023

Tong, X., Nikolic, I., Dijkhuizen, B., van den Hoven, M., Minderhoud, M., Wäckerlin, N., Wang, T., & Tao, D. (2018). Behaviour change in post-consumer recycling: Applying agent-based modelling in social experiment. *Journal of Cleaner Production*, *187*, 1006–1013. https://doi.org/10.1016/j.jclepro.2018.03.261

Tonglet, M., Phillips, P. S., & Read, A. D. (2004). Using the Theory of Planned Behaviour to investigate the determinants of recycling behaviour: A case study from Brixworth, UK.

Resources, Conservation and Recycling, *41*(3), 191–214. https://doi.org/10.1016/j.resconrec.2003.11.001

Tucker, P., & Fletcher, I. (2000). Simulating household waste management behaviours part 2: Home composting. *Jasss*, *3*(3), 1–26.

Tucker, P., & Smith, D. (1999). Simulating Household Waste Management Behaviour. *Journal of Artificial Societies and Social Simulation*, *2*(3–4), 1–26.

Wang, S., Wang, J., Yang, S., Li, J., & Zhou, K. (2020). From intention to behavior: Comprehending residents ' waste sorting intention and behavior formation process. *Waste Management*, *113*, 41–50. https://doi.org/10.1016/j.wasman.2020.05.031

Zhang, B., Lai, K. hung, Wang, B., & Wang, Z. (2019). From intention to action: How do personal attitudes, facilities accessibility, and government stimulus matter for household waste sorting? *Journal of Environmental Management*, *233*(December 2018), 447–458. https://doi.org/10.1016/j.jenvman.2018.12.059

Paper IV

Understanding residential waste sorting behaviour with situational factors: a data-driven approach

J. Cohen, J. Gil & L.Rosado

Submitted to Waste Management & Research
Under review

Understanding residential waste sorting behaviour with situational factors: a data-driven approach

Abstract

Waste separation at source is perceived as an effective Municipal Waste Management strategy, and the success of such a strategy depends on understanding the drivers of proper waste sorting behaviour. The Theory of Planned Behaviour (TPB) has been extensively applied to determining the importance of different psychological constructs in waste sorting behaviour. Despite evidence of its validity in specific contexts, in urban contexts one requires understanding how the built environment affects waste sorting behaviour. Furthermore, the TPB is typically applied starting from pre-defined items assigned to its constructs. This study introduces the use of Exploratory Factor Analysis as a data driven approach to define various TPB constructs from a collection of items, including situational factors such as distance to waste bins or the condition of recycling facilities, and shows how this technique outperforms the top-down approach. This study surveyed residents of Gothenburg, Sweden, to capture empirical data on factors known to affect the planned behaviour of waste separation. Structural Equation Modelling (SEM) is used to develop the extended TPB model and extract the drivers of waste sorting behaviour. Results from the study can extend the application of TPB to inform decision-making processes in residential waste sorting.

Keywords

Waste Management; Theory Planned Behaviour; Case study; Built Environment; TPB

1. Introduction

Municipal waste management is an urban service that imposes high financial and environmental costs on local governments (Kaza et al., 2018). Providing efficient solutions to address waste management issues can contribute to accomplishing several SDG targets. One of the most effective strategies to improve the efficiency of the waste management system is waste sorting at source. This means that residents are responsible for sorting their waste before disposal. Still, it requires committed residents, proper infrastructure, and adequate advertising campaigns to keep residents informed (Barata, 2003).

Although Sweden is one of the frontrunners in waste management (Alonso-Betanzos et al., 2017), according to Swedish Waste Management, 60% of the contents of the residual waste bins are missorted (Swedish Waste Management 2021, 2021). Currently, waste recycling averages 65%, with glass being 86% and plastic being 19% of the total composition. Using estimates from a medium-sized Swedish city of 100 thousand residents, the economic costs of waste missorting can add up to 1.46 million EUR (Rousta & Ekström, 2013). At a national scale, Ibrahim (2020) developed a risk map of improper waste sorting that showed that despite the recycling centres' having information about what can be recycled, the long distance to recycling centres offsets the benefits of clear information. In this study, the authors use geographic information to identify specific sites that need to increase the amount of bins and extend the opening hours window. Although waste sorting is simple enough to be implemented globally, it relies on the behaviour of residents, and municipalities need help finding effective alternatives to improve waste sorting.

The theory of Planned Behaviour (TPB) has been used to assess a variety of behaviours, and it has been extensively used to assess waste sorting and recycling. TPB proposes that the behaviour (in this case of waste sorting) is determined by a combination of attitude, subjective norms, perceived behavioural control and intentions. A better understanding of these constructs and the factors behind each one can provide valuable insights for policy-making seeking to increase waste sorting rates.

This study aims to model the behaviour of waste sorting, establishing a direct link with the built environment by employing the Theory of Planned Behaviour on data from a survey carried out in the city of Gothenburg, Sweden. It contributes to extending the TPB of waste sorting by including new situational factors, and by taking a data-driven approach to modelling the constructs using Exploratory Factor Analysis (EFA) and Structural Equation Modelling (SEM). Ultimately, the knowledge derived from this study can inform the development of more effective and tailored policies to improve residential waste management practices. These policies, grounded in empirical evidence and a nuanced understanding of the factors influencing behaviour, are essential steps towards achieving the dual goals of environmental sustainability and financial well-being in urban centres facing similar waste management challenges.

The following Section introduces the theoretical background, and Section three presents the methodological steps followed to develop the study. Finally, results are presented and discussed.

2. Theoretical Background

TPB is a psychological theory extensively explored to explain waste sorting behaviour (Phulwani et al., 2020). According to Ajzen (1991), the behaviour of people is determined by four primary constructs: Intention (INT), Social Norm (SN), Attitude (ATT), and Perceived Behavioural Control (PBC). Since these constructs are unobserved variables, they are considered latent, and their estimation requires combining observable variables to determine these constructs. In the original conceptualisation proposed by Ajzen, the constructs are defined using observable variables and how these constructs determine behaviour. The TPB states that ATT, SN and PBC predict the INT to behave in a specific way. Then, INT and, to some extent, PBC are used to explain people's behaviour. In addition, the TPB allows the inclusion of other constructs (Armitage & Conner, 2010; Davies et al., 2002; Davis et al., 2006).

Previous research focused on waste sorting and recycling has shown evidence that awareness of consequences (M.-F. Chen & Tung, 2010; Issock Issock et al., 2020; Tonglet et al., 2004a), situational factors (Azlina et al., 2013; Govindan et al., 2022; Tonglet et al., 2004a; B. Zhang et al., 2019), self-identification (Issock Issock et al., 2020; Knussen et al., 2004) or past behaviour habits-(Knussen et al., 2004; Lakhan, 2018) are relevant constructs in specific contexts. Empirically, to test the validity of the pre-defined TPB model, researchers design a survey that captures distinct aspects of each construct.

Waste sorting behaviour using TPB has been extensively studied in different contexts, including Australia (Chan & Bishop, 2013), China (Ma et al., 2018; Shen et al., 2019; Wan et al., 2014; Y. Wang et al., 2021; Xu et al., 2017; D. Zhang et al., 2015), the UK (Tonglet et al., 2004b; Visschers et al., 2016), USA and Canada (Lakhan, 2018; Park & Ha, 2014), South Africa and Nigeria (Issock Issock et al., 2020; Khalil et al., n.d.; Strydom, 2018), Greece, Norway (Ofstad et al., 2017), India (Halder & Singh, 2018a) and Sweden (Stoeva & Alriksson, 2017). In these studies, a survey is conducted to capture empirical data for the TPB constructs. In most cases, because of the survey's extension with numerous questions, specific groups have been targeted, such as students or faculty members. Structural equation modelling (SEM) and confirmatory factor analysis (CFA) are prevalent statistical techniques to model the constructs from the survey results quantitatively.

Overall, there is evidence that together all TPB constructs, specifically for waste sorting, are valid at the same time (Chan & Bishop, 2013; Liu et al., 2022; Ofstad et al., 2017; Oztekin et al., 2017; Razali et al., 2020; Shi et al., 2021; Stoeva & Alriksson, 2017; Taylor & Todd, 1995; C. Wang et al., 2021; S. Wang et al., 2020). It is essential to notice differences across how these studies have measured these constructs and assessed waste sorting behaviour. Despite the evidence provided, there is no significant evidence of attitude affecting intentions (M.-F. Chen & Tung, 2010; Hu et al., 2021; Shen et al., 2019; Wan et al., 2014; Xu et al., 2017). The relevance of Social Norms has also been contested (Lakhan, 2018; Stoeva & Alriksson, 2017; Tonglet et al., 2004a; Y. Wang et al., 2021). There has been more statistical evidence of the importance of PBC towards Behaviour, but again, when seeking to determine intention, it falls short in several cases (M. F. Chen & Tung, 2010; Passafaro et al., 2019; Strydom, 2018; Visschers et al., 2016; Xu et al., 2017; Zaikova et al., 2022).

The study conducted by Stoeva & Alriksson (2017), is noteworthy for its comparative analysis of waste sorting behaviour among students in Bulgaria and Sweden. The study found significant differences in the waste sorting behaviour of the two populations, which highlights the importance of context-specific models like TPB. While the core TPB model was validated in the Swedish case, the subjective norm was not found to be significant in the Bulgarian case. Additionally, the study revealed that the model had a better fit in the Swedish case than in the Bulgarian case. Interestingly, the study extended the TPB model by including satisfaction with local facilities in the analysis. It was found that satisfaction with local facilities was not significant in Sweden, but it was significant in Bulgaria. These findings provide valuable insights into the factors that influence waste sorting behaviour and have implications for waste management policies in different contexts.

Two studies in the Swedish context provide evidence of the importance of three factors to improve waste sorting in cities: (i) better information, (ii) reduced distance to bins, and (iii) improved space and bins inside of homes. All these measures have proven to impact the Swedish context positively. In the first study, stickers were used to increase information, and the distance to bins was reduced from 2km to 50m, significantly affecting how people sorted different waste streams (Rousta et al., 2015). Moreover, better information is combined with improvements in the bins at home. Results (Bernstad, 2014) provided evidence that better information improved organic waste sorting by 10%, compared to 44%.

3. Methodology

The study presented here had two phases. The first phase encompassed all activities related to developing and deploying a TPB questionnaire among residents of Gothenburg city. The second phase included all activities associated with developing the Structural Equation Modelling (SEM) to evaluate the TPB and extract relevant information about how residents behave towards waste separation at source.

3.1. TPB Questionnaire

The literature of TPB specific to waste sorting or recycling was reviewed to extract a list of questions used in previous studies. Questions were preselected and adapted to the local context. Based on previous research, the questionnaire included questions to accommodate an extended version of the TPB with additional constructs. The survey was developed to capture situational factors (Issock Issock et al., 2020; Knussen et al., 2004), awareness of consequences (M.-F. Chen & Tung, 2010; Issock Issock et al., 2020; Tonglet et al., 2004a), self-identification (Issock Issock et al., 2020; Knussen et al., 2004) and past behaviour (Knussen et al., 2004; Lakhan, 2018). Since the survey was delivered to residents of Gothenburg, Sweden, the questionnaire was written in English and Swedish. As in previous studies that focused on a similar challenges, this work aimed to collect a minimum of 200 valid responses given the number of items in the TPB questionare (Chan & Bishop, 2013; Halder & Singh, 2018b; Passafaro et al., 2019; Stoeva & Alriksson, 2017; Tang et al., 2023; Tonglet et al., 2004b; D. Zhang et al., 2015).

A first draft of the questionnaire was translated into Swedish, and a pilot was done to evaluate how residents responded to the survey. Insights collected were used during the final stage of the survey development. The questions were modified, and different wording was used to reflect the response from the respondents. The survey was deployed online and distributed virtually via various social media platforms and physically through pamphlets that were placed in public spaces such as libraries, restaurants, schools, supermarkets, and cafes. The survey questions and results are available as Supplementary material.

3.2. Modelling TPB with Structural Equation Models

As discussed in the literature review section, the TPB investigates three primary constructs to explain an intention or behaviour. Since these constructs are not observed, variables are used to determine them. The survey was developed following a specific structure representing the three primary constructs plus four additional situational constructs. Two approaches were used and compared to create these constructs, and the TPB was validated using Structural Equation Modelling (SEM).

Typically, Confirmatory Factor Analysis (CFA) is used to measure unobservable (latent) variables such as SN or PBC. This approach can be used to validate a hypothesised measurement model or factor structure. It aims to assess the fit between observed data and a pre-specified theoretical model, which includes a priori assumptions about the relationships between observed variables and underlying latent factors. In our case, the main modules of our survey represent these factors and the first statistical model using CFA was developed. Using different goodness of fit indices, these constructs were evaluated to understand the degree of reliability (Kline, 2015).

On the other hand, Exploratory Factor Analysis (EFA) is a data-driven technique used to reduce the dimension of information. It aims to identify the underlying structure and patterns in the data by transforming the original variables into a smaller set of meaningful factors. EFA does not involve hypothesis testing; results are generated from pure mathematical operations. An EFA was implemented to investigate if an agnostic method could contribute to expanding the understanding of how the latent variables might be grouped. In this case, the researcher needs to specify the number of factors used to reduce the dimension of the information. A set of tests can be carried out to determine the optimal number of factors, but there is no unique answer or golden rule, and it is a research decision.

The results from EFA were compared against those from CFA and evaluated. The EFA model is preferred if it can reduce the data's dimension while passing the evaluation. The validity of the factors extracted and their robustness were evaluated using Cronbach's alpha, Composite Reliability (CR), Average Variance Extracted (AVE), Maximum Shared Variance (MSV) and by comparing Heterotrait-Monotrait Ratio of Correlations (HTMT) values against the correlation. When testing for discriminant validity, MSV and AVE must be analysed together. Here, the heuristics suggest that if the Maximum Shared Variance (MSV) is higher than AVE, it might imply discriminant validity problems. In this case, Attitude and Consequences can potentially have some issues. Cronbach's alpha to test internal consistency should be above 0.7.

After evaluating the different methods and combinations to create the constructs, one alternative was selected, and other SEMs were developed to assess the hypothesis raised in the TPB. Different combinations of constructs were tested to model behaviour, and multiple Goodness of Fit Indexes (GFIs) were used to determine the validity of the models (Kline, 2015). Finally, the best-fitting model was identified, and its results will be presented in the next section of the study.

Therefore, SEM or path analysis encompasses both measurement and structural models. The measurement model relates observed to latent variables, while the structural model tests all the hypothetical dependencies among latent variables based on path analysis.

The statistical analysis for this study was performed using R, mainly with a lavaan package to fit the SEMs and an effect size package to calculate the goodness of fit indices. The corresponding code and the reproduction of the results are provided as supplementary material.

4. Results

In this section, we first present descriptive statistics of the survey on waste sorting behaviour in the case of Gothenburg. Second, two methods to develop the TPB constructs are applied to the survey results, and the constructs are evaluated. Finally, the TPB for waste sorting behaviour is developed using SEMs.

4.1. Waste sorting behaviour

Between June 2022 and December 2022, the survey link was accessed by 460 residents of Gothenburg, and 63% of them completed it. After a process of data cleaning and deletion of missing values, a total of 275 valid responses were taken into consideration.

The survey showed that the respondents are relatively well-behaved. On average, they declared to sort their recyclable materials 88% of the time, sort their organic material 79% of the time and sufficiently sort their residual material 73% of the time. These three variables were combined to calculate an average waste sorting behaviour, which has a mean of 80% and a standard deviation of 16%. Regarding the intention of sorting waste, 95% of the residents responded positively, 4% declared neutral, and 1% responded negatively.

On average, 89% of the respondents use the deposit system (pant). Those who do not pant present an average waste sorting behaviour of 70%, and those who do pant have an average behaviour of 82%. Also, the survey revealed that residents who dispose of organic waste more than twice a week dispose of residual waste 1.7 times a week and 1.3 times per week for recyclable waste.

Figure 1 shows the responses to the 29 items from the survey that provided data to determine the latent variables or TPB constructs. The satisfaction levels with the waste management system reveal that 69% of the residents declared to be satisfied or very satisfied, 22% are indifferent, and 9% are not happy. When looking at different items within the general satisfaction, residents have shown dissatisfaction because they believe other residents need to sort their waste correctly (37%) and the containers need cleaning (37%). Although 66% feel that the waste containers are close to their homes, 21% feel dissatisfied with the distance. Among the items explored, residents seem to be most satisfied with the amount of information provided (77%).

It can be observed that the most disagreement in the responses was found in relation to Subjective Norms (SN). In this module, the level of disagreement among respondents varied between 36% and 44%.

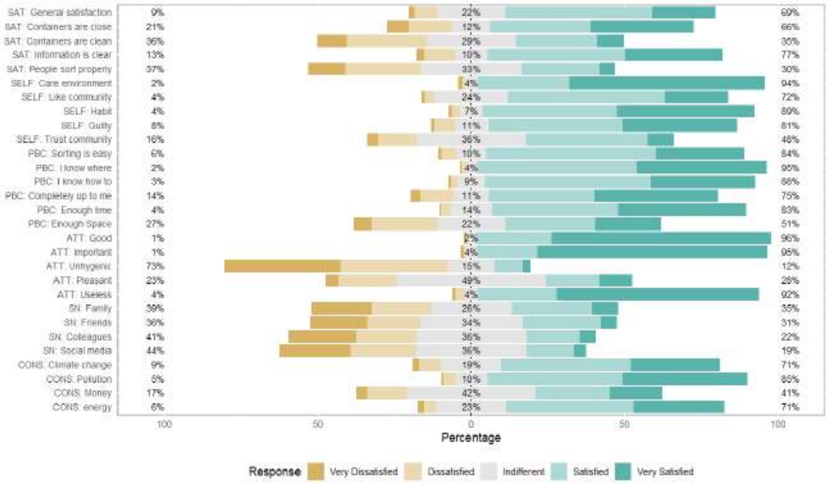


Figure 1 Survey Items used to determine TPB constructs

It is noteworthy that 25% of the participants in the survey provided their feedback through an open-ended text section. These comments offer insightful information on the challenges associated with waste sorting and disposal. A preliminary analysis of the responses revealed that the comments could be classified into four distinct categories, highlighting areas that require attention to improve the waste management system.

The first category refers to "Waste bins availability and usage", reflecting grievances about inadequate space for waste disposal during weekends, with overflowing waste bins, or while commuting to work or dropping off children at school. The second category relates to "Waste sorting challenges", highlighting the difficulties faced in sorting waste, and the lack of appropriate facilities for specific waste streams. The third category relates to "Hygiene and maintenance", expressing concerns about the lack of cleanliness, which in turn attracted insects and rodents. Finally, the fourth category relates to "Convenience and location", where participants suggested measures that could enhance the overall waste sorting experience. These included installing automatic doors, ensuring spacious containers, and making all the waste categories available at all recycling stations.

4.2. TPB Constructs

This section presents the results of the two approaches used to identify TPB constructs from the survey results. First, Confirmatory Factor Analysis (CFA) was used to determine the latent variables. The structure tested in this approach came from the literature review and the structure of the survey. The second approach was data-driven, and Exploratory Factor Analysis (EFA) was used to reduce the dimensionality of the data—resulting in 5 or 6 factors.

The goodness of fit for each case is presented in Table 1 and indicates that EFA models were performing slightly better than the Structure from the CFA. EFA with six factors presents the smaller Chi-square and Root Square Error of Approximation (RMSEA). Moreover, EFA 6 also has the highest Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI). Overall, EFA 6 performed better and was used in the study's next steps.

GFI	**Constructs**		
	CFA	**EFA 5**	**EFA 6**
chisq	787.8	623.6	554.9
df	362	314	284
rmsea	.065	.060	.059
cfi	.827	.868	.883
tli	.806	.852	.866
srmr	.080	.073	.072
aic	19715.7	17791.2	17085.5
bic	19979.7	18022.6	17327.8

Table 1 Evaluation of TPB constructs

After extracting the six factors, the data-driven approach produced a reasonable grouping of the items from the survey. The EFA method succeeded in grouping the items (variables) of the Consequences, Social Norms and Satisfaction constructs as they were included in the survey. The construct of Self-identification disappeared, and its items are distributed among the other constructs, mainly associated with Attitude and Satisfaction. A new factor grouping knowledge-related items was created. This factor includes several variables that initially belonged to PBC, but were capturing the residents' level of knowledge. The item satisfaction 3 in the survey corresponds to the level of satisfaction that the residents have over the available information level. Finally, the PBC construct only contains two items initially assigned to PBC, but includes two items of Attitude related to how hygienic the waste has been and how pleasant residents think sorting waste is.

The tests validating the resulting constructs are presented in Table 2. Most constructs present an acceptable level of Composite Reliability CR (> 0.7), indicating greater internal consistency and reliability of the measurement variables for each construct. PBC is the weaker construct and should be used with caution. The variance captured by these constructs (AVE) ranges from 0.31 to 0.55, providing evidence that the constructs contain a substantial amount of the variance. The Cronbach's alpha for PBC and Satisfaction are below the recommended threshold. Overall, the six constructs identified by EFA pass most of the tests or are within the limits of doing so.

In the calculation of the construct of Consequences, the most critical factor is understanding pollution (0.35), followed by an awareness of the consequences of climate change (0.23). For Social Norms, Friends are the most relevant item (0.45), followed by the perceived pressure by co-workers (0.22). The construct of knowledge was dominated by understanding how to separate waste (0.56), and similarly, in PBC, availability of time was the most influential factor (0.59). For the construct of satisfaction, the most significant coefficient was present in the overall level of satisfaction with the waste system. Finally, having a good attitude and feeling that sorting was necessary were the most influential items, with beta coefficients of 0.31 and 0.21, respectively.

	CR	AVE	MSV	Alpha C	Att	PBC	Soc	Know	Cons	Sat
Attitude	0.725	0.361	0.368	0.77		0.332	0.149	0.245	0.482	0.156
PBC	0.444	0.306	0.295	0,61	0.335		0.118	0.361	0.333	0.263
Soc norm	0.837	0.564	0.089	0.82	0.091	-0.003		0.04	0.308	0.081
Knowledge	0.761	0.443	0.295	0.75	0.248	0.543	-0.015		0.119	0.227
Consequences	0.799	0.510	0.368	0.81	0.606	0.272	0.298	0.139		0.105
Satisfaction	0.644	0.355	0.138	0.66	0.053	0.371	0.003	0.275	0.144	

Table 2 Fit assessment and validity test of the TPB constructs.

4.3. The behaviour of waste sorting

The TPB model of the behaviour of waste sorting was estimated using SEM. Although multiple specifications were tested and evaluated, only the three best-fitting models are presented (Figure 2), where the level of complexity was increased progressively. The first model in Panel a, represents the basic TPB formulation, and the subsequent models (Panel b and Panel c) represent extensions of the model. The three models were evaluated using different goodness of fit measurements following the literature recommendations.

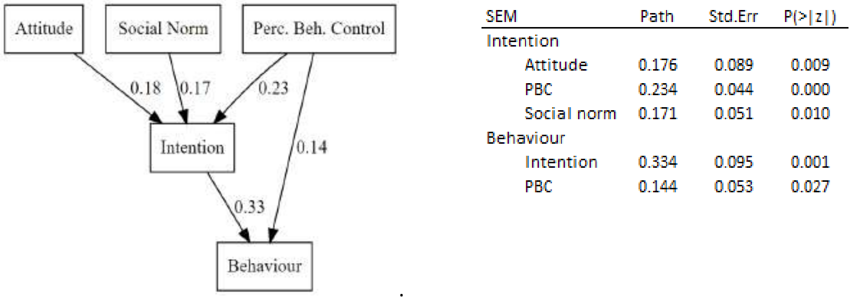
The first SEM (Model A) explores the formation of Behaviour with Intention and PBC and the formation of Intention with Attitude, Social Norms and PBC. Panel a) shows these constructs and the numbers in the arrows are the statistically significant standardised path coefficients with a confidence level of 5%. The model indicates that the path from Intention has more than two times the strength of the path from PBC to Behaviour. Moreover, PBC is the principal factor in explaining Intention. Attitude and Social Norms present similar importance, measured by the standardised path coefficients.

Model B (Panel b) extends the core model, including knowledge, satisfaction, and consequences. It is important to recall that knowledge contains variables of PBC. Still, the results from EFA gave evidence to isolate knowledge-related variables, such as satisfaction with information and knowing how to dispose of different waste materials. As a result, it should not be surprising that this construct provided results statistically significant in explaining both Intention and Behaviour. This model has shown that the consequences and satisfaction of local facilities are not statistically significant at 10%, thus being removed from further models. By including knowledge and extending the TPB, the strength of the intention to behaviour path has decreased, and part of its explanatory power is now explained by Knowledge.

Model C (Panel c) was the most complex and was built on the second SEM specification. This model includes the weighted distance to different bins and the dummy variable used to identify if the respondent engaged with the pant system. In this case, distance is the only construct that has a negative impact on behaviour, its path strength being as strong as PANT or PBC.

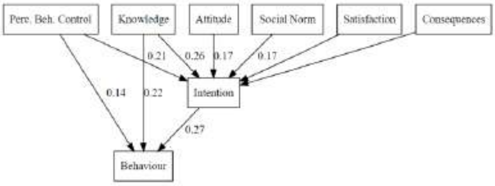
The three SEM specifications provide evidence to support the hypothesis behind the TPB. Model C performs better and contributes to increasing the statistical significance of some of the constructs, such as the coefficient of PBC, to determine behaviour. The p-value of this coefficient decreased from 0.023 to 0.015. In the three specifications, the hypothesis behind the TPB was validated.

The goodness of fit for the models are presented in the Appendix. It is worth noting that the main difference is found in the Relative Fit Index (RFI), which implies a good fit only for Model C. Regarding the Parsimony-Adjusted Measures Index (PANFI), no model gets a value higher than the considered cut-off of 0,5, suggesting that the optimal trade-off between model complexity and goodness of fit is not achieved. This is the only test that Model C fails. Therefore, it is considered a superior and preferable model to A and B. The results from then tests are included as an appendix in Table 3



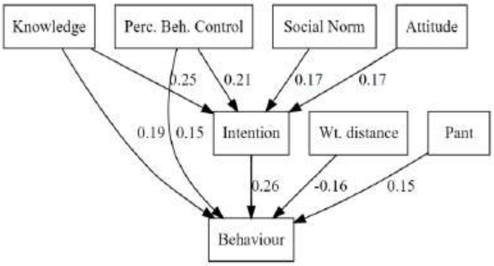
SEM	Path	Std.Err	P(>|z|)
Intention			
Attitude	0.176	0.089	0.009
PBC	0.234	0.044	0.000
Social norm	0.171	0.051	0.010
Behaviour			
Intention	0.334	0.095	0.001
PBC	0.144	0.053	0.027

Panel a. Path diagram of Model A and SEM results. Base TPB



SEM	Path	Std.Err	P(>|z|)
Intention			
Attitude	0.169	0.086	0.010
PBC	0.208	0.044	0.000
Social norm	0.168	0.051	0.012
Knowledge	0.256	0.058	0.000
Satisfaction	0.053	0.050	0.365
Consequence	0.055	0.073	0.441
Behaviour			
Intention	0.273	0.093	0.005
PBC	0.141	0.050	0.022
Knowledge	0.225	0.050	0.000

Panel b. Path diagram of Model B and SEM results. Base TPB extended with knowledge, satisfaction, and consequences



SEM	Path	Std.Err	P(>|z|)
Intention			
Attitude	0.172	0.083	0.006
PBC	0.214	0.044	0.000
Social norm	0.170	0.050	0.008
Knowledge	0.255	0.057	0.000
Behaviour			
Intention	0.255	0.084	0.004
PBC	0.147	0.048	0.013
Knowledge	0.194	0.047	0.000
Distance	-0.157	0.116	0.016
PANT	0.152	2.922	0.006

Panel c. Path diagram of Model C and SEM results. Base TPB extended with knowledge, distance, and RECYCLING

Figure 2 Path diagram of models A, B and C. Complemented with SEM results.

5. Discussion

This study provides three SEM that validate the TPB for residential waste sorting behaviour. In all cases, the primary TPB constructs contribute to determining the intention and behaviour of waste sorting. These results are also consistent with the fact that satisfaction with facilities does not play a role in the Swedish context but that statistical evidence supports the TPB's core hypothesis. Although the constructs' significance is essential, their weight differs from those presented before (Stoeva & Alriksson, 2017), where Attitude was the most critical factor, although this previous study focused on university students. The present study found evidence that PBC and knowledge are more significant factors than attitudes and social norms.

The first extended model (Model B) included Knowledge, and Model C added situational factors such as distance and whether the residents were engaged in the deposit system. Results from Model C are aligned with previous findings from Borås (Sweden) that show that reducing the distance to waste bins and increasing the awareness of residents improve the ratio of properly sorted waste (Rousta et al., 2015). This results are also consistent with previous studies that showed evidence that distance to bins decreases the behaviour to sort and participate in recycling programs (Ibrahim, 2020; Li et al., 2020)

In this study, we used Factor Analysis to test the presumption of how variables from the different survey items should be used to identify pre-defined TPB constructs. Results from this intermediate step showed that the presumed grouping of items via Confirmatory Factor Analysis (CFA) underperformed compared with the data-driven approach (EFA). Moreover, EFA explained better how the different items should be grouped. At this moment, we recommend future studies to include and evaluate the constructs using data-driven approaches. This study demonstrated that the variables require the creation of a construct labelled as knowledge. Moreover, the method suggested that these variables should be regarded as part of Attitudes instead of considering the construct of self-identification. PBC should also capture issues of hygiene and pleasantness since these factors can determine residents' self-efficacy.

In this study, researchers determined the behaviour of waste sorting by surveying how residents dispose of different types of waste. This helped to demonstrate that there is no single way of sorting waste and that different behaviours are associated with different types of waste.

5.1. Limitations

First, the number of valid responses used in the present study is at the lower end of what would be acceptable to generalise the results to the entire population of Gothenburg. Extending the survey to a larger population would guarantee that the results can be representative at the city level, and would increase their statistical power. Moreover, capturing responses from more residents would have enabled the use of the zip code to estimate absolute distances to waste bins instead of relying on self-reported distances. However, the number of surveys is consistent with previous studies, and future efforts should focus on expanding the sample (Chan & Bishop, 2013; Shi et al., 2021; Stoeva & Alriksson, 2017; Tonglet et al., 2004b)

Secondly, as in previous studies, the present study does not survey or monitor the residents' waste bins, and this information is crucial to establish the link between what people declare and what is quantified by waste management agencies. The gap between actual waste separation and how well we think we perform the task is known, and it is suggested that TPB studies should be paired up with actual measurements, in this case, of waste sorting (Ma et al., 2023; Perrin, D; Barton, 2000). Similarly, these models are based on self-declared information, and it would be essential to quantify the social norms better.

Finally, it is essential to improve access to the databases and scripts used in earlier studies that assess the TPB for waste sorting to understand better the context and how previous contributions evaluated it. Since measuring behaviour differently and extending TPB in various directions can lead to inconsistencies, making survey results and methods used openly accessible can enhance the comparability and reproducibility of the results. Furthermore, if TPB is to be relevant in policymaking, a direct link to quantifiable measurements of the built environment or waste amounts should be established.

6. Conclusion

Based on the Theory of Planned Behaviour (TPB), this study presented an extended model of waste sorting behaviour that incorporated knowledge and the distance to waste bins as part of Situational Factors. This model was developed and evaluated using data collected from a survey of residents of Gothenburg, Sweden. The results from the study show that the extended TPB model presents a better fit, but in all cases, the core TPB propositions are valid. Furthermore, a data-driven approach based on Exploratory Factor Analysis was used to determine the TPB constructs and their factors, which outperformed the conventional Confirmatory Factor Analysis approach that relies on pre-defined constructs.

Results from the extended model suggest that improvements in the perceived knowledge and convenience of residents can improve waste sorting. Since receiving a cash deposit when returning packages (Pant) was proven statistically significant in the models, specific attention should be given to the location where this exchange happens. This occurs in some supermarkets, therefore, extending this network and integrating other waste sorting facilities could result in better waste sorting. This study also shows that waste sorting behaviour is multidimensional and that different waste streams can present different behaviours. Usually, the behaviour of waste recycling is assessed, but these results show the importance of considering the behaviour towards other waste streams. Residents can be good-behaved towards packages, but organics are disposed of in residual bags. This suggests that the convenience of organic waste bins can affect the performance of waste management systems. The results from the analysis of the survey show that although, on average, residents from Gothenburg sort waste adequately and are relatively satisfied with the infrastructure, PBC and distance to bins influence the behaviour, meaning that in places where waste sorting is less established, this factor could be of greater importance.

More research on how these findings can be linked to actual waste separation is crucial for designing effective waste management systems. Therefore, it is recommended that psychological models are integrated with quantifiable measurements of the built environment, residents' social networks and actual waste surveys. Future studies could use geographic information on the locations of residents to estimate the distance to recycling facilities. Precise information on distances, time and efforts can help determine how much waste sorting and recycling activities are affected by convenience. Similarly, quantifying the space at home used for waste and recycling could provide insights into how homes could be improved to reduce the barriers towards waste sorting by improving the PBC of residents. Moreover, TPB models and other efforts to determine waste sorting behaviour should be accompanied by accurate measurements of waste. Finally, TPB can be integrated into other modelling techniques, such as systems dynamics or Agent-Based Models. These combined models could be used as Decision Support Systems to enable policymakers to study different what-if scenarios of urban waste management systems.

Acknowledgments

This work is part of the Digital Twin Cities Centre supported by Sweden's Innovation Agency Vinnova under Grant No. 2019-00041

7. References

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Alonso-Betanzos, A., Sanchez-Marono, N., Fontenla-Romero, O., Polhill, J. G., Craig, T., Bajo, J., & Corchado, J. M. (2017). *The Implementation of the Theory of Planned Behavior in an Agent-Based Model for Waste Recycling: A Review and a Proposalof Sustainable Behaviors*. 270. https://doi.org/10.1007/978-3-319-46331-5

Armitage, C. J., & Conner, M. (2010). *Efficacy of the Theory of Planned Behaviour: A Meta-Analytic Review E Y cacy of the Theory of Planned Behaviour: A meta-analytic review*. *July 2017*, 471–499.

Avfall Sverige (Ed.). (2021). *Swedish Waste Management 2021*. https://www.avfallsverige.se/media/lbdg3vcp/svensk_avfallshantering_2021_en.pdf

Azlina, W., Ab, W., Ghani, K., Rusli, I. F., Radiah, D., Biak, A., & Idris, A. (2013). An application of the theory of planned behaviour to study the influencing factors of participation in source separation of food waste. *Waste Management*, *33*(5), 1276–1281. https://doi.org/10.1016/j.wasman.2012.09.019

Barata, E. (2003). Municipal Waste Management in Europe. *Ecological Economics*, *47*(2–3), 215–216. https://doi.org/10.1016/j.ecolecon.2003.07.002

Bernstad, A. (2014). Household food waste separation behavior and the importance of convenience. *Waste Management*, *34*(7), 1317–1323. https://doi.org/10.1016/j.wasman.2014.03.013

Chan, L., & Bishop, B. (2013). A moral basis for recycling: Extending the theory of planned behaviour. *Journal of Environmental Psychology*, *36*, 96–102. https://doi.org/10.1016/j.jenvp.2013.07.010

Chen, M. F., & Tung, P. J. (2010). The moderating effect of perceived lack of facilities on consumers' recycling intentions. *Environment and Behavior*, *42*(6), 824–844. https://doi.org/10.1177/0013916509352833

Chen, M.-F., & Tung, P.-J. (2010). The Moderating Effect of Perceived Lack of Facilities on Consumers' Recycling Intentions. *Environment and Behavior*, *42*(6), 824–844. https://doi.org/10.1177/0013916509352833

Davies, J., Foxall, G. R., & Pallister, J. (2002). Beyond the intention-behaviour mythology: An integrated model of recycling. *Marketing Theory*, *2*(1), 29–113. https://doi.org/10.1177/1470593102002001645

Davis, G., Phillips, P. S., Read, A. D., & Iida, Y. (2006). Demonstrating the need for the development of internal research capacity: Understanding recycling participation using the Theory of Planned Behaviour in West Oxfordshire, UK. *Resources, Conservation and Recycling*, *46*(2), 115–127. https://doi.org/10.1016/j.resconrec.2005.07.001

Govindan, K., Zhuang, Y., & Chen, G. (2022). Analysis of factors influencing residents' waste sorting behavior: A case study of Shanghai. *Journal of Cleaner Production*, *349*, 131126. https://doi.org/10.1016/j.jclepro.2022.131126

Halder, P., & Singh, H. (2018a). *Predictors of Recycling Intentions among the Youth: A Developing Country Perspective*. 1–16. https://doi.org/10.3390/recycling3030038

Halder, P., & Singh, H. (2018b). Predictors of Recycling Intentions among the Youth: A Developing Country Perspective. *Recycling*, *3*(3), 38. https://doi.org/10.3390/recycling3030038

Hu, J., Tang, K., Qian, X., Sun, F., & Zhou, W. (2021). Behavioral change in waste separation at source in an international community: An application of the theory of planned behavior. *Waste Management*, *135*, 397–408. https://doi.org/10.1016/j.wasman.2021.09.028

Ibrahim, M. A. (2020). Modeling of risk for improper sorting of waste at Recycling Centers. *Waste Management*, *102*, 550–560. https://doi.org/10.1016/j.wasman.2019.11.017

Issock Issock, P. B., Roberts-Lombard, M., & Mpinganjira, M. (2020). *Understanding household waste separation in South Africa: An empirical study based on an extended theory of interpersonal behaviour*. *31*(3), 530–547. https://doi.org/10.1108/MEQ-08-2019-0181

Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1329-0

Khalil, M. S., Abdullah, S. H., Manaf, L. A., Sharaai, A. H., & Nabegu, A. B. (n.d.). *Examining the Moderating Role of Perceived Lack of Facilitating Conditions on Household Recycling Intention in Kano , Nigeria*. https://doi.org/10.3390/recycling2040018

Kline, R. B. (2015). *Principles and Practice of Structural Equation Modeling*.

Knussen, C., Yule, F., MacKenzie, J., & Wells, M. (2004). *An analysis of intentions to recycle household waste: The roles of past behaviour, perceived habit, and perceived lack of facilities*. *24*(2), 237–246. https://doi.org/10.1016/j.jenvp.2003.12.001

Lakhan, C. (2018). *The garbage gospel: Using the theory of planned behavior to explain the role of religious institutions in affecting pro-environmental behavior among ethnic minorities*. *49*(1), 43–58. https://doi.org/10.1080/00958964.2017.1337701

Li, C., Zhang, Y., Nouvellet, P., Okoro, J. O., Xiao, W., & Harder, M. K. (2020). Distance is a barrier to recycling – or is it? Surprises from a clean test. *Waste Management*, *108*, 183–188. https://doi.org/10.1016/j.wasman.2020.04.022

Liu, Q., Xu, Q., Shen, X., Chen, B., & Esfahani, S. S. (2022). *The Mechanism of Household Waste Sorting Behaviour—A Study of Jiaxing, China*. *19*(4). https://doi.org/10.3390/ijerph19042447

Ma, J., Hipel, K. W., Hanson, M. L., Cai, X., & Liu, Y. (2018). An analysis of influencing factors on municipal solid waste source-separated collection behavior in Guilin, China by Using the Theory of Planned Behavior. *Sustainable Cities and Society*, *37*, 336–343. https://doi.org/10.1016/j.scs.2017.11.037

Ma, J., Yin, Z., Hipel, K. W., Li, M., & He, J. (2023). Exploring factors influencing the application accuracy of the theory of planned behavior in explaining recycling behavior. *Journal of Environmental Planning and Management*, *66*(3), 445–470. https://doi.org/10.1080/09640568.2021.2001318

Ofstad, S. P., Tobolova, M., Nayum, A., & Klöckner, C. A. (2017). *Understanding the mechanisms behind changing people's recycling behavior at work by applying a comprehensive action determination model*. *9*(2). https://doi.org/10.3390/su9020204

Oztekin, C., Teksöz, G., Pamuk, S., Sahin, E., & Kilic, D. S. (2017). Gender perspective on the factors predicting recycling behavior: Implications from the theory of planned behavior. *Waste Management*, *62*, 290–302. https://doi.org/10.1016/j.wasman.2016.12.036

Park, J., & Ha, S. (2014). Understanding Consumer Recycling Behavior: Combining the Theory of Planned Behavior and the Norm Activation Model. *Family and Consumer Sciences Research Journal*, *42*(3), 278–291. https://doi.org/10.1111/fcsr.12061

Passafaro, P., Livi, S., & Kosic, A. (2019). *Local norms and the theory of planned behavior: Understanding the effects of spatial proximity on recycling intentions and self-reported behavior*. *10*(MAR). https://doi.org/10.3389/fpsyg.2019.00744

Perrin, D; Barton, J. R. (2000). If only households recycled what and when they said they would! *ISWA World Congress*.

Phulwani, P. R., Kumar, D., & Goyal, P. (2020). A Systematic Literature Review and Bibliometric Analysis of Recycling Behavior A Systematic Literature Review and Bibliometric Analysis of Recycling Behavior. *Journal of Global Marketing*, *33*(5), 354–376. https://doi.org/10.1080/08911762.2020.1765444

Razali, F., Daud, D., Weng-Wai, C., & Anthony Jiram, W. R. (2020). Waste separation at source behaviour among Malaysian households: The Theory of Planned Behaviour with moral norm. *Journal of Cleaner Production*, *271*, 122025. https://doi.org/10.1016/j.jclepro.2020.122025

Rousta, K., Bolton, K., Lundin, M., & Dahlén, L. (2015). Quantitative assessment of distance to collection point and improved sorting information on source separation of household waste. *Waste Management*, *40*(2015), 22–30. https://doi.org/10.1016/j.wasman.2015.03.005

Rousta, K., & Ekström, K. (2013). Assessing Incorrect Household Waste Sorting in a Medium-Sized Swedish City. *Sustainability*, *5*(10), 4349–4361. https://doi.org/10.3390/su5104349

Shen, L., Si, H., Yu, L., & Si, H. (2019). *Factors Influencing Young People ' s Intention toward Municipal Solid Waste Sorting*.

Shi, J.-G., Xu, K., Si, H., Song, L., & Duan, K. (2021). *Investigating intention and behaviour towards sorting household waste in Chinese rural and urban–rural integration areas*. *298*. https://doi.org/10.1016/j.jclepro.2021.126827

Stoeva, K., & Alriksson, S. (2017). Influence of recycling programmes on waste separation behaviour. *Waste Management*, *68*, 732–741. https://doi.org/10.1016/j.wasman.2017.06.005

Strydom, W. F. (2018). Applying the theory of planned behavior to recycling behavior in South Africa. *Recycling*, *3*(3). https://doi.org/10.3390/recycling3030043

Tang, D., Cai, X., Nketiah, E., Adjei, M., Adu-Gyamfi, G., & Obuobi, B. (2023). Separate your waste: A comprehensive conceptual framework investigating residents' intention to adopt household waste separation. *Sustainable Production and Consumption*, *39*, 216–229. https://doi.org/10.1016/j.spc.2023.05.020

Taylor, S., & Todd, P. (1995). *An Integrated Model of Waste Management Behavior: A Test of Household Recycling and Composting Intentions*. *27*(5), 603–630. https://doi.org/10.1177/0013916595275001

Tonglet, M., Phillips, P. S., & Read, A. D. (2004a). Using the Theory of Planned Behaviour to investigate the determinants of recycling behaviour: A case study from Brixworth, UK.

Resources, Conservation and Recycling, *41*(3), 191–214. https://doi.org/10.1016/j.resconrec.2003.11.001

Tonglet, M., Phillips, P. S., & Read, A. D. (2004b). Using the Theory of Planned Behaviour to investigate the determinants of recycling behaviour: A case study from Brixworth, UK. *Resources, Conservation and Recycling*, *41*(3), 191–214. https://doi.org/10.1016/j.resconrec.2003.11.001

Visschers, V. H. M., Wickli, N., & Siegrist, M. (2016). *Sorting out food waste behaviour: A survey on the motivators and barriers of self-reported amounts of food waste in households*. *45*, 66–78. https://doi.org/10.1016/j.jenvp.2015.11.007

Wan, C., Shen, G. Q., & Yu, A. (2014). *The role of perceived effectiveness of policy measures in predicting recycling behaviour in Hong Kong*. *83*, 141–151. https://doi.org/10.1016/j.resconrec.2013.12.009

Wang, C., Chu, Z., & Gu, W. (2021). Participate or not: Impact of information intervention on residents' willingness of sorting municipal solid waste. *Journal of Cleaner Production*, *318*(February), 128591. https://doi.org/10.1016/j.jclepro.2021.128591

Wang, S., Wang, J., Yang, S., Li, J., & Zhou, K. (2020). *From intention to behavior: Comprehending residents' waste sorting intention and behavior formation process*. *113*, 41–50. https://doi.org/10.1016/j.wasman.2020.05.031

Wang, Y., Long, X., Li, L., Wang, Q., Ding, X., & Cai, S. (2021). Extending theory of planned behavior in household waste sorting in China: The moderating effect of knowledge, personal involvement, and moral responsibility. *Environment, Development and Sustainability*, *23*(5), 7230–7250. https://doi.org/10.1007/s10668-020-00913-9

Xu, L., Ling, M., Lu, Y., & Shen, M. (2017). Understanding Household Waste Separation Behaviour: Testing the Roles of Moral, Past Experience, and Perceived Policy Effectiveness within the Theory of Planned Behaviour. *Sustainability*, *9*(4), 625. https://doi.org/10.3390/su9040625

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*(4), 52. https://doi.org/10.3390/recycling7040052

Zhang, B., Lai, K. hung, Wang, B., & Wang, Z. (2019). From intention to action: How do personal attitudes, facilities accessibility, and government stimulus matter for household waste sorting? *Journal of Environmental Management*, *233*(December 2018), 447–458. https://doi.org/10.1016/j.jenvman.2018.12.059

Zhang, D., Huang, G., Yin, X., & Gong, Q. (2015). Residents' waste separation behaviors at the source: Using SEM with the theory of planned behavior in Guangzhou, China. *International Journal of Environmental Research and Public Health*, *12*(8), 9475–9491. https://doi.org/10.3390/ijerph120809475

8. Appendix

Goodness Fit	MODEL A		MODEL B		MODEL C		
	Value	Test	Value	Test	Value	Test	*Threshold*
P(Chi-sq)	0.248	Pass	0.239	Pass	0.447	Pass	*0.05*
GFI	1.000	Pass	0.999	Pass	1.000	Pass	*0.95*
AGFI	0.998	Pass	0.994	Pass	0.997	Pass	*0.90*
NFI	0.967	Pass	0.938	Pass	0.972	Pass	*0.90*
NNFI	0.964	Pass	0.891	No pass	1.006	Pass	*0.90*
CFI	0.990	Pass	0.967	Pass	1.000	Pass	*0.90*
RMSEA	0.038	Pass	0.059	No pass	0.000	Pass	*0.05*
SRMR	0.021	Pass	0.022	Pass	0.015	Pass	*0.08*
RFI	0.883	No pass	0.800	No pass	0.911	Pass	*0.90*
PNFI	0.276	No pass	0.289	No pass	0.299	No pass	*0.50*
IFI	0.990	Pass	0.969	Pass	1.002	Pass	*0.90*
N	*275*		*275*		*275*		
Df	*2*		*2*		*4*		
Chi	*2.785*		*2.863*		*7.705*		

Table 3. Conventional cut-off criteria of various goodness of fit.

*Notes: **Chisq** assesses the overall fit and the discrepancy between the sample and fitted covariance matrices. **GFI/AGFI**: (Adjusted) Goodness of Fit is the proportion of variance the estimated population covariance accounts for. Analogous to R2. **NFI/NNFI/TLI**: (Non) Normed Fit Index. **CFI**: Comparative Fit Index is a revised form of NFI. Compare the fit of a target model to the fit of an independent or null model. **RMSEA**: Root Mean Square Error of Approximation is a parsimony-adjusted index. **SRMR**: Standardized Root Mean Square Residual represents the square root of the difference between the residuals of the sample covariance matrix and the hypothesised model. **RFI**: Relative Fit Index, also known as RHO1. **IFI**: Incremental Fit Index adjusts the Normed Fit Index (NFI) for sample size and degrees of freedom. **PNFI**: the Parsimony-Adjusted Measures Index. Extracted from R package effect size. For more details about indexes and cut-offs, visit effectsize at CRAN.*

Paper V

A Spatio-Temporal Simulation of the Construction and Demolition sector. Methodological Advances to quantify embodied carbon of buildings

J. Cohen, J. Gil, L.Rosado & M. Lanau

Manuscript

A Spatio-Temporal Simulation of the Construction and Demolition sector. Methodological Advances to quantify embodied carbon of buildings.

Abstract

Reusing existing material stocks can significantly reduce natural resource extraction, waste, and the environmental footprint of the construction and demolition sector. However, material reuse in urban areas presents technical, temporal, and geographical challenges. While scientific contributions on increasing material reuse exist, they need to pay more attention to the dynamic and spatially explicit nature of construction and demolition activities.

The city of Gothenburg, Sweden, was taken as a case study and using material intensity coefficients, embodied carbon for stages A1-A3 was calculated for residential buildings. The article details the steps to develop a simulation to explore how various conditions determine savings in embodied carbon and shows the potential of employing simulations.

Our research not only provides a proof of concept for incorporating the spatial and temporal dimensions of construction and demolition activities to analyse embodied carbon savings in the built environment, but also offers practical implications. The simulation we developed can be expanded for more materials, and it sets the baseline for future explorations aiming to explore the role of logistics and the availability of recycling stations, thereby paving the way for more sustainable practices in the sector.

1. Introduction

Our research is driven by the urgent need to address the significant environmental impact of the construction and demolition (CND) sector, which is a key player in maintaining, producing, and replacing housing stock in cities. The industry generates substantial waste and greenhouse gases (GHGs), and the buildings and infrastructures it creates have long-term consequences that can span several decades. Our aim is to contribute to the development of more sustainable practices in the sector by providing a comprehensive understanding of buildings' embodied carbon.

In response to the pressing environmental challenges posed by the increase in greenhouse gases and general environmental degradation, the European Union has set ambitious environmental targets. These include a 55% reduction in greenhouse gas emissions by 2030 and a 90% net reduction by 2040 compared to 1990. The construction and demolition (CND) sector, identified as a significant contributor to environmental damage, has been under increasing pressure to adopt more sustainable practices since implementing the EU Green Deal.

The construction sector generates over 35% of the EU's total waste, and greenhouse gas emissions from CND activities are estimated to be as high as 13%. Improving material efficiency in the sector can save 80% of those emissions.

To comply with current regulations, the CND sector needs to improve its practices by implementing selective demolition, increasing material reuse to a minimum of 70% by weight, building durability and flexibility, and reducing the total throughput of materials by recycling.

Second, the CND sector needs to reduce the number of new buildings and renovate the existing stock to relieve the pressure on virgin materials and the environmental impacts of building operations. Currently, only 33% of buildings use renewable heating, and gas usage needs to be reduced by more than half.

Renovating a significant proportion of the European Union's building stock is a massive undertaking. The share of dwellings using renewable heating sources needs to increase to 100% from just 35% today, and gas usage in buildings also needs to fall by more than half.

1.1. Aim of the study

This article presents a methodology for studying changes in the embodied carbon of buildings due to activities in the construction and demolition sector. The method demonstrates the steps to develop the Construction and Demolition (CnD) model that overcomes the previously mentioned research gaps.

The research introduces an explicit spatial and temporal simulation of a city's building life cycle, projecting the likelihood of demolition and future material demand based on the need for future housing. The CnD model material flows and stocks using a rule-based simulation to illustrate the dynamic and spatial aspects of future constructions and demolitions. The CnD model addresses the previously identified research gaps by:

- Spatializing build stocks: Material Intensity Coefficients (MIC) are used to determine the location of various materials at the building level (wood, concrete, glass, bricks, steel, gypsum, steel and stone).
- Modelling material flow and stock changes over time: Every building in the simulation is integrated with a set of rules that contributes to determining inputs and outputs of secondary materials.
- Assessing Co2 offsets: Material stocks and flows are integrated with their associated embodied Co2 from extraction to use (A1-A2)
- Enabling the evaluation of what-if scenarios: The initial conditions, parameters, and rules that determine the heuristics can be explored to determine changes in the embodied carbon resulting from Construction and Demolition.
- Promoting transparency: This article describes the model details and provides the source code used to run it. This characteristic is critical for developing standards for exploring the construction and demolition sector dynamics.

In the next section, the CnD model and related methodology are described. Next, the potential of such a model is presented by applying it to the residential buildings in Gothenburg, Sweden. Various parameter combinations are tested to explore the model's capabilities. Finally, conclusions are drawn about the potential contributions of using the model to examine the effects of different scenarios.

2. Background

[TBC]

3. The CnD model

The methodology used for this research was adapted from System Dynamics because it offers an adequate framework to structure the activities followed during the study of dynamic processes. (Sterman, 2000). Figure 1 This section presents the steps followed during the study's development, describing steps 2 to 5. The first task consisted of identifying the challenge of material use in the construction sector, and the outputs of this first step are reflected in the first two sections of this article.

This section describes the model's elements and the necessary heuristics to execute it. Then, we introduce the following: We describe the model's aspects and the dynamics heuristics. Next, we present the main parameters to explore and explain the calibration process.

In step four, the case study and the data requirements are introduced. In this section, the model is instantiated. After various simulations, data from the model is obtained. The final step consisted of summarising and visualising the information to showcase the potential uses of the model.

The introduction of a case study contributed to determining the model elements and heuristics. These are context-specific and may vary from case to case.

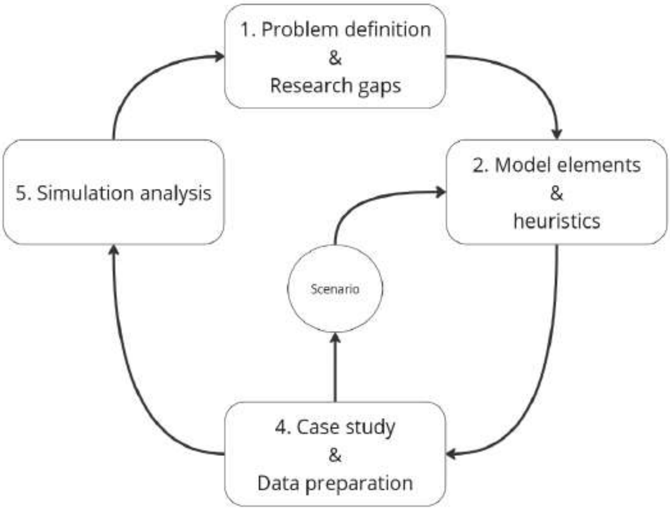


Figure 1 Modelling framework used to develop the simulations (Sterman, 2000)

3.1. Model elements & heuristics

Figure 2 This section presents the overall process of the simulation, which shows the overall processes in the simulation. The simulation features four key agents: buildings, recyclers, planners, and city areas, with buildings serving as the primary agents. The simulation is run from 2010 until 2100, and every step is five years long.

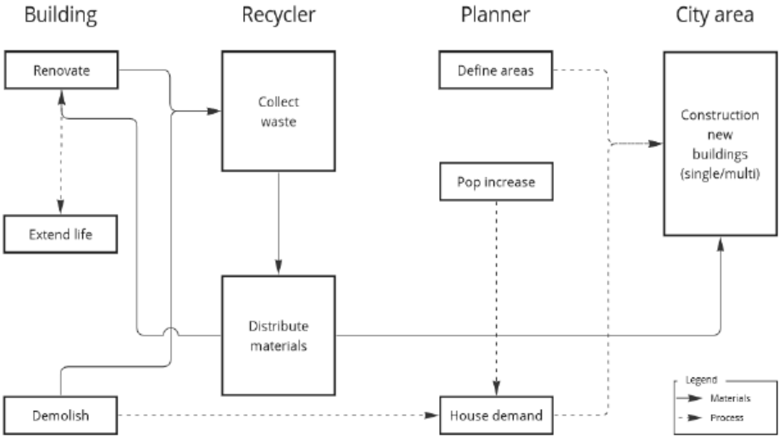


Figure 2 The overall process of the simulation and agents

In this model, each building acts as an independent decision-making entity, determining when to renovate or undergo demolition. Renovation triggers a demand for materials, be they virgin or recycled, and demolition increases the recycled material at the recycler. Based on (Ministry of Infrastructure, n.d.) three renovation strategies were defined and presented in Figure 11 in the appendix. These strategies define the amount of material needed for the renovations, the amount of waste generated and its impact on the EPD of the building. Figure 3 shows a schema of the buildings' processes.

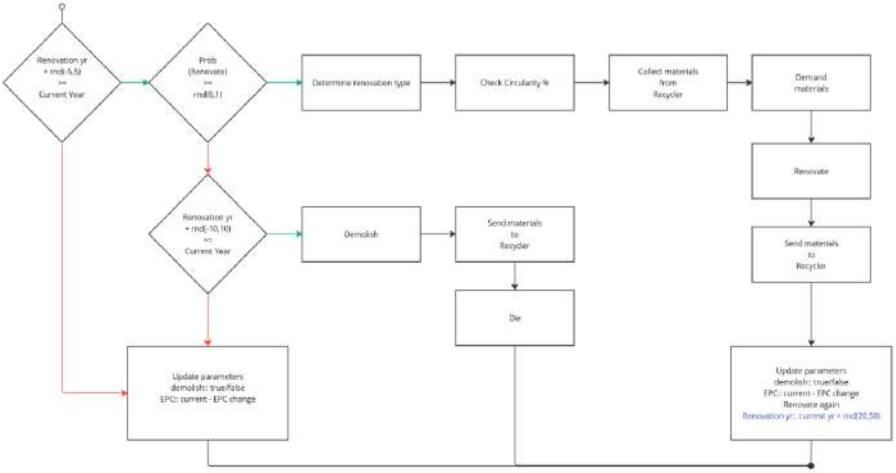


Figure 3 A flow diagram is used to determine building renovations and demolitions.

Although the model anticipates multiple recyclers, it operates with a single recycler, functioning as a material collection and distribution broker. Notably, the recycler is the last agent to execute the simulation, handling aggregations and CO2e estimations. The fact that the model can include several recyclers allows one to study the problem's logistic side.

The planner, another essential agent, considers population increases and lost housing due to demolitions. Population demographics inform the construction of new houses, crucial for replenishing housing stock lost in demolitions. Influenced by a parameter defining housing technology percentages, the model allocates the population demand across single or multifamily units. The implementation dynamically adjusts the distribution, impacting material requirements and the city's embodied carbon.

The city area agent defines areas based on a population grid, leveraging officially published data with attached population information. Over 200 squares, serving as agents, receive input from the planner regarding the required number of buildings. At each step, these squares decide whether to build or not. While the current model employs a random selection process, it is adaptable to incorporate diverse building rules, such as prioritising high-density areas first or experimenting with alternative building sequences.

3.2. Data inputs and processing

To develop the simulation for this study, we integrated various data sources, with the initial dataset originating from Landmateriet, one of the Swedish information authorities. This comprehensive geodatabase served as the foundation for initialising the simulation, and the required data sources are presented in Figure 4.

Initially, the database comprised data on residential buildings throughout Gothenburg. These records contained essential information about the geographical area and each building. By leveraging details on building height, we estimated the gross floor area (GFA). Subsequently, outliers were meticulously removed from the database, resulting in a refined dataset of buildings, each accompanied by its corresponding GFA.

The subsequent phase involved augmenting the database with information about the materials used in each building. Material intensity coefficients, referenced from the research conducted by (Gontia et al., 2018) were employed. This comprehensive study covered material intensity across Sweden. The database categorised different materials per GFA based on various typologies, accounting for whether it was a single-family or multi-family dwelling and the decade of construction. Information from Boverket was used to translate each material to a specific value of CO2e.

Given our interest in understanding the potential impact of the energy certificate declarations policy on the new housing stock in the city, we sought to incorporate information about energy performance. As citywide implementation of energy performance data was still under development, we adopted a stochastic and probabilistic approach to define an Energy Performance Declaration (EPD) for each building. This approach considered both the age of the buildings and the materials used, such as wood, concrete, or brick.

The final piece completing the initial state puzzle involved integrating population data from the city of Gothenburg at a grid resolution of 1 kilometre. This data was incorporated by analysing buildings' distribution and heights within each grid. Consequently, we estimated the number of people and households associated with each grid. The resulting database encapsulated crucial details such as the year of construction, building materials, building height, typology (single-family or multi-family), and energy performance declarations.

This comprehensive database served as the base for initiating our simulation. The subsequent section delves into the agent-based simulation process and the various scenarios explored during its development.

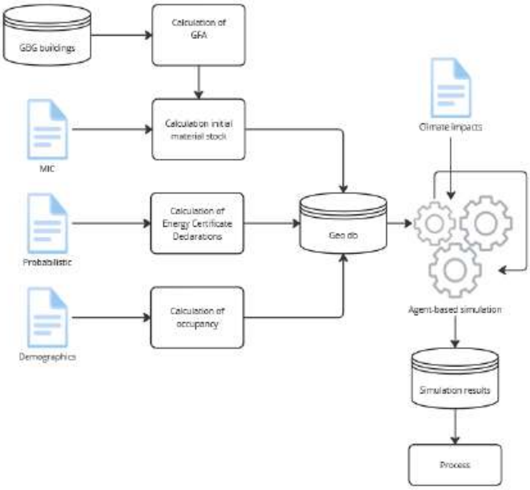


Figure 4 Data sources and processing to develop simulations

3.3. Simulations and scenarios

Various parameters were integrated into the simulation to fulfil these objectives outlined in the introductory phase. These introduced variables facilitate an exploration of how the interplay of different parameters yields diverse outcomes, explicitly concerning the quantity of recycled materials and CO2 emissions. The key parameters include:

- Probability of Demolition: When a building reaches the end of its lifespan, typically around 100 years after construction (Andersen & Negendahl, 2023), the probability of its demolition is determined.

- Probability of Renovation: Buildings may require renovations within 25 to 50 years of construction. This parameter influences the probability of such renovations occurring.
- Percentage of single-family buildings: This parameter determines the typology of newly constructed buildings, specifying the percentage allocated to single-family or multi-family buildings.
- Maximum Percentage of Recycled Material Used for New Constructions: This parameter dictates how much new constructions can incorporate recycled materials. It represents the voluntary amount of recycled material, allowing new buildings to use a maximum percentage (of weight). If, for example, the parameter is set to 0.25, the new construction will search for 25% of each material in recyclers; if unavailable, the remaining 75% is sought in the market of new materials.
- Maximum Percentage of Recycled Material Used for Renovations: Like the parameter for new constructions above, this sets the maximum percentage of recycled material used for renovations (in weight).

Exploring the parameter space, which involves all possible combinations of these parameters, becomes exponentially complex. To manage and streamline simulations, the probability of demolition was assigned values of 1%, 3%, and 5%. At the same time, the remaining parameters were explored within the range of zero to one with an incremental value of 0.25. Each parameter was tested with five values, resulting in 1875 scenarios. Each scenario was simulated ten times to enhance robustness, mitigating the impact of stochastic elements in the model on the results, generating 18,750 simulations.

3.4. Case study: Residential buildings in Gothenburg city

[TBC]

3.4.1. Policy scenario: Energy Performance Regulations

Due to Gothenburg's ambitious pursuit of a climate-neutral future, developing a crucial framework was imperative. This framework outlines the repercussions for buildings with poor energy performance over time. The policy scenario to be evaluated simulates a situation where the local authority imposes a restriction that buildings lacking a minimum energy performance label (such as G) will no longer be permitted. In 2045, structures with a G-grade energy declaration face an explicit request: either undergo mandatory renovation or face demolition. The same parameter spaces were used for comparison purposes, and these scenarios were simulated five times, resulting in 9,375 Simulations.

3.5. Analysis of simulations

Even though 15 repetitions per parameter do not offer enough statistical power, this was compensated by the number of total simulations generated under different parameter combinations. The results from the 28,125 simulations (18,750 with no EPC law and 9,375 without EPC law) were summarised using graphs to evaluate how the changes in parameters affect the amount of material demand and Co2e in the embodied carbon A1-A3. These results were complemented using a linear regression where we evaluated how the percentage of saved Co2e changes. The savings in Co2e as a percentage were used as the relevant Key Performance Indicator to measure the outcomes in the different scenarios.

4. Results and discussion

The findings of this study can be categorised into three main sections. Firstly, it provides a detailed description of the simulation process, offering insights into the parameters that users can manipulate. It also presents an overview of the simulation dashboard layout. Following this, the parameter space is systematically explored through various simulations. Despite the multitude of scenarios modelled, the results in this section highlight the impact of diverse parameters on the outputs, measured explicitly in terms of the new embodied carbon within the city.

Lastly, the study simulates a scenario set in 2045 using the same parameter space. In this envisioned future, the city enforces a prohibition on buildings with an energy performance declaration labelled as G.

4.1. Simulation as a Decision Support System

The image below showcases the simulation dashboard, which monitors various parameters and key performance indicators (KPIs). The parameters available for initialisation or modification during a simulation are presented on the left. These include the probability of demolition, renovation probability, renovation size, and the percentage of recycled materials aimed for in the system. Additionally, the decision to construct new buildings, permit or restrict renovations, and implement a new law prohibiting houses with specific energy performance after a designated time can be toggled on or off.

The dashboard introduces a visual representation of all buildings as dots, with colours changing dynamically during the simulation—reflecting renovations, demolitions, and new constructions. The total city population is tracked to ensure proper population allocation. Matching the expected population growth, the graph in the bottom left corner, adjacent to the population map, shows the total and simulated populations aligning.

The first graph with the panel monitors the status of all buildings, with the initial building stock depicted in black. As the simulation progresses, the status changes, predominantly showcasing green for renovations, blue for new single—and multi-building constructions, and red for demolitions. Below this graph, the distribution of energy performance in buildings is tracked. The rise of labels A and B in green indicates positive performance trends.

Further analysis involves four charts tracking the materials and embodied carbon used in new constructions and renovations. These charts also illustrate the reduction in CO2 emissions achieved. The model is available on the COMSES library, allowing researchers to download and explore it for further enhancements and insights.

This interface is mainly used to run specific scenarios and help during the development of the model. In the next section, the results of running batch simulations are reported.

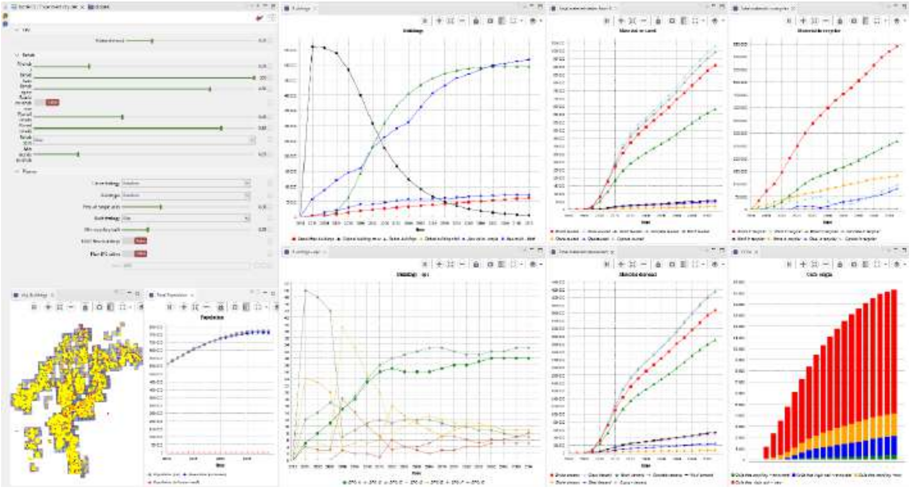


Figure 5. Model dashboard. Selection of parameters and various graphs tracking the simulation

4.2. Changes in material availability

Figure 6 shows how much material is being captured under different scenarios. For each graph, the amount of materials per year was averaged across the simulations under the same conditions, including the probability of demolishing and the proportion of construction of single-family buildings. The figure contains 12 plots organised in a grid. As we move down, the proportion of single-family buildings increases from 0% to 100%. Moving |g to the right, the probability of demolitions increases from 1% to 5%. Figure 6 shows how the materials from the renovations and demolitions were captured to be recycled. The matrix of plots shows how the material availability changes with the level of demolitions and the proportion of single-family buildings, keeping the rest of the parameters constant. For instance, it can be appreciated that as demolitions increase, the amount of materials increases. Moreover, because of the different building typologies used in this investigation, the percentage of single families decreases, and the amount of wool becomes available. Also, the plots show that bricks are a material available, so it is reasonable to find ways of reusing this material.

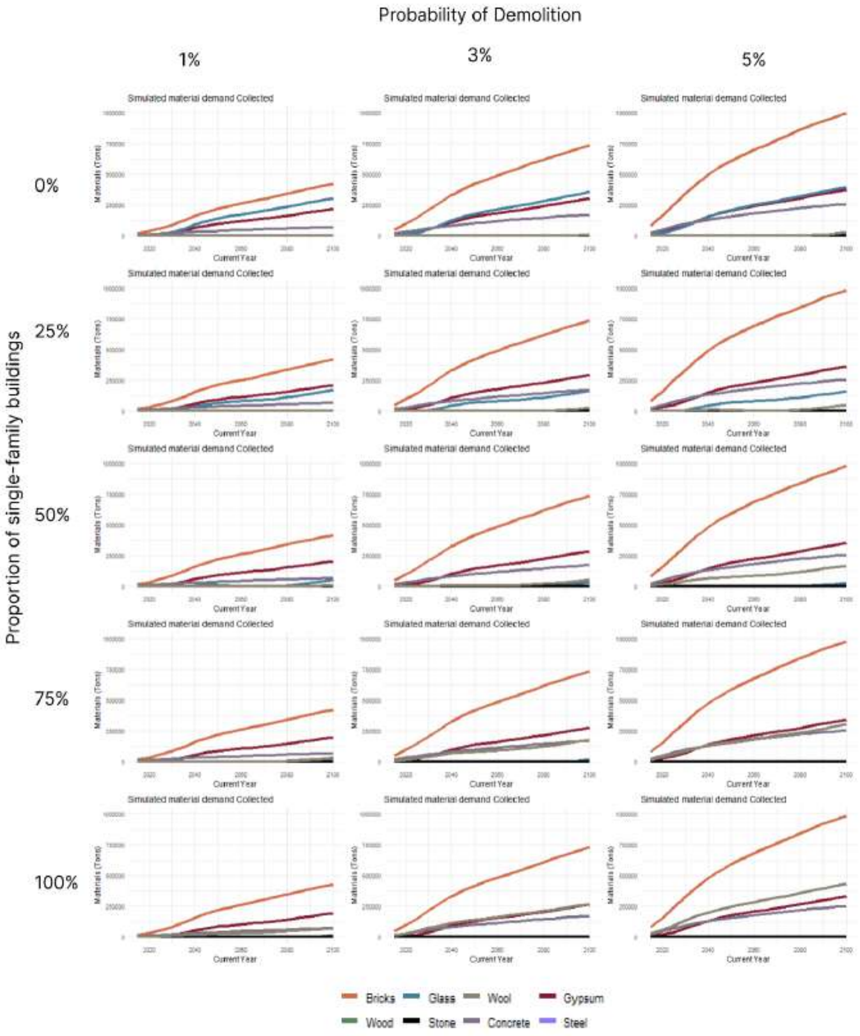


Figure 6 shows Material availability with different values of the probability of demolitions and the percentage of new single-family buildings to be constructed.

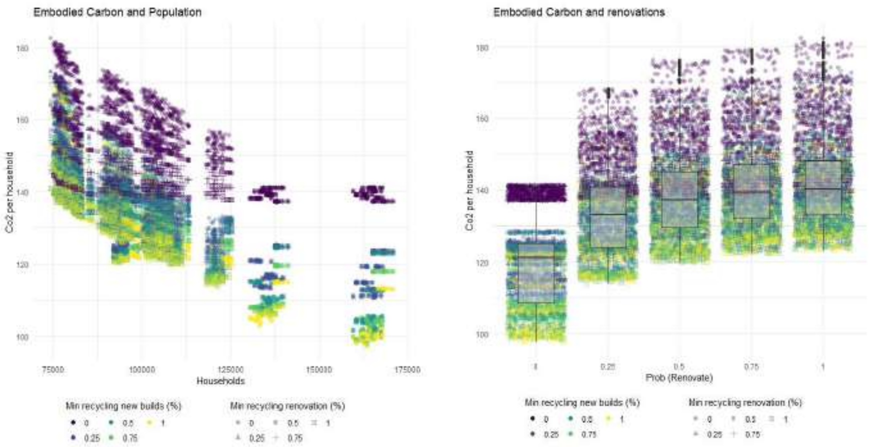
4.3. Changes in embodied carbon

The results of the simulations were explored in relation to five parameters. The simulations were run ten times for each specification for the combination of the following parameters: the percentage of material reuse for renovations, the percentage of material reuse for new constructions, the probability of renovating the building, the likelihood of performing demolition and the proportion of single-family buildings to be constructed. The results present the results of exploring how changes affect the amount of CO2e in each scenario. Because of the stochastic nature of the models, the number of total homes and the total number of residents found at the end of the simulation vary, so it was necessary to standardise the variable in relation to the total number of homes. The results presented in this section are asses with regard to the amount of co2e per home generated in each of the simulated scenarios.

Figure 7 presents the results from the simulations. The results are presented using scatter plots where the Y axis represents the CO2e, and the X axis represents the parameter that is being explored. Each point of the scatter plot represents one simulation for a specific combination of parameters in the last state of the simulation in the year 2100. The colour and symbol of all the scatter plots remain the same and show the percentages of material reuse for renovations (shape) and new constructions (colour)—the different panels of the figure next show the resulting visualisation for the other parameters. The range of the amount of CO2e remains constant across the four charts. Panel (a) presents the relationship between embodied carbon per household and the amount of households created under the various simulations. Panel (b) presents the results across the probability of renovation. Panel (c) presents the results about the proportion of single-family units, and panel (d) presents the results about the probability of demolition.

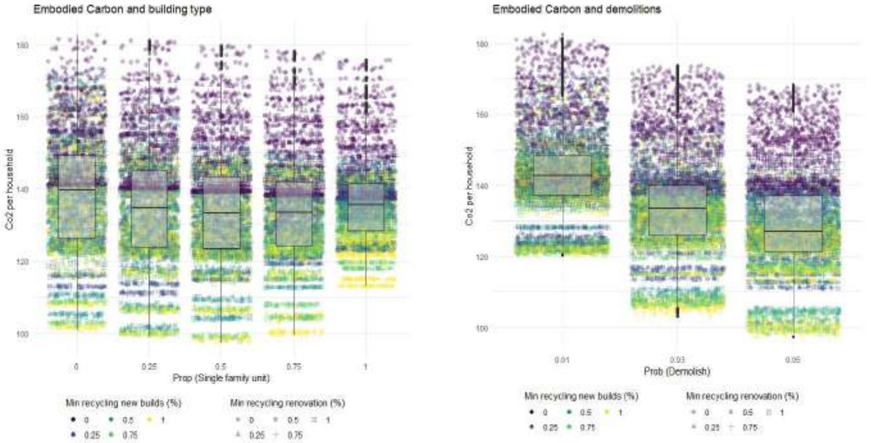
For more detailed information about the outcome of the simulations, more detail is provided in Table 3 in Appendix. This table, divided into three parts, shows the percentage difference across the maximum output of embodied carbon across all scenarios. In the tables, a 0%.

As a result of the stochasticity of the model, there is a resulting variation in the number of households and population in the year 2100. It can be appreciated that the total households range between 84,442 and 174,545, and therefore, the KPI used to analyse the results is the embodied carbon per household. Panel(a) shows that as the number of households increases, the CO2e per household decreases.



(a) Embodied carbon per household and amount of households

(b) Embodied carbon per household and probability of renovations



(c) Embodied carbon per household and proportion of single-family buildings

(d) Embodied carbon per household and probability of demolition

Figure 7 Simulation results for selected variables. Total households, renovations, demolitions, and Single-family buildings.

To study the influence of renovations over the embodied carbon of the city of Gothenburg, the parameters associated with the probability of renovations were set to 0%, 25%, 50%, 75% and 100%. Panel (b) presents the results of all the simulations, but the focus of the plot is set to extract insights about the proportion of renovated buildings. As expected, as more buildings are renovated, more embodied carbon will be present in the buildings because more materials will be needed to update the housing stock; however, after the probability of renovations is set to 50%, the amount of Co2e remains approximately around 140 Co2e per households in the model. Moreover, it is possible to observe how this parameter interacts with the maximum ratio of materials to circulate for new constructions and renovations. Naturally, in scenarios where there is less recycling of construction materials, the level of Co2e is higher.

Panel (c) presents the relationship of embodied carbon and the proportion of single-family buildings ranging from 0% to 100%. The scatter plot suggests no relationship between the embodied carbon per household and the building typology. And if there is a relationship, it is not linear (on average).

Finally, Panel (d) shows that as the parameter of the probability of demolitions increased from 1% to 5%, the resulting amount of embodied carbon per household decreased. Although this result could motivate the thesis that argues in favour of increasing demolition rates, Table 3 in the Appendix indicates that an average of 5% of demolition generates the most significant amount of total embodied carbon, the maximum of all simulations in the scenario, with no reuse of material for either renovation or new constructions. The proportion of single-family buildings was 0%, and the probability of renovation was 0%.

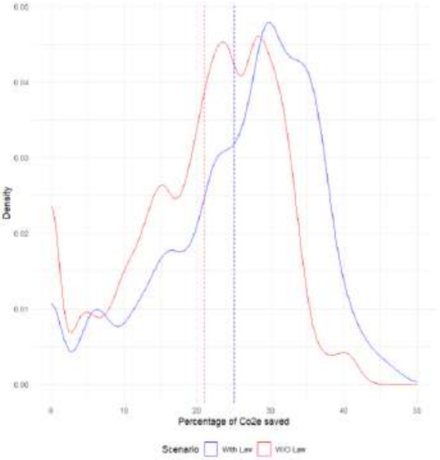
4.4. Evaluation of scenarios

As before, the results of the scenario under the new regulation are presented in the Table 3. The table shows the percentage change in embodied carbon under the scenario with the EPD regulation. Similar relationships were found in the case of adopting a minimal EPD for buildings, so for the economy of the paper, these were left out of the current article.

Figure 8 This paper presents the distribution of the savings in terms of CO2e for the scenario with and without regulation, together with a regression analysis to study the contribution of each parameter in the model. First, the analysis of the distribution of the savings shows that the scenarios with a law aimed at upgrading the building stock generate more significant savings, increasing on average from 21.1 to 25.9. This mean difference in the savings of the scenarios is statistically significant with a p-value of 0.000.

Finally, to determine the relevance of each parameter and identify the role of such a policy in CO2e savings, Table 1 it presents the output of a regression model. The regression models include all simulation results for the year 2100. Scenario I was estimated without the new regulation to force housing upgrades, and in Scenario II, the law's parameter was present, equal to 1 when the law was active and 0 in the other case. The results from the simulation show that 60% and 72% of the total variability was explained by the model, indicating a relatively good fit.

Overall, both models present similar results with minor differences. The percentage of reused material for new constructions and renovations is the most critical parameter that determines the rate of CO2e savings.



	W/o Law	W Law	t-value	p-value
Mean	21.1	25.9	-37.28	0.000
SD	9.8	10.4		

Figure 8 shows the Distribution of CO2e savings for the simulations with and without regulation and the regression model output to estimate the percentage of CO2e savings.

Dependent variable: Co2e savings as a percentage		
	Scenario I	**Scenario II**
(Intercept)	3.32**	15.97***
	-1.14	-2.94
Demolitions (1,000)	12.25***	11.62***
	-0.62	-1.23
Renovations (1,000)	2.50***	1.33*
	-0.04	-0.66
Multi-family buildings (%)	-0.01***	-0.03***
	0.00	0.00
Households (10,000)	-1.47***	-2.19***
	-0.17	-0.19
Material reuse - New Building (%)	17.28***	16.77***
	-0.13	-0.16
Material reuse - Renovation (%)	8.57***	17.53***
	-0.13	-0.16
Adj. R^2	0.6	0.72
Num. obs.	18,750	9,375

Table 1 Regression analysis results with dependent variable Co2e savings from buildings considering A1-A3.

4.5. Contributions

The simulation assessed what would happen if the municipality places a regulation after 2045; the buildings should comply with a minimum energy performance declaration. More specifically, buildings with an EPC of G would only be accepted to avoid the stochastic renovation process. Otherwise, they will be demolished. Two simulation batches were run using the same set of parameters. The results are presented in detail in the appended tables, as well as the differences between the scenarios of not enforcing such a law and another with the law in place. Besides looking at these tables in detail, the following table of plots is used to see the evolution of the main variables of the models over the simulated time; this summary is presented in Figure 9. In both cases, the plots present the averaged result of various simulations run for a probability of demolition of 1%, a proportion of single housing units of 25%, and a probability of renovation of 25%, with new construction and renovation projects trying to reuse up to 25% of the materials.

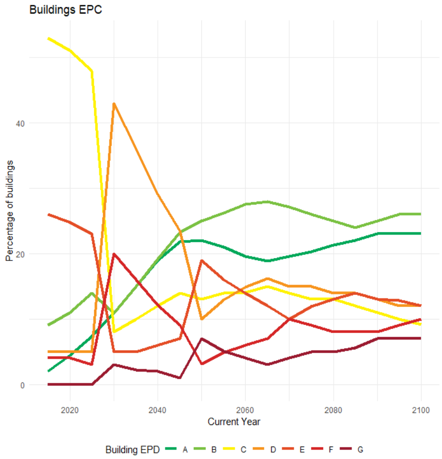
As expected, the first thing to notice in the evolution of the building stock EPD, we can see in panel a, that without a law by the end of the period, in the year 2100, almost 10% of the building stock will have an EPC of G and 25% A. However, if the law is enforced, in panel b, we can see that no buildings will have an EPC of G, and as a result of new construction and more renovations, 60% of the buildings will have an EPC of A or B and no building will be of category G.

The following row of plots (c and d) shows how the number of demolitions, renovations and new constructions evolved over simulated time. Because of the law, it can be noted that there is an increase in the total number of demolitions and that, as a result, more new buildings are being constructed. Moreover, regarding renovations, the total amount is around 45 thousand in both cases, but in the scenario with the EPD law, these renovations are anticipated on time. By 2045, the scenario with no regulations had 35 house renovations, but if a law prevents buildings labelled as G in the EPC, the number of renovations will reach almost 40 thousand.

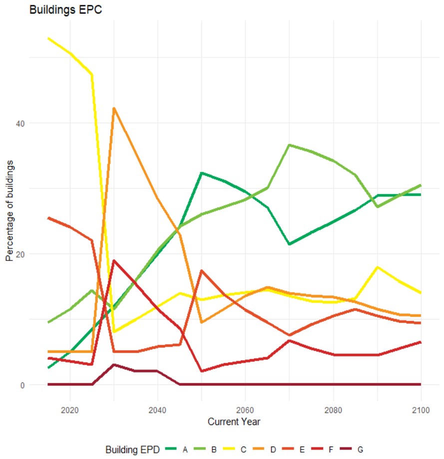
Because more buildings are renovated in this scenario and will require bricks, the demand for bricks in the regulated scenario shows a higher demand for bricks. Also, in terms of the total material demands, since there will be more demolitions, the total amount of materials is more significant. These two situations result in a greater overall Co2e under this scenario.

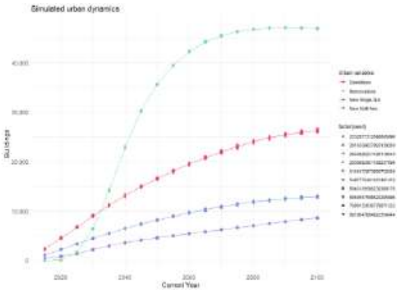
Since the boundaries delimited in this study do not account for the environmental impacts of the use phase, it is clear that the increase in ecological footprint needs to be compensated by the savings in energy by upgrading the building stock.

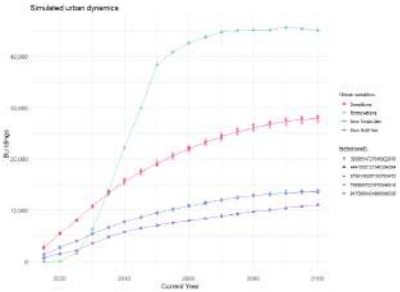
Scenario with no EPD restrictions



Scenario with EPD restrictions







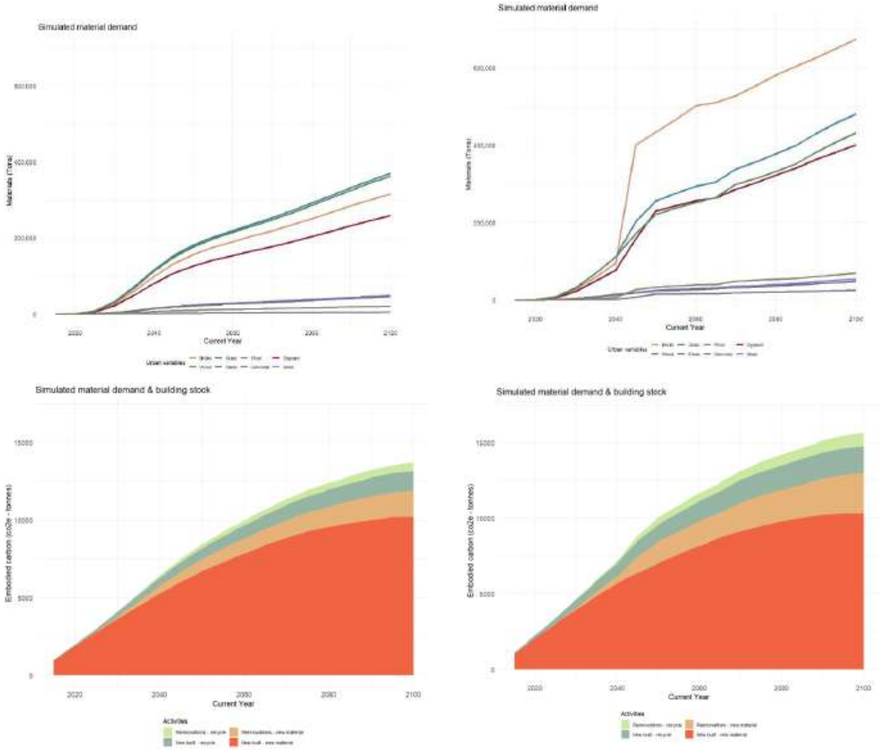


Figure 9 shows the Temporal dynamics of the simulations for scenarios with and without law. The panels show the evolution of the distribution of buildings' energy performance and the number of renovations, new constructions, and demolitions. They also present the material demand and the embodied carbon in each scenario.

Last, the simulation offers the possibility of exporting geographic information generated by the model for analysis. The following figure shows the total status of the demolished buildings. Using a heatmap, as shown in Figure 10 It was possible to determine areas of the city that would need demolition. Although, and to some extent, this map will overlap with a map showing the concentration of old buildings, this information is more prosperous because it has been generated bottom-up and will result from the agents (buildings).

Also, it is interesting to notice that Gothenburg is an archipelago, and construction and demolition activities will continue to occur in these territories, meaning a need to bring logistics solutions to the communities living on the islands.

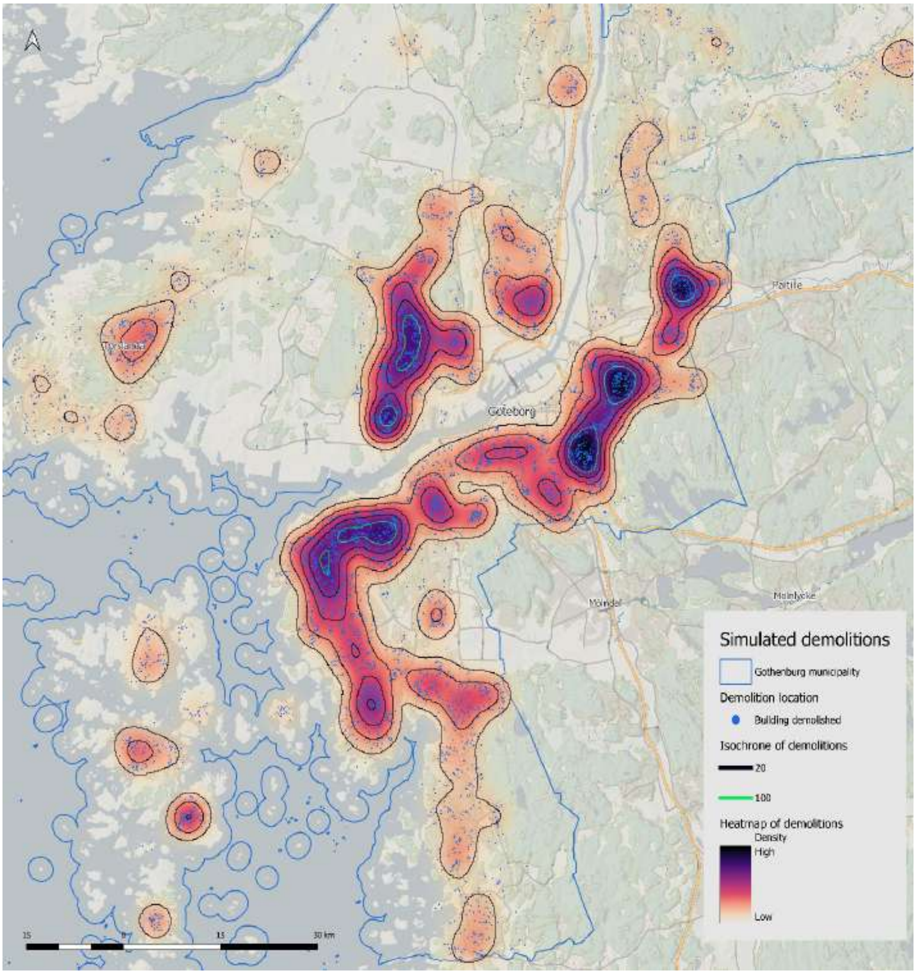


Figure 10 Map of potential demolitions based on simulations

4.6. Limitations

The consideration of only two building typologies for future construction poses a limitation. These typologies were based on statistical analysis derived from past constructions, raising concerns about their applicability in the near or distant future. This study's new buildings and future renovations do not consider radical changes in new materials. To some extent, they evaluate how “doing business as usual” can play out. The model can be improved by changing the material needs of the new buildings and the materials used for renovations. Changing these building characteristics will impact the total CO2 generated by the housing stock in the city.

The adoption of a probabilistic approach to demolitions, renovations, and future constructions introduces an element of uncertainty. Resolving this uncertainty requires acquiring more detailed information, highlighting the necessity for comprehensive data.

Contemplating the city's long-term perspective in the year 2100 unveils potential transformations, particularly concerning climate change and rising water levels. This holds significant relevance for cities like Gothenburg, divided by the Gota River, where environmental shifts may have pronounced impacts.

Due to data limitations, the analysis exclusively considers residential buildings. Assumptions were employed to determine the Environmental Performance Declarations (EPD) and the use of 8 materials. Additionally, the estimation of CO2e relies on products found in the Boverket climate database, potentially oversimplifying the richness of materials and components in each building.

A notable limitation stems from treating the entire building as a unit rather than analysing it at the component level. This approach, focusing only on materials, leads to rough estimates. Working at the component level allows for detailed maintenance tracking, a feature the model does not offer.

The model's initial conditions assume no materials are recycled until renovations or demolitions occur, resulting in environmental degradation. Addressing this non-realistic assumption requires exploring different starting conditions based on objective information to provide more accurate scenarios.

The analysis is constrained to the municipality of Gothenburg due to limitations in data and data silos. This limitation, driven by data availability rather than methodological scope, overlooks the interconnected nature of neighbouring municipalities such as Mondal or Partille. This underscores the importance of addressing environmental goals at a metropolitan or regional scale, acknowledging the need to share infrastructure and resources across administrative boundaries for more effective environmental management.

4.7. Future steps

Enhancing data integration involves establishing a direct link between material flows and Sankey diagrams. A meticulous exploration of more accurate and comprehensive datasets is imperative to alleviate uncertainties in the analysis. Stakeholder engagement emerges as a crucial avenue for refining model parameters, including renovation probability, demolition rates, and environmental costs associated with recycling materials. Collaboration with urban planning experts is pivotal for crafting a robust decision support tool.

Integrating agency into development processes within the model is a crucial consideration. This involves evaluating different diffusion mechanisms that influence business in the construction and demolition sector. Exploration of diverse demolition and construction strategies, emphasising their environmental impacts, will be pivotal. The model should evolve to incorporate behavioural aspects, reflecting changes in the sector's performance concerning ecological challenges.

The adaptability of building typologies to evolving technologies and materials warrants exploration. This includes investigating material substitution practices, such as addressing the surplus of bricks to mitigate embodied carbon, in alignment with emerging construction trends, such as wood.

Moreover, the shift towards a component-level analysis offers a nuanced perspective on the life cycle of individual building components. This departure from viewing buildings as holistic entities ensures a more granular understanding of environmental impacts. Incorporating spatial rules into the model is essential to enhance agent interactions, with specific consideration given to location-based regulations that align with population densification strategies. Lastly, the model's evolution should encompass a broader range of building types and technologies, offering a more comprehensive assessment of environmental performance based on Energy Performance Declarations. Different building typologies or assumptions regarding the material need of renovations can be implemented with ease, and future studies should evaluate the impact of more radical changes that will affect the city's footprint.

It is worth noting that some of the results presented here depend on the metric used. For example, three KPIs were used to show results: the total amount of embodied carbon per household and the percentage saved in terms of embodied carbon. It is important to discuss further what is desired to pursue in terms of sustainable cities because there can be scenarios that present a high level of savings (as percentages) but are higher in absolute value.

Finally, the current model's computational intensity and limited material inclusion underscore the need for a more efficient approach. Transitioning to a graph-based model, utilising nodes and edges, presents an opportunity for accelerated simulations. This refined model can accommodate additional materials, transport dynamics, and agency factors, fostering a closer integration with the road network and logistics planning.

5. Conclusion

The rule-based simulation developed for this study supports urban planners by providing a virtual laboratory to explore potential implications of urban policies related to demolitions, renovations, material reuse, and building typologies. The model was extended to incorporate Energy Performance Declarations in response to anticipated policies becoming active soon in Gothenburg, Sweden, and the rest of Europe.

The simulation developed for this study was never intended to predict the future city, a task that might prove challenging if not impossible. Instead, it serves as a tool for dialogue and exploration of how the city might evolve under various scenarios.

The rules incorporated are simple and adjustable, allowing for flexibility in the model. The model has proven its capability to generate alternatives, exploring how CO2e emissions can be reduced. Among the scenarios enabled by this model are variations in the percentage of demolitions, renovations, building typologies, and the impact of an energy performance declaration law stating that specific buildings cannot be constructed in the city.

From the modelling perspective, the simulation treats each building with agency. Although this idea can be challenged by arguing that the future city rises from the interaction between developers, real estate agents, and public administrators who manage construction and demolition projects, the model presented here provides a general overview of the potential outcomes of different scenarios.

The model serves as a proof of concept, showcasing opportunities and challenges ahead for the construction and demolition sector in addressing future environmental goals. It provides valuable insights into the potential trajectories of the urban landscape and offers a platform for informed decision-making in urban planning.

6. References

Andersen, R., & Negendahl, K. (2023). Lifespan prediction of existing building typologies. *Journal of Building Engineering*, *65*, 105696. https://doi.org/10.1016/j.jobe.2022.105696

Development Strategy Göteborg 2035. (2014). City of Gothenburg.

Environment and Climate Programme for the City of Gothenburg 2021–2030. (n.d.).

Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., & Österbring, M. (2018). Material-intensity database of residential buildings: A case study of Sweden in the international context. *Resources, Conservation and Recycling*, *130*(November 2017), 228–239. https://doi.org/10.1016/j.resconrec.2017.11.022

Gontia, P., Thuvander, L., Ebrahimi, B., Vinas, V., Rosado, L., & Wallbaum, H. (2019). Spatial analysis of urban material stock with clustering algorithms: A Northern European case study. *Journal of Industrial Ecology*, 1–16. https://doi.org/10.1111/jiec.12939

Gontia, P., Thuvander, L., & Wallbaum, H. (2020). Spatiotemporal characteristics of residential material stocks and flows in urban, commuter, and rural settlements. *Journal of Cleaner Production*, *251*, 119435. https://doi.org/10.1016/j.jclepro.2019.119435

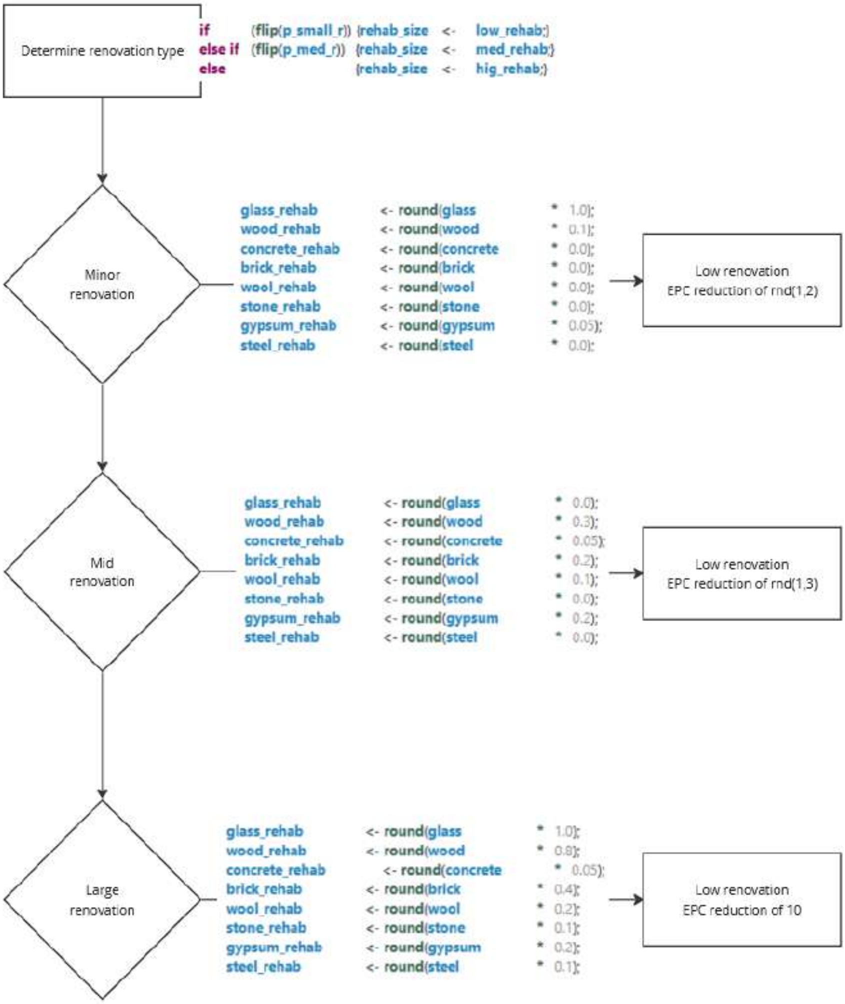
Ministry of Infrastructure. (n.d.). *Sweden's Third National Strategy for Energy Efficient Renovation* [Report].

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modelling for a complex world* (International student edition). Irwin, McGraw-Hill.

Appendix

EPD	Brick	Concrete	Wood	Total	Relative
A	0	7	0	**7**	**0%**
B	0	450	3681	**4131**	**7%**
C	0	0	31334	**31334**	**56%**
D	0	3061	0	**3061**	**5%**
E	0	720	14623	**15343**	**27%**
F	2221	0	0	**2221**	**4%**
G	0	0	148	**148**	**0%**
Total	**2221**	**4238**	**49786**	**56245**	**100%**
Relative	**4%**	**8%**	**89%**	**100%**	

Table 2 The resulting distribution of EPD is based on building materials.



```
if       (flip(p_small_r)) {rehab_size  <-   low_rehab;}
else if  (flip(p_med_r))   {rehab_size  <-   med_rehab;}
else                       {rehab_size  <-   hig_rehab;}
```

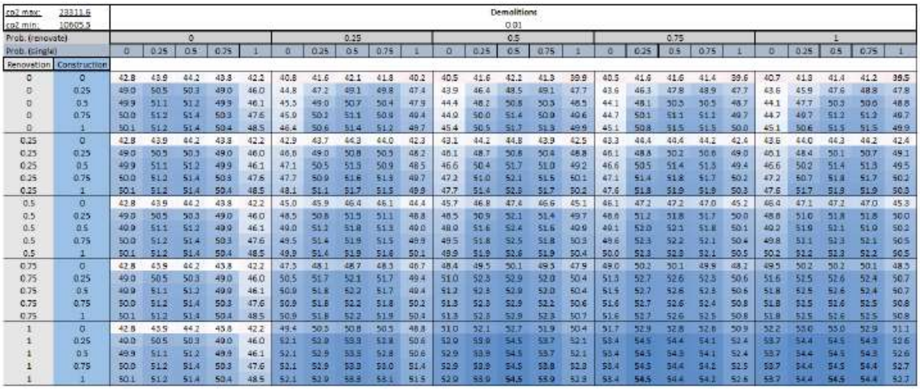
```
glass_rehab        <- round(glass          *  1.0);
wood_rehab         <- round(wood           *  0.1);
concrete_rehab     <- round(concrete       *  0.0);
brick_rehab        <- round(brick          *  0.0);
wool_rehab         <- round(wool           *  0.0);
stone_rehab        <- round(stone          *  0.0);
gypsum_rehab       <- round(gypsum         *  0.05);
steel_rehab        <- round(steel          *  0.0);
```

```
glass_rehab        <- round(glass          *  0.0);
wood_rehab         <- round(wood           *  0.3);
concrete_rehab     <- round(concrete       *  0.05);
brick_rehab        <- round(brick          *  0.2);
wool_rehab         <- round(wool           *  0.1);
stone_rehab        <- round(stone          *  0.0);
gypsum_rehab       <- round(gypsum         *  0.2);
steel_rehab        <- round(steel          *  0.0);
```

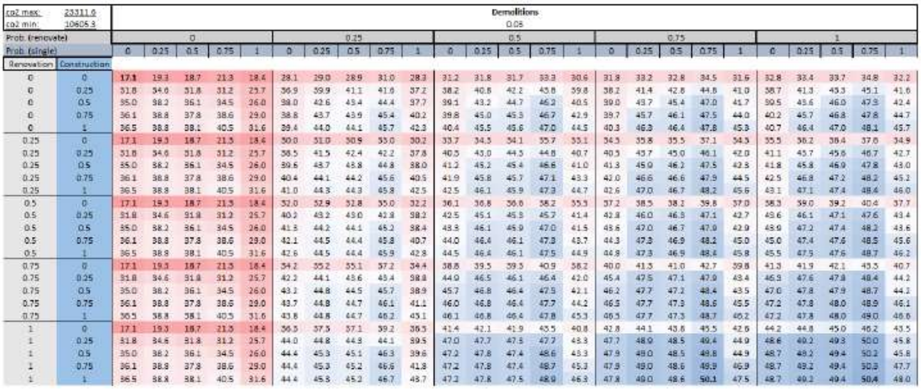
```
glass_rehab        <- round(glass          *  1.0);
wood_rehab         <- round(wood           *  0.8);
concrete_rehab       <- round(concrete       *  0.05);
brick_rehab        <- round(brick          *  0.4);
wool_rehab         <- round(wool           *  0.2);
stone_rehab        <- round(stone          *  0.1);
gypsum_rehab       <- round(gypsum         *  0.2);
steel_rehab        <- round(steel          *  0.1);
```

Figure 11 Renovation strategy flow diagram

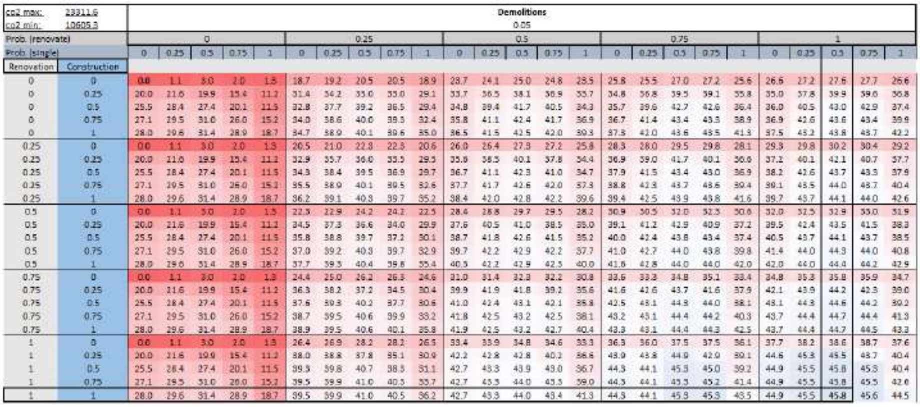
No Law



co2 max: 23311.6 co2 min: 10605.5		Demolitions 0.01																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	42.8	43.9	44.2	43.8	42.2	40.8	41.6	42.1	41.8	40.2	40.5	41.6	42.2	41.3	39.9	40.5	41.6	41.6	41.4	39.6	40.7	41.3	41.4	41.2	39.5
0	0.25	49.0	50.5	50.3	49.0	46.0	44.8	47.2	49.1	49.8	47.4	43.9	46.4	48.5	49.1	47.7	43.6	46.3	47.8	48.9	47.7	43.6	45.9	47.6	48.8	47.8
0	0.5	49.9	51.1	51.2	49.9	46.1	45.3	49.0	50.7	50.4	47.9	44.4	48.2	50.8	50.3	48.5	44.1	48.1	50.3	50.5	48.7	44.1	47.7	50.3	50.6	48.8
0	0.75	50.0	51.2	51.4	50.3	47.6	45.9	50.1	51.1	50.9	49.4	44.9	50.0	51.4	50.9	49.6	44.7	50.1	51.1	51.1	49.7	44.7	49.7	51.2	51.2	49.7
0	1	50.1	51.2	51.4	50.4	48.5	46.4	50.6	51.4	51.2	49.7	45.4	50.5	51.7	51.3	49.9	45.1	50.8	51.5	51.5	50.0	45.1	50.6	51.5	51.5	49.9
0.25	0	42.8	43.9	44.2	43.8	42.2	42.9	43.7	44.3	44.0	42.3	43.1	44.2	44.8	43.9	42.5	43.3	44.4	44.4	44.2	42.4	43.6	44.0	44.3	44.2	42.4
0.25	0.25	49.0	50.5	50.3	49.0	46.0	46.6	49.0	50.8	50.5	48.2	46.1	48.7	50.6	50.4	48.8	46.1	48.8	50.2	50.6	49.0	46.1	48.4	50.1	50.7	49.1
0.25	0.5	49.9	51.1	51.2	49.9	46.1	47.1	50.5	51.5	50.9	48.5	46.6	50.4	51.7	51.0	49.2	46.6	50.5	51.4	51.3	49.4	46.6	50.2	51.4	51.3	49.5
0.25	0.75	50.0	51.2	51.4	50.3	47.6	47.7	50.9	51.6	51.3	49.7	47.2	51.0	52.1	51.5	50.1	47.1	51.4	51.8	51.7	50.2	47.2	50.7	51.8	51.7	50.2
0.25	1	50.1	51.2	51.4	50.4	48.5	48.1	51.1	51.7	51.5	49.9	47.7	51.4	52.3	51.7	50.2	47.6	51.8	51.9	51.9	50.3	47.6	51.7	51.9	51.9	50.3
0.5	0	42.8	43.9	44.2	43.8	42.2	45.0	45.9	46.4	46.1	44.4	45.7	46.8	47.4	46.6	45.1	46.1	47.2	47.2	47.0	45.2	46.4	47.1	47.2	47.0	45.3
0.5	0.25	49.0	50.5	50.3	49.0	46.0	48.5	50.8	51.5	51.1	48.8	48.5	50.9	52.1	51.4	49.7	48.6	51.2	51.8	51.7	50.0	48.8	51.0	51.8	51.8	50.0
0.5	0.5	49.9	51.1	51.2	49.9	46.1	49.0	51.3	51.8	51.3	49.0	48.9	51.6	52.4	51.6	49.9	49.1	52.0	52.1	51.8	50.1	49.2	51.9	52.1	51.9	50.2
0.5	0.75	50.0	51.2	51.4	50.3	47.6	49.5	51.4	51.9	51.5	49.9	49.5	51.8	52.5	51.8	50.3	49.6	52.3	52.2	52.1	50.4	49.8	51.1	52.3	52.1	50.5
0.5	1	50.1	51.2	51.4	50.4	48.5	49.9	51.4	51.9	51.6	50.1	49.9	51.9	52.6	51.9	50.4	50.0	52.3	52.3	52.1	50.5	50.2	52.2	52.3	52.2	50.5
0.75	0	42.8	43.9	44.2	43.8	42.2	47.3	48.1	48.7	48.3	46.7	48.4	49.5	50.1	49.5	47.9	49.0	50.2	50.1	49.9	48.1	49.5	50.2	50.2	50.1	48.5
0.75	0.25	49.0	50.5	50.3	49.0	46.0	50.5	51.7	52.1	51.7	49.4	51.0	52.3	52.9	52.0	50.4	51.3	52.7	52.6	52.3	50.6	51.6	52.5	52.6	52.4	50.7
0.75	0.5	49.9	51.1	51.2	49.9	46.1	50.9	51.8	52.2	51.7	49.4	51.2	52.3	52.9	52.0	50.4	51.5	52.7	52.6	52.3	50.6	51.8	52.5	52.6	52.4	50.7
0.75	0.75	50.0	51.2	51.4	50.3	47.6	50.9	51.8	52.2	51.8	50.2	51.3	52.3	52.9	52.2	50.6	51.6	52.7	52.6	52.4	50.8	51.8	52.5	52.6	52.5	50.8
0.75	1	50.1	51.2	51.4	50.4	48.5	50.9	51.8	52.2	51.9	50.4	51.3	52.3	52.9	52.3	50.7	51.6	52.7	52.6	52.5	50.8	51.8	52.5	52.6	52.5	50.8
1	0	42.8	43.9	44.2	43.8	42.2	49.4	50.3	50.8	50.3	48.8	51.0	52.1	52.7	51.9	50.4	51.7	52.9	52.8	52.8	50.9	52.2	53.0	53.0	52.9	51.1
1	0.25	49.0	50.5	50.3	49.0	46.0	52.1	52.9	53.9	52.8	50.6	52.9	53.9	54.5	53.7	52.1	53.4	54.5	54.4	54.1	52.4	53.7	54.4	54.5	54.3	52.6
1	0.5	49.9	51.1	51.2	49.9	46.1	52.1	52.9	53.5	52.8	50.6	52.9	53.9	54.5	53.7	52.1	53.4	54.5	54.3	54.1	52.4	53.7	54.4	54.5	54.3	52.6
1	0.75	50.0	51.2	51.4	50.3	47.6	52.1	52.9	53.3	53.0	51.4	52.9	53.9	54.5	53.8	52.3	53.4	54.5	54.4	54.2	52.5	53.7	54.4	54.5	54.4	52.7
1	1	50.1	51.2	51.4	50.4	48.5	52.1	52.9	53.3	53.1	51.5	52.9	53.9	54.5	53.9	52.3	53.4	54.5	54.4	54.1	52.6	53.7	54.4	54.5	54.4	52.7



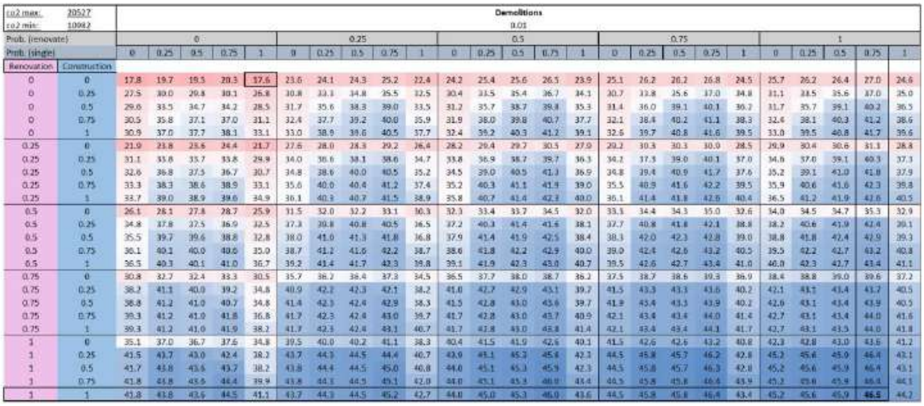
co2 max: 23311.6 co2 min: 10605.3		Demolitions 0.03																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	17.1	19.3	18.7	21.3	18.4	28.1	29.0	28.9	31.0	28.3	31.2	31.8	31.7	33.3	30.6	31.8	33.2	32.8	34.5	31.6	32.8	33.4	33.7	34.8	32.2
0	0.25	31.8	34.6	31.8	31.2	25.7	36.9	39.9	41.1	41.6	37.2	38.2	40.8	42.2	43.8	39.8	38.2	41.4	42.8	44.8	41.0	38.7	41.3	43.3	45.1	41.6
0	0.5	35.0	38.2	36.1	34.5	26.0	38.0	42.6	43.4	44.4	37.7	39.1	43.2	44.7	46.2	40.5	39.0	43.7	45.4	47.0	41.7	39.5	43.6	46.0	47.3	42.4
0	0.75	36.1	38.8	37.8	38.6	29.0	38.8	43.7	43.9	45.4	40.2	39.8	45.0	45.3	46.7	42.9	39.7	45.7	46.1	47.5	44.0	40.2	45.7	46.8	47.8	44.7
0	1	36.5	38.8	38.1	40.5	31.6	39.4	44.0	44.1	45.7	42.3	40.4	45.5	45.6	47.0	44.5	40.3	46.3	46.4	47.8	45.3	40.7	46.4	47.0	48.1	45.7
0.25	0	17.1	19.3	18.7	21.3	18.4	30.0	31.0	30.9	33.0	30.2	33.7	34.3	34.1	35.7	33.1	34.5	35.8	35.5	37.1	34.5	35.5	36.2	36.4	37.6	34.9
0.25	0.25	31.8	34.6	31.8	31.2	25.7	38.5	41.5	42.4	42.2	37.8	40.5	43.0	44.5	44.8	40.7	40.5	45.7	45.0	46.1	42.0	41.1	45.7	45.6	46.7	42.7
0.25	0.5	35.0	38.2	36.1	34.5	26.0	39.6	43.7	43.8	44.8	38.0	41.2	45.2	45.4	46.6	41.0	41.3	45.9	46.2	47.5	42.3	41.8	45.8	46.9	47.8	43.0
0.25	0.75	36.1	38.8	37.8	38.6	29.0	40.4	44.1	44.2	45.6	40.5	41.9	45.8	45.7	47.1	43.3	42.0	46.6	46.6	47.9	44.5	42.5	46.8	47.2	48.2	45.2
0.25	1	36.5	38.8	38.1	40.5	31.6	41.0	44.3	44.3	45.8	42.5	42.5	46.1	45.9	47.3	44.7	42.6	47.0	46.7	48.2	45.6	43.1	47.1	47.4	48.4	46.0
0.5	0	17.1	19.3	18.7	21.3	18.4	32.0	32.9	32.8	35.0	32.2	36.1	36.8	36.6	38.2	35.3	37.2	38.5	38.2	39.8	37.0	38.3	39.0	39.2	40.4	37.7
0.5	0.25	31.8	34.6	31.8	31.2	25.7	40.2	43.2	43.0	42.8	38.2	42.5	45.1	45.3	45.7	41.4	42.8	46.0	46.3	47.1	42.7	43.6	46.1	47.1	47.6	43.4
0.5	0.5	35.0	38.2	36.1	34.5	26.0	41.3	44.2	44.1	45.2	38.4	43.3	46.1	45.9	47.0	41.5	43.6	47.0	46.7	47.9	42.9	43.9	47.2	47.4	48.2	43.6
0.5	0.75	36.1	38.8	37.8	38.6	29.0	42.1	44.5	44.4	45.8	40.7	44.0	46.4	46.1	47.3	43.7	44.3	47.3	46.9	48.2	45.0	45.0	47.4	47.6	48.5	45.6
0.5	1	36.5	38.8	38.1	40.5	31.6	42.6	44.5	44.4	45.9	42.8	44.5	46.4	46.1	47.5	44.9	44.8	47.3	46.9	48.4	45.8	45.5	47.5	47.6	48.7	46.2
0.75	0	17.1	19.3	18.7	21.3	18.4	34.2	35.2	35.1	37.2	34.4	38.8	39.5	39.3	40.9	38.2	40.0	41.3	41.0	42.7	39.8	41.3	41.9	42.1	43.3	40.7
0.75	0.25	31.8	34.6	31.8	31.2	25.7	42.2	44.1	43.6	45.4	38.8	44.9	46.5	46.1	46.4	42.0	45.4	47.5	47.1	47.9	43.4	46.9	47.6	47.8	48.4	44.2
0.75	0.5	35.0	38.2	36.1	34.5	26.0	43.1	44.8	44.5	45.7	38.9	45.7	46.8	46.4	47.5	41.1	46.2	47.7	47.2	48.4	43.5	47.0	47.8	47.9	48.7	44.1
0.75	0.75	36.1	38.8	37.8	38.6	29.0	43.7	44.8	44.7	46.1	41.1	46.0	46.8	46.4	47.7	44.2	46.5	47.7	47.3	48.6	45.5	47.2	47.8	48.0	48.9	46.1
0.75	1	36.5	38.8	38.1	40.5	31.6	43.8	44.8	44.7	46.2	43.1	46.1	46.8	46.4	47.8	45.3	46.5	47.7	47.3	48.7	46.2	47.2	47.8	48.0	49.0	46.6
1	0	17.1	19.3	18.7	21.3	18.4	36.5	37.5	37.1	39.2	36.5	41.4	42.1	41.9	43.5	40.8	42.8	44.1	43.8	45.5	42.6	44.2	44.8	45.0	46.2	43.5
1	0.25	31.8	34.6	31.8	31.2	25.7	44.0	44.8	44.9	44.1	39.5	47.0	47.7	47.5	47.7	43.3	47.7	48.9	48.5	49.4	44.9	48.6	49.2	49.3	50.0	45.8
1	0.5	35.0	38.2	36.1	34.5	26.0	44.4	45.3	45.1	46.3	39.6	47.2	47.8	47.4	48.6	43.3	47.9	49.0	48.5	49.8	44.9	48.7	49.2	49.4	50.2	45.8
1	0.75	36.1	38.8	37.8	38.6	29.0	44.4	45.3	45.2	46.6	41.8	47.2	47.8	47.4	48.7	45.3	47.9	49.0	48.6	49.9	46.9	48.7	49.2	49.4	50.3	47.7
1	1	36.5	38.8	38.1	40.5	31.6	44.4	45.3	45.2	46.7	43.7	47.2	47.8	47.5	48.9	46.3	47.8	49.0	48.6	50.1	47.5	48.7	49.2	49.4	50.4	48.0



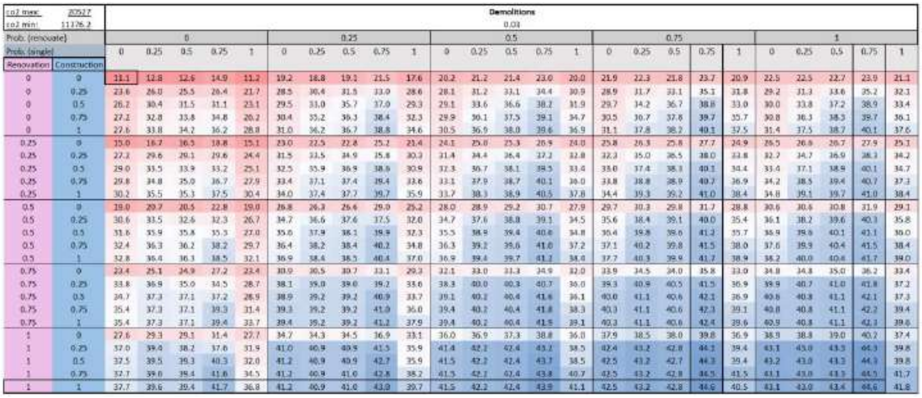
co2 max: 23311.6 co2 min: 10605.3		Demolitions 0.05																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	0.0	1.1	3.0	2.0	1.3	18.7	19.2	20.5	20.5	18.9	23.7	24.1	25.0	24.8	23.5	25.8	25.5	27.0	27.2	25.6	26.6	27.2	27.6	27.7	26.6
0	0.25	20.0	21.6	19.9	15.4	11.2	31.4	34.2	35.0	35.0	29.1	33.7	36.5	38.1	36.9	33.7	34.8	36.8	39.5	39.1	35.8	35.0	37.8	39.9	39.6	36.8
0	0.5	25.5	28.4	27.4	20.1	11.5	32.8	37.7	39.2	36.5	29.4	34.8	39.4	41.7	40.5	34.3	35.7	39.6	42.7	42.6	36.4	36.0	40.5	43.0	42.9	37.4
0	0.75	27.1	29.5	31.0	26.0	15.2	34.0	38.6	40.0	39.3	32.4	35.8	41.1	42.4	41.7	36.9	36.7	41.4	43.4	43.3	38.9	36.9	42.6	43.6	43.4	39.9
0	1	28.0	29.6	31.4	28.9	18.7	34.7	38.9	40.1	39.6	35.0	36.5	41.5	42.5	42.0	39.3	37.3	41.0	43.6	43.5	41.3	37.5	43.2	43.8	43.7	42.2
0.25	0	0.0	1.1	3.0	2.0	1.3	20.5	21.0	22.8	22.8	20.6	26.0	26.4	27.3	27.2	25.8	28.3	28.0	29.5	29.8	28.1	29.3	29.8	30.2	30.4	29.2
0.25	0.25	20.0	21.6	19.9	15.4	11.2	32.9	35.7	36.0	35.5	29.5	35.8	38.5	40.1	37.8	34.4	36.9	39.0	41.7	40.1	36.6	37.2	40.1	42.1	40.7	37.7
0.25	0.5	25.5	28.4	27.4	20.1	11.5	34.3	38.4	39.5	36.9	29.7	36.7	41.1	42.3	41.0	34.7	37.9	41.5	43.4	43.0	36.9	38.2	41.6	43.7	43.3	37.9
0.25	0.75	27.1	29.5	31.0	26.0	15.2	35.5	38.9	40.1	39.5	32.6	37.7	41.7	42.6	42.0	37.3	38.8	42.3	43.7	43.6	39.4	39.1	43.5	44.0	43.7	40.4
0.25	1	28.0	29.6	31.4	28.9	18.7	36.2	39.1	40.3	39.7	35.2	38.4	42.0	42.8	42.2	39.6	39.4	42.5	43.9	43.8	41.6	39.7	43.7	44.1	44.0	42.6
0.5	0	0.0	1.1	3.0	2.0	1.3	22.3	22.9	24.2	24.2	22.5	28.4	28.8	29.7	29.5	28.2	30.9	30.5	32.0	32.3	30.6	32.0	32.5	32.9	33.0	31.9
0.5	0.25	20.0	21.6	19.9	15.4	11.2	34.5	37.3	36.6	34.0	29.9	37.6	40.5	41.0	38.5	35.0	39.1	41.2	42.9	40.9	37.2	39.5	42.4	43.5	41.5	38.3
0.5	0.5	25.5	28.4	27.4	20.1	11.5	35.8	38.8	39.7	37.2	30.1	38.7	41.8	42.6	41.5	35.2	40.0	42.4	43.8	43.4	37.4	40.5	43.7	44.1	43.7	38.5
0.5	0.75	27.1	29.5	31.0	26.0	15.2	37.0	39.2	40.3	39.7	32.9	39.7	42.2	42.9	42.2	37.7	41.0	42.7	44.0	43.8	39.8	41.4	44.0	44.3	44.0	40.8
0.5	1	28.0	29.6	31.4	28.9	18.7	37.7	39.3	40.4	39.8	35.4	40.3	42.2	42.9	42.3	40.0	41.6	42.8	44.0	44.0	42.0	42.0	44.0	44.4	44.2	42.9
0.75	0	0.0	1.1	3.0	2.0	1.3	24.4	25.0	26.2	26.3	24.6	31.0	31.4	32.3	32.2	30.8	33.6	33.3	34.8	35.1	33.4	34.8	35.3	35.8	35.9	34.7
0.75	0.25	20.0	21.6	19.9	15.4	11.2	36.3	38.2	37.2	34.5	30.4	39.9	41.9	41.8	39.2	35.6	41.6	41.6	43.7	41.6	37.9	42.1	43.9	44.2	42.3	39.0
0.75	0.5	25.5	28.4	27.4	20.1	11.5	37.6	39.3	40.2	37.7	30.6	41.0	42.4	43.1	42.1	35.8	42.5	43.1	44.3	44.0	38.1	43.1	44.3	44.6	44.2	39.2
0.75	0.75	27.1	29.5	31.0	26.0	15.2	38.7	39.5	40.6	39.9	33.2	41.8	42.5	43.2	42.5	38.1	43.2	43.1	44.4	44.2	40.3	43.7	44.4	44.7	44.4	41.3
0.75	1	28.0	29.6	31.4	28.9	18.7	38.9	39.5	40.6	40.1	35.8	41.9	42.5	43.2	42.7	40.4	43.3	43.1	44.4	44.3	42.5	43.7	44.4	44.7	44.5	43.3
1	0	0.0	1.1	3.0	2.0	1.3	26.4	26.9	28.2	28.2	26.5	33.4	33.9	34.8	34.6	33.1	36.3	36.0	37.5	37.5	36.1	37.7	38.2	38.6	38.7	37.6
1	0.25	20.0	21.6	19.9	15.4	11.2	38.0	38.8	37.8	35.1	30.9	42.2	42.8	42.8	40.2	36.6	43.9	43.8	44.9	42.9	39.1	44.6	45.3	45.5	43.7	40.4
1	0.5	25.5	28.4	27.4	20.1	11.5	39.3	39.8	40.7	38.5	31.1	42.7	43.3	43.9	43.0	36.7	44.3	44.1	45.3	45.0	39.2	44.9	45.5	45.8	45.3	40.4
1	0.75	27.1	29.5	31.0	26.0	15.2	39.5	39.9	41.0	40.5	35.7	42.7	43.3	44.0	43.3	39.0	44.3	44.1	45.3	45.2	41.4	44.9	45.5	45.8	45.5	42.6
1	1	28.0	29.6	31.4	28.9	18.7	39.5	39.9	41.0	40.5	36.2	42.7	43.3	44.0	43.4	41.3	44.3	44.1	45.3	45.3	43.5	44.9	45.5	45.8	45.6	44.5

Table 3 Comparison of simulations under different scenarios with no regulation

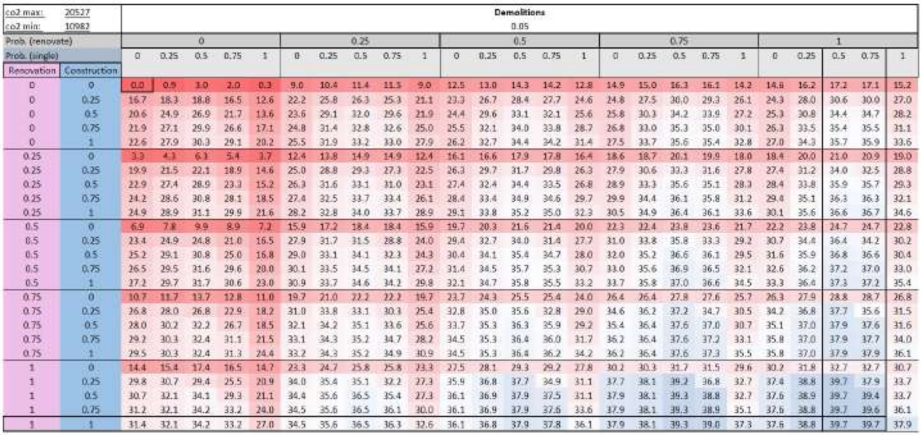
Law



co2 max: 20527 co2 min: 10982		Demolitions 0.01																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	17.8	19.7	19.5	20.3	17.6	23.6	24.1	24.3	25.2	22.4	24.2	25.4	25.6	26.5	23.9	25.1	26.2	26.2	26.8	24.5	25.7	26.2	26.4	27.0	24.6
0	0.25	27.5	30.0	29.8	30.1	26.8	30.8	33.1	34.8	35.5	32.5	30.4	33.5	35.4	36.7	34.1	30.7	33.8	35.6	37.0	34.8	31.1	33.5	35.6	37.0	35.0
0	0.5	29.6	33.5	34.7	34.2	28.5	31.7	35.6	38.3	39.0	33.5	31.2	35.7	38.7	39.8	35.3	31.4	36.0	39.1	40.1	36.2	31.7	35.7	39.1	40.2	36.5
0	0.75	30.5	35.8	37.1	37.0	31.1	32.4	37.7	39.2	40.0	35.9	31.9	38.0	39.8	40.7	37.7	32.1	38.4	40.2	41.1	38.3	32.4	38.1	40.3	41.2	38.6
0	1	30.9	37.0	37.7	38.1	33.1	33.0	38.9	39.6	40.5	37.7	32.4	39.2	40.3	41.2	39.1	32.6	39.7	40.8	41.6	39.5	33.0	39.5	40.8	41.7	39.6
0.25	0	21.9	23.8	23.6	24.4	21.7	27.6	28.0	28.3	29.2	26.4	28.2	29.4	29.7	30.5	27.9	29.2	30.3	30.3	30.0	28.5	29.9	30.4	30.6	31.1	28.8
0.25	0.25	31.1	33.8	33.7	33.8	29.9	34.0	36.6	38.1	38.6	34.7	33.8	36.9	38.7	39.7	36.3	34.2	37.3	39.0	40.1	37.0	34.6	37.0	39.1	40.3	37.3
0.25	0.5	32.6	36.8	37.5	36.7	30.7	34.8	38.6	40.0	40.5	35.2	34.5	39.0	40.5	41.3	36.9	34.8	39.4	40.9	41.7	37.6	35.2	39.1	41.0	41.8	37.9
0.25	0.75	33.3	38.3	38.6	38.9	33.1	35.6	40.0	40.4	41.2	37.4	35.2	40.3	41.1	41.9	39.0	35.5	40.9	41.6	42.2	39.5	35.9	40.6	41.6	42.3	39.8
0.25	1	33.7	39.0	38.9	39.6	34.9	36.1	40.3	40.7	41.5	38.9	35.8	40.7	41.6	42.3	40.0	36.1	41.4	41.8	42.6	40.4	36.5	41.2	41.9	42.6	40.5
0.5	0	26.1	28.1	27.8	28.7	25.9	31.5	32.0	32.2	33.1	30.3	32.3	33.4	33.7	34.5	32.0	33.5	34.4	34.3	35.0	32.6	34.0	34.5	34.7	35.3	32.9
0.5	0.25	34.8	37.8	37.5	36.9	32.5	37.3	39.8	40.8	40.5	36.5	37.2	40.3	41.4	41.6	38.1	37.7	40.8	41.8	42.1	38.8	38.2	40.6	41.9	42.4	39.1
0.5	0.5	35.5	39.7	39.6	38.8	32.8	38.0	41.0	41.3	41.8	36.8	37.9	41.4	41.9	42.5	38.4	38.3	42.0	42.3	42.8	39.0	38.8	41.8	42.4	42.9	39.3
0.5	0.75	36.1	40.1	40.0	40.6	35.0	38.7	41.2	41.6	42.2	38.7	38.6	41.8	42.2	42.9	40.0	39.0	42.4	42.6	43.2	40.5	39.5	42.2	42.7	43.2	40.8
0.5	1	36.5	40.3	40.1	41.0	36.7	39.2	41.4	41.7	42.3	39.8	39.1	41.9	42.3	43.0	40.7	39.5	42.6	42.7	43.4	41.0	40.0	42.3	42.7	43.4	41.1
0.75	0	30.8	32.7	32.4	33.3	30.5	35.7	36.2	36.4	37.3	34.5	36.5	37.7	38.0	38.7	36.2	37.5	38.7	38.6	39.3	36.9	38.4	38.8	39.0	39.6	37.2
0.75	0.25	38.2	41.1	40.0	39.2	34.8	40.9	42.2	42.3	42.1	38.2	41.0	42.7	42.9	43.1	39.7	41.5	43.3	43.3	43.6	40.2	42.1	43.1	43.4	43.7	40.5
0.75	0.5	38.8	41.2	41.0	40.7	34.8	41.4	42.3	42.4	42.9	38.3	41.5	42.8	43.0	43.6	39.7	41.9	43.4	43.3	43.9	40.2	42.0	43.1	43.4	43.9	40.5
0.75	0.75	39.3	41.2	41.0	41.8	36.8	41.7	42.3	42.4	43.0	39.7	41.7	42.8	43.0	43.7	40.9	42.1	43.4	43.4	44.0	41.4	42.7	43.1	43.4	44.0	41.6
0.75	1	39.3	41.2	41.0	41.9	38.2	41.7	42.3	42.4	43.1	40.7	41.7	42.8	43.0	43.8	41.4	42.1	43.4	43.4	44.1	41.7	42.7	43.1	43.5	44.0	41.8
1	0	35.1	37.0	36.7	37.6	34.8	39.5	40.0	40.2	41.1	38.3	40.4	41.5	41.9	42.6	40.1	41.5	42.6	42.6	43.2	40.8	42.3	42.8	43.0	43.6	41.2
1	0.25	41.5	43.7	43.0	42.4	38.2	43.7	44.3	44.5	44.4	40.7	43.9	45.1	45.3	45.4	42.3	44.5	45.8	45.7	46.2	42.8	45.2	45.6	45.0	46.4	43.1
1	0.5	41.7	43.8	43.6	43.7	38.2	43.8	44.4	44.5	45.0	40.8	44.0	45.1	45.3	45.9	42.3	44.5	45.8	45.7	46.3	42.8	45.2	45.6	45.9	46.4	43.1
1	0.75	41.8	43.8	43.6	44.4	39.9	43.8	44.3	44.5	45.1	42.0	44.0	45.1	45.3	46.0	43.4	44.5	45.8	45.8	46.4	43.9	45.2	45.6	45.9	46.4	44.1
1	1	41.8	43.8	43.6	44.5	41.1	43.7	44.3	44.5	45.2	42.7	44.0	45.0	45.3	46.0	43.6	44.5	45.8	45.8	46.4	43.4	45.2	45.6	45.9	46.5	44.2



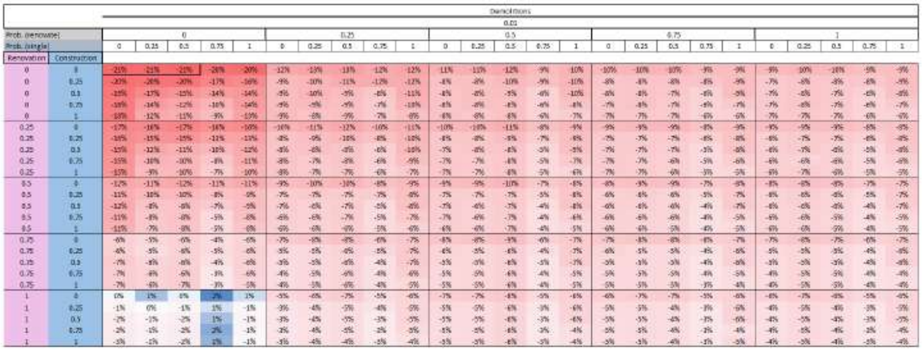
co2 max: 20527 co2 min: 11176.2		Demolitions 0.03																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	11.1	12.8	12.6	14.9	11.2	19.2	18.8	19.1	21.5	17.6	20.2	21.2	21.4	23.0	20.0	21.9	22.3	21.8	23.7	20.9	22.5	22.5	22.7	23.9	21.1
0	0.25	23.6	26.0	25.5	26.4	21.7	28.5	30.4	31.5	33.0	28.6	28.1	31.2	33.1	34.4	30.9	28.9	31.7	33.1	35.1	31.8	29.2	31.3	33.6	35.2	32.1
0	0.5	26.2	30.4	31.5	31.1	23.1	29.5	33.0	35.7	37.0	29.3	29.1	33.6	36.6	38.2	31.9	29.7	34.2	36.7	38.8	33.0	30.0	33.8	37.2	38.9	33.4
0	0.75	27.2	32.8	33.8	34.8	26.2	30.4	35.2	36.3	38.4	32.3	29.9	36.1	37.5	39.1	34.7	30.5	36.7	37.8	39.7	35.7	30.8	36.3	38.3	39.7	36.1
0	1	27.6	33.8	34.2	36.2	28.8	31.0	36.2	36.7	38.8	34.6	30.5	36.9	38.0	39.6	36.9	31.1	37.8	38.2	40.1	37.5	31.4	37.5	38.7	40.1	37.6
0.25	0	15.0	16.7	16.5	18.8	15.1	23.0	22.5	22.8	25.2	21.4	24.1	25.0	25.3	26.9	24.0	25.8	26.3	25.8	27.7	24.9	26.5	26.6	26.7	27.9	25.1
0.25	0.25	27.2	29.6	29.1	29.6	24.4	31.5	33.5	34.9	35.8	30.3	31.4	34.4	36.4	37.2	32.8	32.3	35.0	36.5	38.0	33.8	32.7	34.7	36.9	38.3	34.2
0.25	0.5	29.0	33.5	33.9	33.2	25.1	32.5	35.9	36.9	38.6	30.9	32.3	36.7	38.1	39.5	33.4	33.0	37.4	38.3	40.1	34.4	33.4	37.1	38.9	40.1	34.7
0.25	0.75	29.8	34.8	35.0	36.7	27.9	33.4	37.1	37.4	39.4	33.6	33.1	37.9	38.7	40.1	36.0	33.8	38.8	38.9	40.7	36.9	34.2	38.5	39.4	40.7	37.3
0.25	1	30.2	35.5	35.3	37.5	30.4	34.0	37.4	37.7	39.7	35.9	33.7	38.3	38.9	40.5	37.8	34.4	39.3	39.2	41.0	38.4	34.8	39.1	39.7	41.0	38.4
0.5	0	19.0	20.7	20.5	22.8	19.0	26.8	26.3	26.4	29.0	25.2	28.0	28.9	29.2	30.7	27.9	29.7	30.3	29.8	31.7	28.8	30.6	30.6	30.8	31.9	29.1
0.5	0.25	30.6	33.5	32.6	32.3	26.7	34.7	36.6	37.6	37.5	32.0	34.7	37.6	38.8	39.1	34.5	35.6	38.4	39.1	40.0	35.4	36.1	38.2	39.6	40.3	35.8
0.5	0.5	31.6	35.9	35.8	35.3	27.0	35.6	37.9	38.1	39.9	32.3	35.5	38.9	39.4	40.6	34.8	36.4	39.8	39.6	41.2	35.7	36.9	39.6	40.1	41.1	36.0
0.5	0.75	32.4	36.3	36.2	38.2	29.7	36.4	38.2	38.4	40.2	34.8	36.3	39.2	39.6	41.0	37.2	37.1	40.2	39.8	41.5	38.0	37.6	39.9	40.4	41.5	38.4
0.5	1	32.8	36.4	36.3	38.5	32.1	36.9	38.4	38.5	40.4	37.0	36.9	39.4	39.7	41.2	38.0	37.7	40.3	39.9	41.7	38.9	38.2	40.0	40.6	41.7	39.0
0.75	0	23.4	25.1	24.9	27.2	23.4	30.9	30.5	30.7	33.1	29.3	32.1	33.0	33.3	34.9	32.0	33.9	34.5	34.0	35.8	33.0	34.8	34.8	35.0	36.2	33.4
0.75	0.25	33.8	36.9	35.0	34.5	28.7	38.1	39.0	39.0	39.2	33.6	38.3	40.0	40.3	40.7	36.0	39.3	40.9	40.5	41.5	36.9	39.9	40.7	41.0	41.8	37.2
0.75	0.5	34.7	37.3	37.1	37.2	28.9	38.9	39.2	39.2	40.9	33.7	39.1	40.2	40.4	41.6	36.1	40.0	41.1	40.6	42.1	36.9	40.6	40.8	41.1	42.1	37.3
0.75	0.75	35.4	37.3	37.1	39.3	31.4	39.3	39.2	39.2	41.0	36.0	39.4	40.2	40.4	41.8	38.3	40.3	41.1	40.6	42.3	39.1	40.8	40.8	41.1	42.2	39.4
0.75	1	35.4	37.3	37.1	39.4	33.7	39.4	39.2	39.2	41.2	37.9	39.4	40.2	40.4	41.5	39.1	40.3	41.1	40.6	42.4	39.6	40.9	40.8	41.1	42.3	39.6
1	0	27.6	29.3	29.1	31.4	27.7	34.7	34.3	34.5	36.9	33.1	36.0	36.9	37.3	38.8	36.0	37.9	38.5	38.0	39.8	36.9	38.9	38.8	39.0	40.2	37.4
1	0.25	37.0	39.4	38.2	37.6	31.9	41.0	40.9	40.9	41.5	35.9	41.4	42.2	42.4	43.2	38.5	42.4	43.2	42.8	44.1	39.4	43.1	43.0	43.3	44.3	39.8
1	0.5	37.5	39.5	39.3	40.3	32.0	41.2	40.9	40.9	42.7	35.9	41.5	42.2	42.4	43.7	38.5	42.5	43.2	42.7	44.3	39.4	43.2	43.0	43.3	44.3	39.8
1	0.75	37.7	39.0	39.4	41.6	34.5	41.2	40.9	41.0	42.8	38.2	41.5	42.1	42.4	43.8	40.7	42.5	43.2	42.8	44.5	41.5	43.1	43.0	43.3	44.5	41.7
1	1	37.7	39.6	39.4	41.7	36.8	41.2	40.9	41.0	43.0	39.7	41.5	42.2	42.4	43.9	41.1	42.5	43.2	42.8	44.6	40.5	43.1	43.0	43.4	44.6	41.8



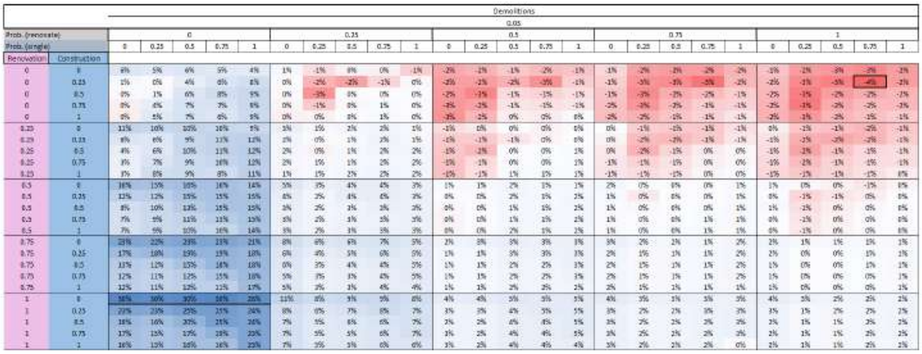
co2 max: 20527 co2 min: 10982		Demolitions 0.05																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	0.0	0.9	3.0	2.0	0.3	9.0	10.4	11.4	11.5	9.0	12.5	13.0	14.3	14.2	12.8	14.9	15.0	16.3	16.1	14.2	14.6	16.2	17.2	17.1	15.2
0	0.25	16.7	18.3	18.8	16.5	12.6	22.2	25.8	26.3	25.3	21.1	23.3	26.7	28.4	27.7	24.6	24.8	27.5	30.0	29.3	26.1	24.3	28.0	30.6	30.0	27.0
0	0.5	20.6	24.9	26.9	21.7	13.6	23.6	29.1	32.0	29.6	21.9	24.4	29.6	33.1	32.1	25.6	25.8	30.3	34.2	33.9	27.2	25.3	30.8	34.4	34.7	28.2
0	0.75	21.9	27.1	29.9	26.6	17.1	24.8	31.4	32.8	32.6	25.0	25.5	32.1	34.0	33.8	28.7	26.8	33.0	35.3	35.0	30.1	26.3	33.5	35.4	35.5	31.1
0	1	22.6	27.9	30.3	29.1	20.2	25.5	31.9	33.2	33.0	27.9	26.2	32.7	34.4	34.2	31.4	27.5	33.7	35.6	35.4	32.8	27.0	34.3	35.7	35.9	33.6
0.25	0	3.3	4.3	6.3	5.4	3.7	12.4	13.8	14.9	14.9	12.4	16.1	16.6	17.9	17.8	16.4	18.6	18.7	20.1	19.9	18.0	18.4	20.0	21.0	20.9	19.0
0.25	0.25	19.9	21.5	22.1	18.9	14.6	25.0	28.8	29.3	27.3	22.5	26.3	29.7	31.7	29.8	26.3	27.9	30.6	33.3	31.6	27.8	27.4	31.2	34.0	32.5	28.8
0.25	0.5	22.9	27.4	28.9	23.3	15.2	26.3	31.6	33.1	31.0	23.1	27.4	32.4	34.4	33.5	26.8	28.9	33.3	35.6	35.1	28.3	28.4	33.8	35.9	35.7	29.3
0.25	0.75	24.2	28.6	30.8	28.1	18.5	27.4	32.5	33.7	33.4	26.1	28.4	33.4	34.9	34.6	29.7	29.9	34.4	36.1	35.8	31.2	29.4	35.1	36.3	36.3	32.1
0.25	1	24.9	28.9	31.1	29.9	21.6	28.2	32.8	34.0	33.7	28.9	29.1	33.8	35.2	35.0	32.3	30.5	34.9	36.4	36.1	33.6	30.1	35.6	36.6	36.7	34.6
0.5	0	6.9	7.8	9.9	8.9	7.2	15.9	17.2	18.4	18.4	15.9	19.7	20.3	21.6	21.4	20.0	22.3	22.4	23.8	23.6	21.7	22.2	23.8	24.7	24.7	22.8
0.5	0.25	23.4	24.9	24.8	21.0	16.5	27.9	31.7	31.5	28.8	24.0	29.4	32.7	34.0	31.4	27.7	31.0	33.8	35.8	33.3	29.2	30.7	34.4	36.4	34.2	30.2
0.5	0.5	25.2	29.1	30.8	25.0	16.8	29.0	33.1	34.1	32.3	24.3	30.4	34.1	35.4	34.7	28.0	32.0	35.2	36.6	36.1	29.5	31.6	35.9	36.8	36.6	30.4
0.5	0.75	26.5	29.5	31.6	29.6	20.0	30.1	33.5	34.5	34.1	27.2	31.4	34.5	35.7	35.3	30.7	33.0	35.6	36.9	36.5	32.1	32.6	36.2	37.2	37.0	33.0
0.5	1	27.2	29.7	31.7	30.6	23.0	30.9	33.7	34.6	34.2	29.8	32.1	34.7	35.8	35.5	33.2	33.7	35.8	37.0	36.6	34.5	33.3	36.4	37.3	37.2	35.4
0.75	0	10.7	11.7	13.7	12.8	11.0	19.7	21.0	22.2	22.2	19.7	23.7	24.3	25.5	25.4	24.0	26.4	26.4	27.8	27.6	25.7	26.3	27.9	28.8	28.7	26.8
0.75	0.25	26.8	28.0	26.8	22.9	18.2	31.0	33.8	33.1	30.3	25.4	32.8	35.0	35.6	32.8	29.0	34.6	36.2	37.2	34.7	30.5	34.2	36.8	37.7	35.6	31.5
0.75	0.5	28.0	30.2	32.2	26.7	18.5	32.1	34.2	35.1	33.6	25.6	33.7	35.3	36.3	35.9	29.2	35.4	36.4	37.6	37.0	30.7	35.1	37.0	37.9	37.6	31.6
0.75	0.75	29.2	30.3	32.4	31.1	21.5	33.1	34.3	35.2	34.7	28.2	34.5	35.3	36.4	36.0	31.7	36.2	36.4	37.6	37.2	33.1	35.8	37.0	37.9	37.7	34.0
0.75	1	29.5	30.3	32.4	31.3	24.4	33.2	34.3	35.2	34.9	30.9	34.5	35.3	36.4	36.2	34.2	36.2	36.4	37.6	37.3	35.5	35.8	37.0	37.9	37.9	36.1
1	0	14.4	15.4	17.4	16.5	14.7	23.3	24.7	25.8	25.8	23.3	27.5	28.1	29.3	29.2	27.8	30.2	30.3	31.7	31.5	29.6	30.2	31.8	32.7	32.7	30.7
1	0.25	29.8	30.7	29.4	25.5	20.9	34.0	35.4	35.1	32.2	27.3	35.9	36.8	37.7	34.9	31.1	37.7	38.1	39.2	36.8	32.7	37.4	38.8	39.7	37.9	33.7
1	0.5	30.7	32.1	34.1	29.3	21.1	34.4	35.6	36.5	35.4	27.3	36.1	36.9	37.9	37.5	31.1	37.9	38.1	39.3	38.8	32.7	37.6	38.9	39.7	39.4	33.7
1	0.75	31.2	32.1	34.2	33.2	24.0	34.5	35.6	36.5	36.1	30.0	36.1	36.9	37.9	37.6	33.6	37.9	38.1	39.3	38.9	35.1	37.6	38.8	39.7	39.6	36.1
1	1	31.4	32.1	34.2	33.2	27.0	34.5	35.6	36.5	36.3	32.6	36.1	36.8	37.9	37.8	36.1	37.9	38.1	39.3	39.0	37.3	37.6	38.8	39.7	39.7	37.9

Table 4 Comparison of simulations under different scenarios with regulation

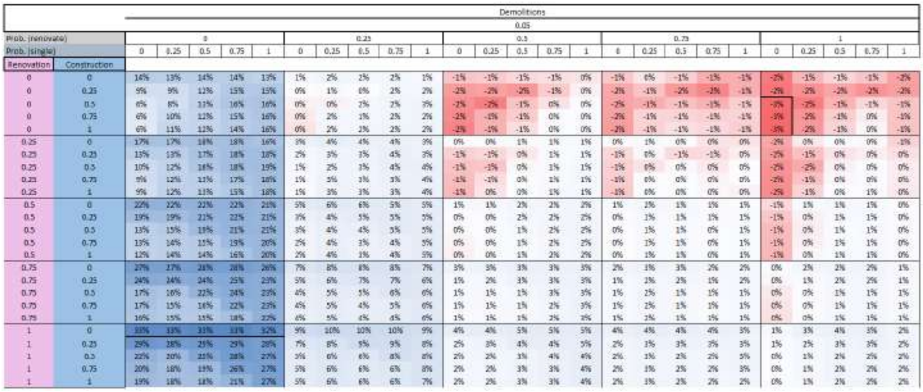
Difference



		Demolitions																								
		0.01																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	-21%	-21%	-21%	-20%	-20%	-12%	-13%	-13%	-12%	-12%	-11%	-11%	-12%	-9%	10%	-10%	-10%	10%	-9%	-9%	-9%	10%	-10%	-9%	-9%
0	0.25	-20%	-20%	-20%	-17%	-16%	-9%	-10%	-11%	-12%	-12%	-8%	-8%	-10%	-9%	-10%	-8%	-8%	-8%	-8%	-9%	-7%	-8%	-8%	-8%	-9%
0	0.5	-15%	-17%	-15%	-14%	-14%	-9%	-10%	-9%	-8%	-11%	-8%	-8%	-9%	-8%	-10%	-8%	-8%	-7%	-8%	-9%	-7%	-8%	-7%	-8%	-8%
0	0.75	-18%	-14%	-12%	-10%	-14%	-9%	-9%	-9%	-7%	-10%	-8%	-8%	-8%	-8%	-8%	-7%	-8%	-7%	-8%	-7%	-7%	-8%	-7%	-8%	-7%
0	1	-18%	-12%	-11%	-9%	-13%	-9%	-8%	-9%	-7%	-8%	-8%	-8%	-8%	-6%	-7%	-7%	-7%	-7%	-6%	-6%	-7%	-7%	-7%	-6%	-6%
0.25	0	-17%	-18%	-17%	-18%	-16%	-16%	-11%	-12%	-10%	-11%	-10%	-10%	-11%	-8%	-9%	-9%	-9%	-9%	-8%	-9%	-9%	-9%	-9%	-8%	-8%
0.25	0.25	-16%	-15%	-15%	-13%	-13%	-8%	-9%	-10%	-8%	-10%	-8%	-8%	-9%	-7%	-8%	-7%	-7%	-7%	-8%	-8%	-8%	-7%	-7%	-8%	-8%
0.25	0.5	-15%	-12%	-11%	-10%	-12%	-8%	-8%	-8%	-6%	-10%	-7%	-8%	-8%	-5%	-8%	-7%	-7%	-7%	-5%	-8%	-6%	-7%	-6%	-5%	-8%
0.25	0.75	-15%	-10%	-10%	-8%	-11%	-8%	-7%	-8%	-6%	-9%	-7%	-7%	-8%	-5%	-7%	-7%	-7%	-6%	-5%	-6%	-6%	-6%	-6%	-5%	-6%
0.25	1	-15%	-9%	-10%	-7%	-10%	-8%	-7%	-7%	-6%	-7%	-7%	-7%	-8%	-5%	-6%	-7%	-7%	-6%	-5%	-5%	-6%	-7%	-6%	-5%	-5%
0.5	0	-12%	-11%	-12%	-11%	-11%	-9%	-10%	-10%	-8%	-9%	-9%	-9%	-10%	-7%	-8%	-8%	-9%	-9%	-7%	-8%	-8%	-8%	-8%	-7%	-7%
0.5	0.25	-11%	-10%	-10%	-8%	-9%	-7%	-7%	-7%	-7%	-8%	-7%	-7%	-7%	-5%	-8%	-6%	-6%	-6%	-5%	-7%	-6%	-6%	-6%	-5%	-7%
0.5	0.5	-12%	-8%	-8%	-7%	-9%	-7%	-6%	-7%	-5%	-8%	-7%	-6%	-7%	-4%	-8%	-6%	-6%	-6%	-4%	-7%	-6%	-6%	-6%	-4%	-7%
0.5	0.75	-11%	-8%	-8%	-5%	-8%	-6%	-6%	-7%	-5%	-7%	-7%	-6%	-7%	-4%	-6%	-6%	-6%	-6%	-4%	-5%	-6%	-6%	-5%	-4%	-5%
0.5	1	-11%	-7%	-8%	-5%	-8%	-6%	-6%	-6%	-5%	-6%	-6%	-6%	-7%	-4%	-5%	-6%	-6%	-5%	-4%	-5%	-6%	-6%	-5%	-4%	-5%
0.75	0	-6%	-5%	-6%	-4%	-6%	-7%	-8%	-8%	-6%	-7%	-8%	-8%	-9%	-6%	-7%	-7%	-8%	-8%	-8%	-7%	-7%	-8%	-7%	-6%	-7%
0.75	0.25	-6%	-5%	-6%	-5%	-6%	-5%	-5%	-6%	-5%	-7%	-6%	-5%	-6%	-4%	-7%	-6%	-5%	-5%	-4%	-6%	-5%	-5%	-5%	-4%	-6%
0.75	0.5	-7%	-8%	-8%	-4%	-6%	-3%	-5%	-6%	-4%	-7%	-5%	-5%	-6%	-5%	-7%	-5%	-5%	-5%	-4%	-6%	-5%	-5%	-5%	-4%	-6%
0.75	0.75	-7%	-6%	-6%	-3%	-6%	-4%	-5%	-6%	-4%	-6%	-5%	-5%	-6%	-4%	-5%	-5%	-5%	-5%	-4%	-5%	-4%	-5%	-5%	-4%	-4%
0.75	1	-7%	-6%	-7%	-3%	-5%	-4%	-5%	-6%	-4%	-5%	-5%	-5%	-6%	-4%	-5%	-5%	-5%	-5%	-3%	-4%	-4%	-5%	-5%	-4%	-4%
1	0	0%	1%	0%	2%	1%	-5%	-6%	-7%	-5%	-6%	-7%	-7%	-8%	-5%	-6%	-6%	-7%	-7%	-5%	-6%	-6%	-7%	-8%	-5%	-6%
1	0.25	-1%	0%	-1%	1%	-1%	-3%	-4%	-5%	-4%	-5%	-5%	-5%	-6%	-3%	-6%	-5%	-5%	-4%	-3%	-6%	-4%	-5%	-4%	-3%	-5%
1	0.5	-2%	-1%	-2%	1%	-1%	-3%	-4%	-5%	-3%	-5%	-5%	-5%	-6%	-3%	-6%	-5%	-5%	-4%	-3%	-6%	-4%	-5%	-4%	-3%	-5%
1	0.75	-2%	-1%	-2%	2%	-1%	-3%	-4%	-5%	-2%	-5%	-5%	-5%	-6%	-3%	-4%	-5%	-5%	-4%	-2%	-4%	-4%	-5%	-4%	-2%	-4%
1	1	-3%	-1%	-2%	1%	-1%	-3%	-4%	-4%	-3%	-4%	-5%	-5%	-6%	-3%	-4%	-5%	-5%	-4%	-3%	-5%	-4%	-5%	-4%	-3%	-4%



		Demolitions																								
		0.05																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	8%	5%	6%	5%	4%	1%	-1%	0%	0%	-1%	-2%	-2%	-1%	-2%	-1%	-1%	-2%	-3%	-2%	-2%	-1%	-2%	-3%	-2%	-2%
0	0.25	1%	0%	4%	6%	8%	0%	-2%	-2%	-1%	0%	-2%	-2%	-2%	-3%	-1%	-1%	-3%	-3%	-3%	-2%	-2%	-3%	-3%	-4%	-2%
0	0.5	0%	1%	6%	8%	9%	0%	-3%	0%	0%	0%	-2%	-3%	-1%	-1%	-1%	-1%	-3%	-2%	-2%	-1%	-2%	-3%	-2%	-2%	-2%
0	0.75	0%	4%	7%	7%	8%	0%	-1%	0%	1%	0%	-3%	-2%	-1%	-1%	-1%	-2%	-3%	-3%	-1%	-1%	-2%	-3%	-2%	-2%	-3%
0	1	0%	5%	7%	6%	9%	0%	0%	0%	1%	0%	-3%	-2%	0%	0%	0%	-2%	-2%	-1%	-1%	-1%	-2%	-3%	-2%	-1%	-1%
0.25	0	11%	10%	10%	10%	9%	3%	1%	2%	2%	1%	-1%	0%	0%	0%	0%	0%	-1%	-1%	-1%	-1%	0%	-1%	-1%	-2%	-1%
0.25	0.25	8%	6%	9%	11%	12%	2%	0%	1%	2%	1%	-1%	-1%	-1%	0%	0%	0%	-2%	-2%	-1%	-1%	-1%	-2%	-2%	-2%	-1%
0.25	0.5	4%	6%	10%	11%	12%	2%	0%	1%	2%	2%	-1%	-2%	0%	0%	1%	0%	-2%	-1%	0%	0%	-1%	-2%	-1%	-1%	-1%
0.25	0.75	3%	7%	9%	10%	12%	2%	1%	1%	2%	2%	-1%	-1%	0%	0%	1%	-1%	-1%	-1%	0%	0%	-1%	-2%	-1%	-1%	-1%
0.25	1	3%	8%	9%	8%	11%	1%	1%	2%	2%	2%	-1%	-1%	1%	1%	1%	-1%	-1%	-1%	0%	0%	-1%	-1%	-1%	-1%	0%
0.5	0	16%	15%	16%	16%	14%	5%	3%	4%	4%	3%	1%	1%	2%	1%	1%	2%	0%	0%	0%	1%	1%	0%	0%	-1%	0%
0.5	0.25	12%	12%	15%	15%	15%	4%	2%	4%	4%	3%	0%	0%	2%	1%	2%	1%	0%	0%	0%	1%	0%	-1%	-1%	0%	0%
0.5	0.5	8%	10%	13%	15%	15%	3%	2%	3%	3%	3%	0%	0%	1%	1%	2%	1%	0%	0%	0%	1%	1%	-1%	0%	0%	0%
0.5	0.75	7%	9%	11%	13%	15%	3%	2%	3%	3%	3%	0%	0%	1%	1%	2%	1%	0%	0%	1%	1%	0%	-1%	0%	0%	0%
0.5	1	7%	9%	10%	16%	14%	3%	2%	3%	3%	3%	0%	0%	2%	1%	2%	1%	0%	0%	1%	1%	0%	-1%	0%	0%	0%
0.75	0	23%	22%	23%	23%	21%	8%	6%	6%	7%	5%	2%	3%	3%	3%	3%	3%	2%	2%	1%	2%	2%	1%	1%	1%	1%
0.75	0.25	17%	18%	19%	19%	18%	6%	4%	5%	6%	5%	1%	1%	3%	3%	3%	2%	1%	1%	1%	2%	2%	0%	0%	1%	1%
0.75	0.5	13%	12%	15%	16%	18%	0%	3%	4%	4%	5%	1%	1%	2%	2%	3%	2%	1%	1%	1%	2%	1%	0%	0%	1%	1%
0.75	0.75	12%	11%	12%	15%	18%	5%	3%	3%	4%	5%	1%	1%	2%	2%	3%	2%	1%	1%	1%	2%	1%	0%	0%	0%	1%
0.75	1	12%	11%	12%	11%	17%	5%	3%	3%	4%	4%	1%	1%	2%	2%	2%	2%	1%	1%	1%	1%	1%	0%	0%	0%	1%
1	0	31%	30%	30%	30%	28%	11%	8%	9%	9%	8%	4%	4%	5%	5%	5%	4%	3%	3%	3%	3%	4%	3%	2%	2%	2%
1	0.25	23%	23%	25%	25%	24%	8%	6%	7%	8%	7%	3%	3%	4%	5%	5%	3%	2%	2%	3%	3%	3%	1%	2%	2%	2%
1	0.5	18%	16%	20%	21%	24%	7%	5%	6%	6%	7%	2%	2%	4%	4%	5%	3%	2%	2%	2%	2%	2%	1%	1%	2%	2%
1	0.75	17%	15%	17%	19%	20%	7%	5%	5%	6%	7%	3%	2%	4%	4%	5%	3%	2%	2%	2%	2%	2%	1%	1%	2%	2%
1	1	16%	15%	18%	16%	20%	7%	5%	5%	6%	6%	3%	2%	4%	4%	4%	3%	2%	2%	2%	0%	2%	1%	1%	2%	2%



		Demolitions																								
		0.05																								
Prob. (renovate)		0					0.25					0.5					0.75					1				
Prob. (single)		0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1	0	0.25	0.5	0.75	1
Renovation	Construction																									
0	0	14%	13%	14%	14%	13%	1%	2%	2%	2%	1%	-1%	-1%	-1%	-1%	0%	-1%	0%	-1%	-1%	-1%	-2%	-1%	-1%	-1%	-2%
0	0.25	9%	9%	12%	15%	15%	0%	1%	0%	2%	2%	-2%	-2%	-2%	-1%	0%	-2%	-1%	-2%	-2%	-1%	-2%	-2%	-2%	-2%	-2%
0	0.5	6%	8%	11%	16%	16%	0%	0%	2%	2%	3%	-2%	-2%	-1%	0%	0%	-2%	-1%	-1%	-1%	-1%	-3%	-2%	-1%	-1%	-1%
0	0.75	6%	10%	12%	15%	16%	0%	2%	1%	2%	2%	-2%	-1%	-1%	0%	0%	-2%	-1%	-1%	-1%	-1%	-3%	-2%	-1%	0%	-1%
0	1	6%	11%	12%	14%	16%	0%	2%	2%	2%	2%	-2%	-1%	-1%	0%	0%	-2%	-1%	-1%	-1%	-1%	-3%	-2%	-1%	0%	-1%
0.25	0	17%	17%	18%	18%	16%	3%	4%	4%	4%	3%	0%	0%	1%	1%	1%	0%	1%	0%	0%	0%	-2%	0%	0%	0%	-1%
0.25	0.25	13%	13%	17%	18%	18%	2%	3%	3%	4%	3%	-1%	-1%	0%	1%	1%	-1%	0%	-1%	-1%	0%	-2%	-1%	0%	0%	0%
0.25	0.5	10%	12%	16%	18%	19%	1%	2%	3%	4%	4%	-1%	-1%	0%	1%	1%	-1%	0%	0%	0%	0%	-2%	-2%	0%	0%	0%
0.25	0.75	9%	12%	13%	17%	18%	1%	3%	3%	3%	4%	-1%	-1%	0%	1%	1%	-1%	0%	0%	0%	0%	-2%	-1%	0%	0%	0%
0.25	1	9%	12%	13%	15%	18%	1%	3%	3%	3%	4%	-1%	0%	0%	1%	1%	-1%	0%	0%	0%	0%	-2%	-1%	0%	1%	0%
0.5	0	22%	22%	21%	22%	21%	5%	6%	6%	5%	5%	1%	1%	2%	2%	2%	1%	2%	1%	1%	1%	-1%	1%	1%	1%	0%
0.5	0.25	19%	19%	21%	22%	21%	3%	4%	5%	5%	5%	0%	0%	2%	2%	2%	0%	1%	1%	1%	1%	-1%	0%	1%	1%	0%
0.5	0.5	13%	15%	19%	21%	21%	3%	4%	4%	5%	5%	0%	0%	1%	2%	2%	0%	1%	1%	0%	1%	-1%	0%	1%	1%	0%
0.5	0.75	13%	14%	15%	19%	20%	2%	4%	3%	4%	5%	0%	0%	1%	2%	2%	0%	1%	1%	0%	1%	-1%	0%	1%	1%	0%
0.5	1	12%	14%	14%	16%	20%	2%	4%	3%	4%	5%	0%	0%	1%	2%	2%	0%	1%	1%	0%	1%	-1%	0%	1%	1%	0%
0.75	0	27%	27%	28%	28%	26%	7%	8%	8%	8%	7%	3%	3%	3%	3%	3%	2%	3%	3%	2%	2%	0%	2%	2%	2%	1%
0.75	0.25	24%	24%	24%	25%	23%	5%	6%	7%	7%	6%	1%	2%	3%	3%	3%	1%	2%	2%	1%	2%	0%	1%	2%	2%	1%
0.75	0.5	17%	16%	22%	24%	23%	4%	5%	5%	6%	6%	1%	1%	1%	3%	3%	1%	2%	1%	1%	1%	0%	0%	1%	1%	1%
0.75	0.75	17%	15%	16%	22%	23%	4%	5%	4%	5%	6%	1%	1%	1%	2%	3%	1%	2%	1%	1%	1%	0%	0%	1%	1%	1%
0.75	1	16%	15%	15%	18%	22%	4%	5%	4%	4%	6%	1%	1%	1%	2%	3%	1%	2%	1%	1%	1%	0%	0%	1%	1%	1%
1	0	33%	33%	33%	33%	32%	9%	10%	10%	10%	9%	4%	4%	5%	5%	5%	4%	4%	4%	4%	3%	1%	3%	4%	3%	2%
1	0.25	29%	28%	25%	29%	28%	7%	8%	9%	9%	8%	2%	3%	4%	4%	5%	2%	3%	3%	3%	3%	1%	2%	3%	3%	2%
1	0.5	22%	20%	25%	28%	27%	5%	6%	6%	8%	8%	2%	2%	3%	4%	4%	2%	3%	2%	2%	3%	0%	1%	2%	2%	2%
1	0.75	20%	18%	19%	26%	27%	5%	6%	6%	6%	8%	2%	2%	3%	3%	4%	2%	3%	2%	2%	3%	0%	1%	2%	2%	2%
1	1	19%	18%	18%	21%	27%	5%	6%	6%	6%	7%	2%	2%	3%	3%	4%	2%	3%	2%	2%	2%	0%	1%	2%	2%	2%

Table 5 Comparison of simulations with and without regulation