Geographies of Waste

Significance, Semantics and Statistics in pursuit of a Circular Economy

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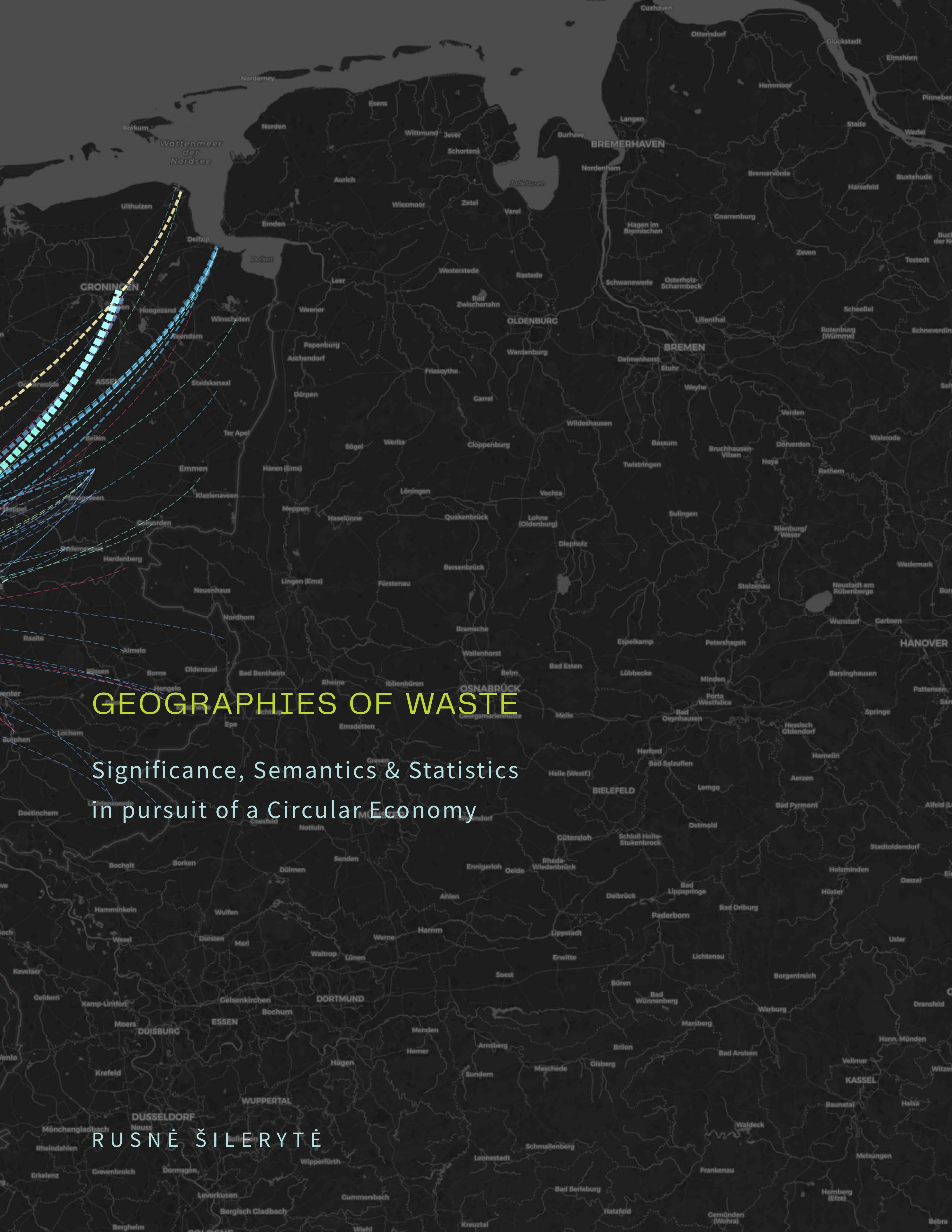
DOI
10.4233/uuid:745aee5b-75a3-42e7-a044-01aa1f9cdcf5

Publication date
2023

Document Version
Final published version

Citation (APA)
Sileryte, R. (2023). *Geographies of Waste: Significance, Semantics and Statistics in pursuit of a Circular Economy*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:745aee5b-75a3-42e7-a044-01aa1f9cdcf5



GEOGRAPHIES OF WASTE

Significance, Semantics & Statistics in pursuit of a Circular Economy

RUSNĖ ŠILERYTĖ

Geographies of Waste:

Significance, Semantics & Statistics

in pursuit of a Circular Economy

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus prof.dr.ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates

to be defended publicly on
Thursday 19 January 2023 at 12:30 o'clock

by

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This dissertation has been approved by the promotors.

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Dr. A. Ballatore	King's College London, England
Dr. J. Gil	Chalmers University of Technology, Sweden
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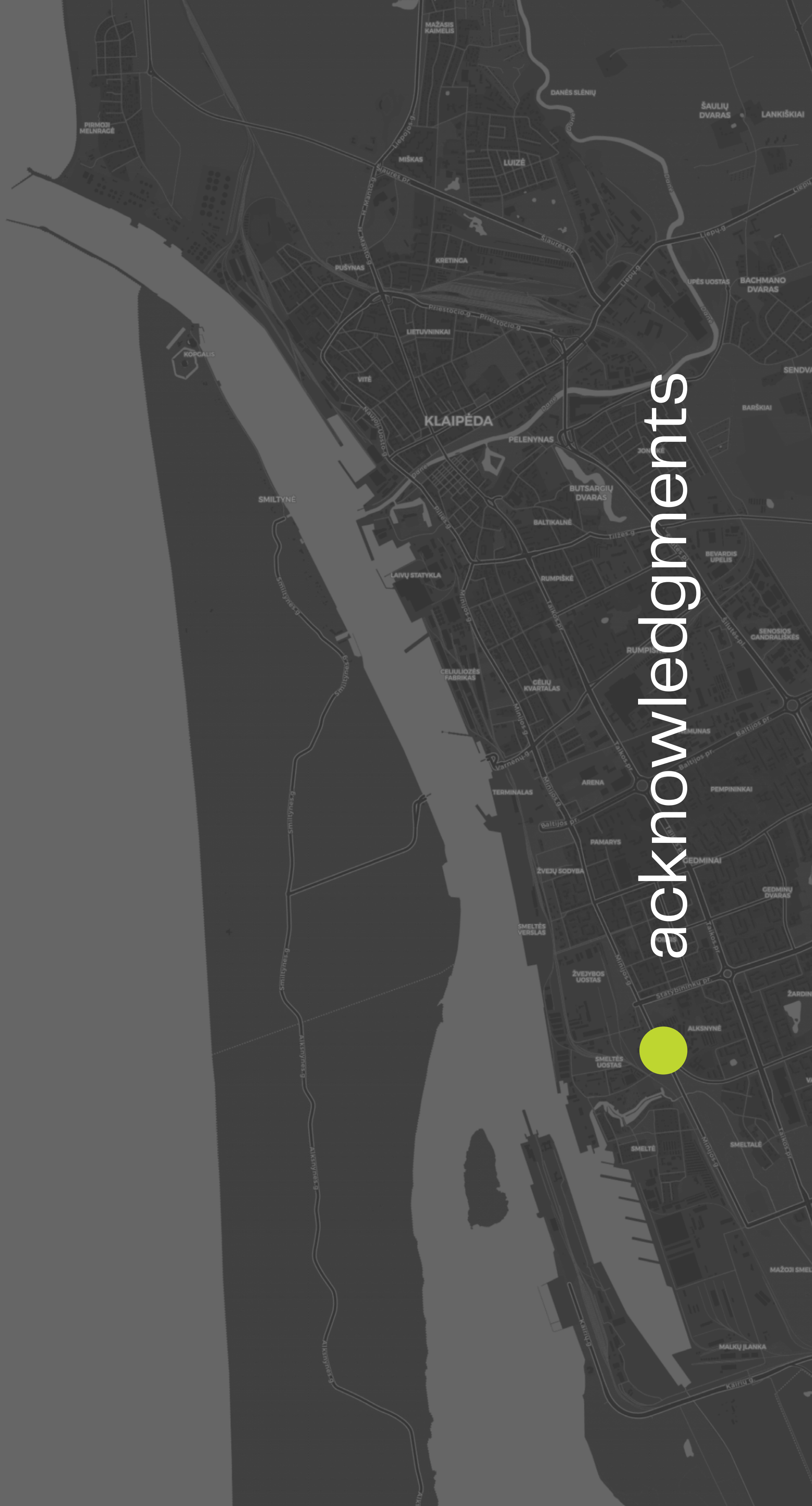
This research has been supported by the Amsterdam Institute of Advanced Metropolitan Solutions.

This research has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No 688920 (REPAiR) and No 776751 (CINDERELA)

acknowledgments



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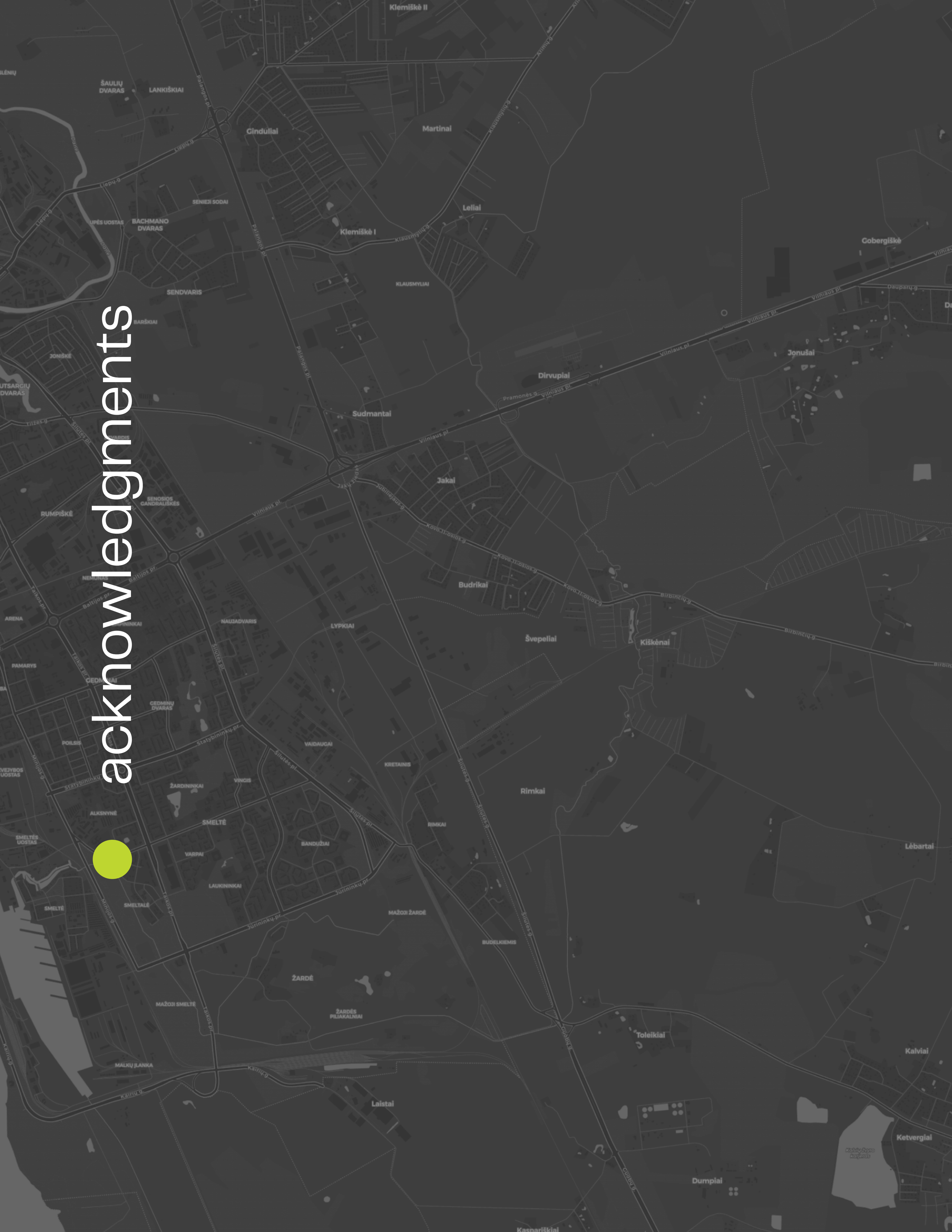

THANK YOU / DANKJEWEL / AČIŪ

Zosė Šilerienė

My interest in waste dates back as far as I can remember. I certainly owe it to my grandmother, who must have been the first zero-waste supporter in my life before the movement even got a name. She has taught me how to recover stale bread, neatly patch socks, re-knit old sweaters, use plastic boxes as tiny tomato greenhouses, and a hundred different things that old newspapers are good for. She was also the one who explained to me that it is important to prevent waste for two reasons: first, because it is disrespectful to waste all the energy and work which somebody put in producing a thing; second, because it is disrespectful to expect that nature needs to take care of what we dispose of. I find it beautiful and ironic, at the same time, that my six years of academic work led to the same conclusions.

Danutė Šilerytė

Viktoras Mikhailinas

My passion for algorithms, mathematics, and statistics has been bred by my parents, my mom in particular. A passionate mathematician herself, she believed that I was gifted at understanding the most difficult mathematical concepts. She taught me programming as early as age 10, before we even owned a computer at home. It is thanks to her and to my dad's neverending puzzles that I never found numbers and algorithms intimidating and always sought to be challenged by them.

I wish both my mother and my grandmother lived long enough to see me graduate as a doctor, as I am sure that it would have made them both especially happy and proud.

Ramunė Umarienė

Tadas Umaras

Paulius Umaras

Although during my journey at TU Delft I lost the people who brought me up, I am especially thankful to the rest of my family, my aunt Ramunė and my two cousins (who I always refer to as my brothers) Tadas and Paulius, for their all-round support and for simply being my home and my family. They have contributed more to this work than they think.

Pirouz Nourian

I definitely have to earnestly thank Prof. Pirouz Nourian for playing an important role in me starting this research in the first place, from sharing the available positions with me to giving me confidence that I have what it takes to complete a Ph.D. research. He taught me that all I need to succeed is curiosity and persistence, the advice I carried with me throughout the whole Ph.D. period, which appeared to be exactly true.

The six years of this work have been a grandiose exploration more than anything else, with some trips that led to complete dead-ends and others that had opened opportunities that I never expected to find. I must thank my promotor Prof. Arjan van Timmeren and my co-promotor Prof. Alexander Wandl for letting me participate in these explorations, even if some of them were risky not only for me, but also for them. I greatly appreciate their trust, lack of restrictions, and willingness to think along, dive with me into unfamiliar topics, and defend my choices when necessary. If not for their remarkable openness, this work would have been significantly less exciting.

Arjan van Timmeren
Alexander Wandl

It is a pity that I only got to be guided by Prof. Jorge Gil at the beginning of my research, as I am sure his insights and advice would have made this research stronger. Nevertheless, it was a bliss to have him as a supervisor at the very beginning as he taught me a number of fundamental lessons in setting up research methodology, writing, and understanding the difference between research scope and research ambitions.

Jorge Gil

I was lucky to conduct my research within the framework of REPAiR, a H2020 project that had provided me not only access to several rare sources of data, site visits to waste management facilities, and relevant learning opportunities, but also close friendships and terrifically enjoyable WP10 nights throughout Europe. Thanks for that to Gustavo Arciniegas, Carolin Bellsted, Janneke van der Leer, Michelle Steenmeijer, Libera Amenta, Alessandro Arlati, Andreas Obersteg, Tamas Szabo, Marcin Dabrowski, Cecilia Furlan, Denis Ceric, Pasquale Inglese, and all the others who were part of it.

Gustavo Arciniegas
Carolin Bellsted
Janneke van der Leer
Michelle Steenmeijer
Libera Amenta
Alessandro Arlati
Andreas Obersteg
Tamas Szabo
Marcin Dabrowski
Cecilia Furlan
Denis Ceric
Pasquale Inglese

Jens-Martin Gutsche, Max Bohnet, and Christoph Franke, who have also been part of the REPAiR consortium, deserve a special mention. First, due to the immense patience while navigating between the rigidity of digital development and the creativity required by research. Second, because of their patience with me personally, giving me A-to-Z classes on web-development. Third, for always being up for another beer, another bar, and another giggle. I greatly miss working with them.

Jens-Martin Gutsche
Max Bohnet
Christoph Franke

It would not be an exaggeration to say that nothing beyond Chapter 4 would have been possible without the openness and effort of the LMA heroes, especially Tjerk ter Ven and Henk Verwoerd. It takes great courage to break the old institutional patterns and open up research data that had never been opened before.

Tjerk ter Ven
Henk Verwoerd

The same can be said about the Municipality of Amsterdam. My encounter with Juan-Carlos Goilo at a bar in New York (of all places) led to a very fruitful collaboration and encouraged taking this research from the theoretical realm into a

Juan-Carlos Goilo

practical one and without a doubt made it much stronger and more relevant.

Daniel Nust
Frank Ostermann
Barbara Hofer
Carlos Granell Canut

Research reproducibility had never been a topic that I found important until I met Daniel Nust, Frank Ostermann, Barbara Hofer, and Carlos Granell Canut. In less than an hour, they managed to convince me to join them for the Research Reproducibility Initiative. Being part of the initiative not only led to several meaningful international workshops but also provided me with a different angle through which to look at the process of governmental data collection. This perspective is clearly reflected in the Conclusions and Recommendations of this book.

Yan Song
Daniella Maiollari
Daniele Cannatella
Ulf Hackauf
Eftychia Kalogianni
Kaixuan Zhou
Jinjin Yan
Anna Labetski
Claudiu Forgaci
Bardia Mashhoodi
Tanya Tsui
Alistair Beames

Many lessons, reciprocal support, and enjoyment during the last 6 years of my life were definitely due to my fellow Ph.D. students: Yan Song, Daniella Maiollari, Daniele Cannatella, Ulf Hackauf, Eftychia Kalogianni, Kaixuan Zhou, Jinjin Yan, Anna Labetski, Claudiu Forgaci, Bardia Mashhoodi, Tanya Tsui, Alistair Beames, and many others who have been there for shorter or longer periods of time.

Davey Oldenburg
Pablo Ruben
Panagiotis Karydakis
Roos Teeuwen
Yannick Schrik

While doing my own research, I was also lucky to supervise some really bright master students, all of whom have been a great pleasure to work with and who have achieved extraordinary results. I am really proud of the thesis of Davey Oldenburg, Pablo Ruben, Panagiotis Karydakis, Roos Teeuwen, and Yannick Schrik - in some way or another they have all contributed to this book too.

Simon Scheider
Andrea Ballatore
Martin Tomko
Angelo Jonas Imperiale

This thesis has also been strongly formed by a few conferences that have introduced me to other relevant cutting-edge research and, more importantly, forward-thinking researchers. AGILE laboratories have helped me discover ontologies and get exclusive feedback on my work from experts such as Simon Scheider, Andrea Ballatore, and Martin Tomko. The SCNY conference pushed me the farthest out of my comfort zone and acted as a stepping stone toward the start-up world. Finally, the IAIA Conference in Durban, South Africa, was a pivotal event in realising the global effects of material consumption and scarcity. The visit to the Amadiba community on the Wild Coast made me reassess my values. I especially have to thank Angelo Jonas Imperiale for being my wake-up call, guide, and inspiration for the changes that this journey has caused.

Kenneth Heijns
Stephan van Dijk
Eveline van Leeuwen

At the AMS Institute, I would like to thank Kenneth Heijns, Stephan van Dijk en Eveline van Leeuwen, for creating a very pleasant and productive working environment and place and the continued fight they deliver in translating and valorising promising research into application and real-world impact. Marije Wassenaar-Verschuur deserves a special mention in this regard: she was one of the first believers in the idea which later became geoFluxus and through her relentless energy, support and referrals, she played an incredibly important role in daring to take this enormous step.

Half of this research has been conducted in parallel to starting up geoFluxus.

Vasilieos Bouzas, Kozmo Meister, Bram Vercamer, and Evert Van Hirtum were the first to take the leap of faith and start working in a company that had just started to exist. They were later joined by Jolanta Jasiulionytė and Rui De Klerk, who went with us through very difficult and uncertain times. Ylva Wolter and Siebren Meines were the last ones to date to join the geoFluxus family. I would like to thank them wholeheartedly for their hard work, stubbornness, remarkable patience, and critical attitude. Their faith and dedication allowed me to successfully juggle between start-up and academia for the last three years. Their hands-on contribution to algorithms, visualisations, real-life validation, and several other aspects of this research is also rather significant.

Vasilieos Bouzas
Kozmo Meister
Bram Vercamer
Evert Van Hirtum
Jolanta Jasiulionytė
Rui De Klerk
Ylva Wolter
Siebren Meines

Statistically, this research took almost a fifth of my life. So, it goes without saying that my non-academic friends should be thanked for being there for me, after and before work. Aistė Eidukevičiūtė and Berta Gruodytė in the last six years have become as close as sisters to me, and just as real sisters they have been critical in my choices and supportive of all my troubles. I would like to sincerely thank them for that. Ever since I came to The Netherlands, Iris Theunisse has been my closest Dutch friend, who also made sure that I was eager to have my free time and holidays. I must thank her for reminding me of the importance of time off, sports, nature and adventure. Thanks to Iris, I have also been able to build around me the whole rock climber community: Siegrid, Nina, Bas, Plamen, Matthijs, Emil, Illiana, Roxanne, Tim, and everyone else who adds significant weight to my work-life balance.

Aistė Eidukevičiūtė
Berta Gruodytė

Iris Theunisse

Before the last sprint of my writing, I happened to test positive for COVID-19 while visiting Cape Town, resulting in an extended quarantine without my laptop. I feel obliged to thank Pieter Pluym for helping me out and lending me a laptop on which a substantial part of this book has been written during those ten days.

Pieter Pluym

Thanks to being part of the Amsterdam Institute for Advanced Metropolitan Solutions (AMS Institute), I have enjoyed three years of living in Amsterdam, a city in which I have dreamed of living since I was a teenager. In addition to being the main city for my waste flow studies, it has also been my cherished home that I have shared with Dimitris Zervakis, Maria Tsilogianni, Niky Guillon, Adrien Delorme, and Francesca Angeloni. I would like to thank all of them for keeping me company and taking care of me, most of the time, by cooking for me.

Dimitris Zervakis
Maria Tsilogianni
Niky Guillon
Adrien Delorme
Francesca Angeloni

The other three years of my research coincided with the global COVID-19 pandemic that I have spent in my new home in Rotterdam Zuid. I have been warmly welcomed into a Blokslag co-housing community with whom I could share evenings around the bonfire and care for each other during the months of quarantine. Paradoxical, but exactly during the times of isolation, I have finally managed to learn Dutch, for which I owe my gratitude to several community members who have been patient and supportive with my initial stammering.

BLOKSLAG

Arnout Sabbe

Finally, Arnout Sabbe is the person I would have needed to thank in almost every previous paragraph. Arnout is my partner, as much in my life as in my work. We met each other as Ph.D. students of the same promotor. We have worked alongside each other for the two H2020 projects described in this book, analysing the same data and mapping the same waste flows. As colleagues, we travelled together to New York and started a collaboration with the City of Amsterdam, which eventually led to the birth of geoFluxus. Together we have started and grown the company, together we have survived the pandemic, together we have supervised master students, and together we have created a home in Rotterdam. There are a million things for which I have to thank him, but first and foremost I have to thank Arnout for always daring to take on an extra challenge. As we always say, for as long as it is not impossible, it is worth doing. That is essentially what this book is about.

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AMA - Amsterdam Metropolitan Area

AMS Institute - Amsterdam Institute of Advanced Metropolitan Solutions

AS-MFA - Spatial Activity Based Material Flow Analysis

CE - Circular Economy

CEAP - EU Circular Economy Action Plan (2020)

CEM - Circular Economy Monitor

CINDERELA - H2020 Research & Innovation Action project CINDERELA (New Circular Economy Business Model for More Sustainable Urban Construction)

CRS - Coordinate Reference System

CTA - Cognitive Task Analysis

DEfD - Data Exploration for Design

EC - European Commission

EDA - Exploratory Data Analysis

EIA - Environmental Impact Assessment

EIA Directive - Directive 2011/92/EU as amended by Directive 2014/52/EU on the assessment of the effects of certain public and private projects on the environment

EU - European Union

EWC or EWC-Stat - European Waste Classification (classification system)

EWS - European Waste Statistics

GDSE - Geodesign Decision Support Environment

GHG - Greenhouse Gas Emissions

GIS - Geographic Information Systems

GN - General Nomenclature (classification system)

IA - Impact Assessment

KvK - NL: Kamer van Koophandel, Chamber of Commerce

LAP - NL: Landelijk Afvalbeheer Plan, Dutch National Waste Management Plan

LCA - Life Cycle Assessment

LMA - NL: Landelijk Meldpunt Afvalstoffen, Waste Registry Division of the Dutch Ministry of Infrastructure and Public Works

LoW - List of Waste (classification system)

MFA - Material Flow Analysis

NACE - FR: Nomenclature statistique des Activités économiques dans la Communauté Européenne, The Statistical Classification of Economic Activities in the European Community

NIMBY - Not-in-my-backyard

NUTS - Nomenclature of Territorial Units for Statistics

PULL - Peri-Urban Living Lab

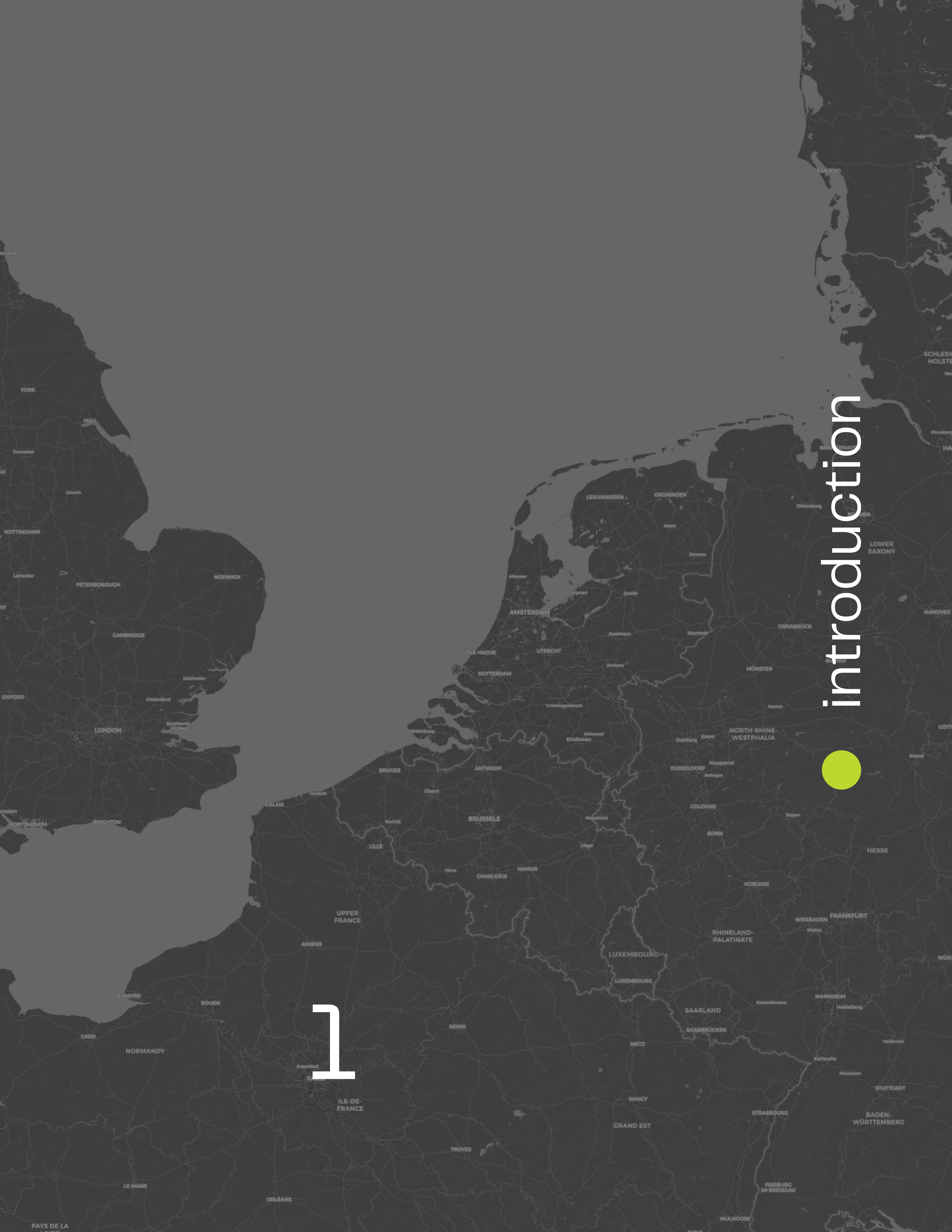
REPAiR - H2020 Research & Innovation Action project REPAiR (REsource Management in Peri-urban Areas: Going Beyond Urban Metabolism)

RQ - Research Question

SDSS - Spatial Decision Support System

SEM - Socioeconomic Metabolism

WStatR - Regulation (EC) No. 2150/2002 on Waste Statistics



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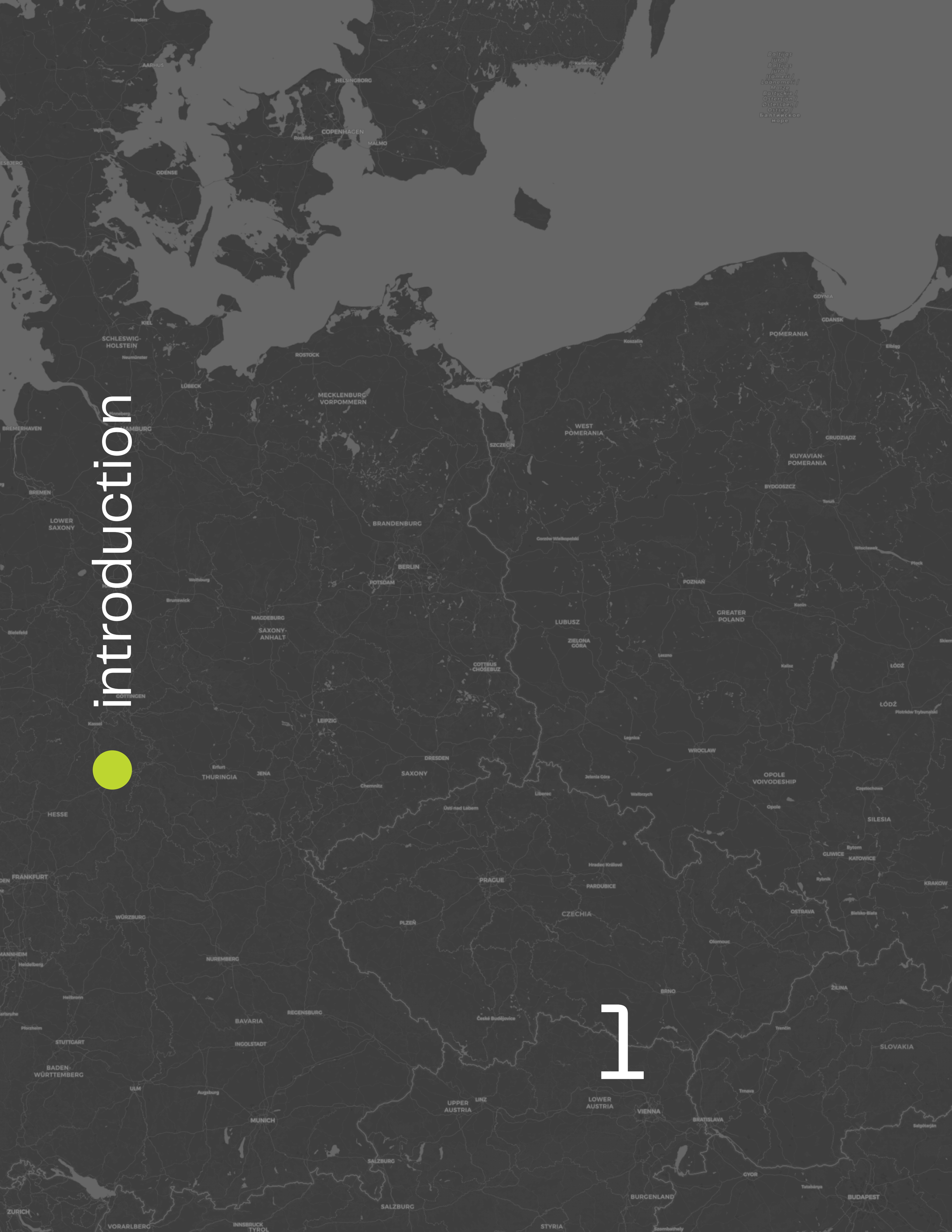


1.1 THE CIRCULAR ECONOMY PARADIGM

Sustainability - a property of development to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987)

Resource scarcity and rapid urbanisation both in light of rapidly changing demographics, socioeconomic power shifts, and climate change create a snowballing challenge of sustainability that is being addressed with ever increasing urgency. Fortunately, another major and more positive trend is the acceleration of technological innovation that could provide important contributions to human well-being, improve labour efficiency, communication and education, and in this way rise to the aforementioned challenges (Retief et al., 2016). Indeed, the technological innovation of rapidly increasing computational power, means of sharing data and information, and digital literacy are the main drivers behind this research, which aims to employ and direct them in the pursuit of more sustainable development.

The idea of reusing resources to overcome their scarcity is not innovative. Historically, it has many origins, depending on the material we are looking at (Jorgensen, 2019). The reuse of organic waste as a fertiliser for the new harvest is as old as agricultural practise itself. Medieval monks have been reusing old parchments to publish new books, and glass bottle deposit systems have existed at least since the beginning of the 20th century. The amount of energy spent on recycling or reuse processes has always depended on historical circumstances and political values (Gille, 2007). Following World War II, recycling practises in central European countries have been shaped by wartime destructions, embargo over precious metals, and limited access to virgin materials. In Hungary, it even went as far as introducing waste quotas to fuel industrialisation.

What is new is the scale of scarcity. All past material crises have been temporary, and the problem could always be solved by simply gaining access to the resources that were previously lying elsewhere. However, since the 1970s it became apparent that Earth is not a cornucopia and the problem soon will not be caused by hindered access but by the shortage of resources themselves. In April 1968, an Italian industrialist Aurelio Peccei and a Scottish scientist Alexander King convened the first meeting of The Club of Rome. Concerned by the prevailing short-term thinking in international affairs, their mission was to focus on the long-term consequences of the growing global interdependence (van Timmeren, 2006). 'The

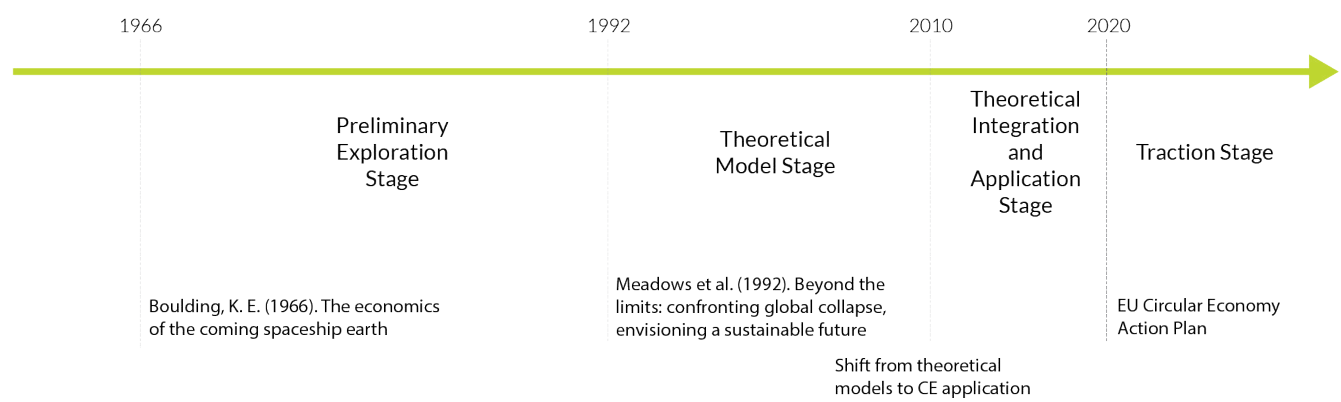
Limits to Growth' (1972), a report for the Club of Rome's project on the 'Predicament of Mankind', was one of the pioneering works aimed at identifying the limits to growth in population and industrial capital by using digital simulations in relation to the amount of the base materials.

The concept of a circular economy was born from growing concerns about the sustainability of the growing needs for resources. At that time, the idea of circular systems had been mostly discussed in an agricultural context. Justus von Liebig has adapted the term metabolism to refer to biochemical processes of natural systems: 'If it were practicable to collect, with the least loss, all the solid and fluid excrement of the inhabitants of the town and return to each farmer the portion arising from produce originally supplied by him to the town, the productiveness of the land might be maintained almost unimpaired for ages to come, and the existing store of mineral elements in every fertile field would be amply sufficient for the wants of increasing populations' (von Liebig, 1863).

However, more than a half-century ago, Kenneth Boulding conceptualised Earth as 'a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution' (Boulding, 1966). The allegory at the time was in agreement with the broader context in which ecological regionalism had started combining planning, design, and a biocentric understanding of natural processes within a politically grounded and civic-minded environmentalism. The concept of regional development has been advanced by Mumford who set the social world in the context of the natural ecosystem, for the first time recognising the mutual importance of both (Critchley, 2014). In this period, David Riesman (1958) was one of the first authors to use the term 'postindustrial,' referring to a society that turns its main focus of attention from work to leisure. Later, Daniel Bell (1973) offered the concept of 'a post-industrial society', defining it in terms of five dimensions. The first suggested a change from manufacturing to a service economy. The other four have defined the new relation between science and technology, representing new principles of innovation, new modes of social organisation, and new classes in society.

In this context, the Spaceship Earth metaphor has called for a new paradigm in science motivated by a utopian image of nature as a circular system that is stable, closed, and zero waste. According to Gao et al. (2020) to date, the evolution of the concept of circular economy can be divided into three stages: Preliminary Exploration Stage (1966-1992), Theoretical Model Stage (1992-2010), and Theoretical Integration and Application Stage (since 2010). However, since the beginning of this research an emergence of a new stage can be observed: a Traction Stage.

Paradigm - a world view underlying the theories and methodology of a particular scientific subject (Kuhn, 1962)



The Preliminary Exploration Stage is characterised by the reports of Kneese et al. (1970), Commoner (1971), Holdren and Ehrlich ('71 and '74 a.o.), Stahel and Reday (1976), Brundtland (1987), Pearce and Turner (1989), and others. They emphasised the importance of environmental sustainability of economic development and coined the term 'linear economy' as an antithesis of the ideal circular system. Early attempts have also been made to conceptualise industrial approaches for waste prevention, cradle-to-cradle impact assessment, local job creation, resource efficiency, and dematerialisation of the growing economy. It has been recognised that 'consumption patterns induced under capitalism <...> [and] the nature of private enterprise, with its predilection for shifting costs onto society in order to improve the competitive position of the firm', play a role in large-scale ecological problems (Harvey, 1974). Outside of the academic world, in this stage the Netherlands and Germany pioneered concepts of waste prevention and reduction driven by a desire to divert waste from landfills as early as 1979.

During **the Theoretical Model** Stage a number of methods have emerged that aimed to operationalise a dynamic closed-loop system while keeping track of social and environmental implications. The beginning of this time period is marked by the Meadows et al. (1992) report 'Beyond the Limits', which uses a digital model to test a series of basic global policy assumptions to show a range of outcomes, from collapse to a sustainable state. This period of time introduced or rediscovered concepts and metaphors that have been widely used since, such as industrial ecology (Graedel, 1996), biomimicry (Benyus, 1997), resilience and metabolism (Ehrenfeld, 2004), blue economy (Pauli, 2010), and others. Quantitative approaches to study the biophysical basis of human society have developed into standardised methods of Material Flow Accounting (MFA) (Fischer-Kowalski et al., 1994; Eurostat, 2001), input-output analysis (Miller and Blair, 2009) and Life Cycle Assessment (LCA) (Heijungs and Suh (2002), ISO 14044 (2006)). In Germany, the concept of the circular economy was introduced into environmental policy with the enactment of the 'Closed Substance Cycle and Waste Management Act' (1996).

Policy - the course of action of a governmental body, which translates into strategies, tools, or other public decision. It commonly involves: 1) setting goals, objectives, and 2) developing instruments of regulatory (e.g., bans), economic (e.g., taxes) and informational/voluntary (e.g., labels) nature (Costa et al., 2010)

In 2002 Japan followed with the 'Basic Law for Establishing a Recycling-Based Society', and, finally, China's 2009 'Circular Economy Promotion Law of the People's Republic of China' was the first policy document to adopt the term.

This research began in 2016, in **the Theoretical Integration and Application Stage**. Since 2010 the body of literature on the circular economy has gained momentum (Geissdoerfer et al., 2017) and increases exponentially each year (Calisto Friant et al., 2020). The beginning of this stage is no longer marked by a key theoretical publication but by an overall increase of academic and non-academic interest. The focus has changed from theoretical models to their application at the enterprise level and relevant business models (Gao et al., 2020). At the same time, an integration of different models has begun to take place to capture the complexity and interdependencies of all systems involved in material flows and their socio-economic impacts (Geissdoerfer et al., 2017). The Ellen MacArthur Foundation has emerged as a collaborative hub for businesses, policy makers, academia and consultancies (MacArthur and others, 2013). During this time period, the realisation came that the transition towards a circular economy requires enormous collaborative efforts between businesses themselves and supportive efforts from governments (van Buren et al., 2016; Amenta et al., 2019; Cramer, 2020). In 2015, the European Union also incorporated the concept by introducing a circular economy strategy into its action plans (European Commission, 2015), and several European countries have created dedicated strategies for resource efficiency (McDowall et al., 2017).

The beginning of **the Traction Stage** should be marked by two coinciding events. First, in 2019 the President of the European Commission, Ursula von der Leyen, has appointed Frans Timmermans as the executive Vice-President for the European Green Deal. Timmermans emphasised the importance of a circular economy 'to achieve climate neutrality by 2050, to preserve our natural environment and to strengthen our economic competitiveness' (Commission, 2020). As a consequence, an EU Circular Economy Action Plan (CEAP) has been released at the beginning of 2020 as the main building block of the European Green Deal.

Traction - the extent to which an idea, product, etc. gains popularity or acceptance

At the same time, the COVID-19 pandemic has spawned disruptions in global supply chains that caused the most severe economic crisis since the Great Depression in the 1930s. In turn, governments and businesses have recognised the need to reduce raw materials dependence, shorten supply chains, and create job opportunities in repairing, maintaining, recycling, and reuse (Network, 2021). Many countries have called for a 'green recovery' and saw the recovery from the crisis as an opportunity to speed up the transition (EMF, 2020). The focus has finally shifted from the circular economy being understood as a better strategy to manage waste to the circular economy as a strategy to prevent the looming crisis of resource scarcity.

As a result of the two events, the concept of a circular economy has started to

Friction - conflict or animosity caused by a clash of wills, temperaments, or opinions

gain significant traction in policy documents, the mainstream media, and marketing strategies. However, enormous traction has generated friction between the implementations in practise and the theoretical models preceding the concept. More and more recent academic papers are published that criticise practises that call themselves 'supporting circular economy' for not considering the balance between stock and flows, wrongly considering renewable resources as infinite, not taking into account energy needs and impacts, neglecting social considerations, and, overall, not sufficiently focused on general reduction of non-circular flows (Kirchherr et al., 2017; Haas et al., 2020; Calisto Friant et al., 2020; Clube and Tennant, 2020; Corvellec et al., 2021; Panchal et al., 2021; Schaubroeck et al., 2021; Savini, 2021).

The field of research itself is also scrutinised for not being able to agree on a single definition, displacing the problems across time and space instead of solving them, focussing on techno-capitalistic improvements instead of proposing cultural changes, prioritising developed economies, and finally being just a utopian concept, not yet proven by its successful implementation (Kirchherr et al., 2017; Skene, 2018; Kirchherr and van Santen, 2019; Haas et al., 2020; Calisto Friant et al., 2020; Alexander and O'Hare, 2020; Harris et al., 2020; Zwiers et al., 2020; Corvellec et al., 2021; Savini, 2021; Genovese and Pansera, 2021).

While the paradigm of the circular economy itself seems to be highly contested, there are no more discussions about the need for such a paradigm. The revolutionary search for a replacement paradigm - as Kuhn put it in his 1962 book 'The Structure of Scientific Revolutions' - is driven by the failure of the existing paradigms to solve relevant puzzles and respond to the rising challenges. Governments, businesses, and academia all strive to find a solution for a sustainable and resilient economy, while consumers increasingly require environmental and social accountability for their products and services. Therefore, reliable, transparent, comprehensible, and just representations of material flows and stocks are in high demand more than ever.

1.2 DEFINITIONS OF THE CIRCULAR ECONOMY

Circular economy refers to the type of economy that favours decoupling resource extraction from economic growth and aims at eliminating waste. Although it could be perceived as a purely economic term, paradoxically, it is not a theory about economics, but rather a theory of how material flows should be managed. In fact, it is not based on any economic, social, or philosophical model or theory (Velis, 2018; Calisto Friant et al., 2020). The term itself is sometimes described as 'means' or 'approach' to achieve sustainability or means to evaluate the productivity of resources, sometimes as the paradigm shift, but also just an umbrella term for all activities and solutions related to resource loops and their efficiency (Geissdoerfer et al., 2017). It tends to be purposely associated with other benefits, such as reducing pressure on the environment, improving the security of raw material supply, increasing competitiveness, stimulating innovation, boosting economic growth, creating jobs, providing consumers with more durable and innovative products, improving quality of life, and financial savings (Parliament, 2022).

Resource - objects of nature that are extracted by man from nature and taken as useful input to man-controlled processes (Udo de Haes, 2006)

Although the flexibility of the term and its plurality make the concept easier to promote and adopt, it also faces inconsistencies and limitations in its understanding, applicability, and validity (Geissdoerfer et al., 2017; Korhonen et al., 2018). As a result, there exists an extensive academic debate on the need for a unified definition of the circular economy (Kirchherr et al., 2017; Merli et al., 2018; Homrich et al., 2018; Corona et al., 2019; Tapia et al., 2021) motivated by the risk that a contested concept may collapse or remain in a deadlock due to permanent conceptual contention (Kirchherr et al., 2017) or even become discredited and disregarded as a new form of greenwashing (Calisto Friant et al., 2020).

Yet, framing the circular economy concept by a definition would mean accepting either

A circular economy can be achieved and there is a need to define the state in which the transition from our current economy to a circular one can be considered successful; or

B circular and non-circular economies exist in parallel and a definition is needed to label different elements of the economy as belonging to one or the other.

However, Assumption A is 'a modernist variant of the myth of eternal return' as Corvellec et al. (2021) put it. Due to thermodynamic principles, even if a material loop is successfully closed, it will inevitably create dissipation and entropy, resulting in losses of quantity and quality. Therefore, new materials and, consequently, energy will be necessary to overcome these dissipative losses (Cullen, 2017). Moreover, such an assumption would completely disregard uneven geographies of extraction and consumption, making the image of closed-loop sustainability 'profoundly unethical,' as explained by Alexander and O'Hare (2020):

'Even suggesting that such a thing is possible removes any impulse to reduce consumption or waste generation, since both are neatly recast as potential 'resources'. Arguments for a circular economy or closed loop waste processing are premised on flattening out scales, and framing the images such that leaks, disconnections, and uneven geographies are outside the frame. Perhaps a recognition that there will always be wastes that we will never know how to transmute into something harmless or positive is the first step to a collective responsibility towards resource extraction and consumption. Acknowledgement of ignorance can thus be recast as an ethical stance.'

At the same time, Assumption B is not meaningful, given that a circular economy has not yet proven to be a more sustainable kind of economy. While these two terms tend to appear hand in hand, unsustainable circular systems can also create a lot of social, economic, and environmental damage (e.g. due to excessive use of transport and energy, unattractive working conditions, or business abandonment due to failed adoption) (van Buren et al., 2016). Some previous studies upon conducting Life Cycle Assessment (LCA) have shown that closed loops are also not always favourable from an environmental point of view (Haupt and Zschokke, 2017). Geyer et al. (2016) argue that closed-loops do neither intrinsically substitute more primary resources owing to multiple loops nor per se guarantee higher environmental benefits on a unit basis. And finally, the potential rebound effect, also known as the Jevon paradox, especially likely in developing economies, may offset efficiency improvements by general growth in consumption and therefore material use (Schroeder et al., 2019; Siderius and Poldner, 2021; Zink and Geyer, 2017). Although CE may often prioritise the economic system as influential for the environment and society, sustainability is based on the balanced integration of economic, environmental and social performance (Geissdoerfer et al., 2017), which the circular economy cannot yet prove to deliver.

Therefore, this research intentionally does not choose a definition of a circular economy as the main principle. It takes the position that circular economy is rather an umbrella concept for diverse theories and approaches, which encompasses the determination to:

1. reduce overall virgin resource extraction;
2. reduce overall material disposal;
3. reduce overall externalities related to material flows and usage.

In this light, if responsible production and consumption is deemed an important criterion for any decision-making process - whether the project or proposal at hand is itself concerned with improving the circularity or not - the decision in question has to be assessed against those 3 commitments. No additional conditions are explicitly included in this determination, as all remaining challenges of the 21st century (roughly summarised by, e.g., the UN Sustainable Development Goals (SDGs)) should be implicitly included in any present and future policy, approach, and decision, simply from an ethical standpoint.

In this way, even if the concept of a circular economy ceases to exist, changes its name, or devolves into a marketing slogan, the research done under its name will not be discredited as long as it strives for a still relevant purpose.

1.3 MONITORING CIRCULAR ECONOMY

A growing number of policy documents are putting CE high on the agenda. However, the next step after the targets are set and the actions are listed is tracking progress and monitoring their effectiveness. While separate industries are able to set up monitoring mechanisms that concern their own material purchasing and disposal patterns and (in)direct impacts, governments hold the power to set up overarching monitoring systems. Although systems have the primary goal of educating government officials themselves, they may also serve and secure private efforts to accelerate the transition.

One of the powers governments hold is access to large-scale data from multiple sources in their area of power that can provide an overarching baseline model as a general benchmark against which the transition can be monitored. To avoid misplacing the impacts or wasting resources on low impact measures, governments are increasingly looking for macro-level monitoring frameworks (Harris et al., 2020; Saidani et al., 2019; Parchomenko et al., 2019) that would not only describe the status quo, but also provide direction for future decision-making (Planbureau voor de Leefomgeving, 2021).

In the European Union, it is the EU Circular Economy Action Plan (CEAP), published as part of the European Green Deal strategy (COM/2020/98), that describes targets, actions, and challenges for the transition towards a circular economy. The actions apply to the EU as a single system with shared regulatory frameworks, financial measures, and trade agreements. The success of the plan implementation is intended to be monitored by a shared Circular Economy Monitoring Framework, which tracks selected high-level indicators. However, even though effective international agreements and strategies are essential for sustainable development, most required actions take place at the local level. Thus, the very nature of the concept asks one to 'think globally - act locally.'

Being a supranational document, the CEAP has rippling effects on national, regional, and local policies throughout Europe. Several cities and urban regions have already announced their own circularity ambitions and strategies to improve circularity at the local level (Petit-Boix and Leipold, 2018; D'Amico et al., 2022), while others will be mandated by the Commission to prepare plans to 'make the best use of EU funds' (European Commission, 2020). Therefore, monitoring frameworks are a crucial component of CE strategies of many European cities. Their main purpose is to assess how the city is performing towards the achievement of set targets and to guide decision-making based on measurements (OECD, 2020).

Although the monitoring frameworks are already being set up and developed at different administrative and geographic scales (e.g. a study by OECD has found 29 monitors, of which 8 are applied at the national level, 8 at the regional level and 11 at the local level with the majority of them originating from Europe (OECD, 2020)), there are certain challenges that hinder their implementation and effective usefulness.

First, there is an ongoing debate about exactly what it is that needs to be monitored, likely due to the lack of agreement on exactly what the transition towards a CE is supposed to achieve (Kirchherr et al., 2017; Corona et al., 2019). Currently, existing frameworks are widely criticised for being too aggregate and therefore generic (Haberl et al., 2019), disconnected from environmental impacts, not able to measure reduction or prevention (Harris et al., 2020), and not related to concrete targets nor accompanying policies (Friant et al., 2020). Moreover, due to the large variety of existing frameworks, comparison between different cases is barely possible (Mayer et al., 2019). Finally, if everyone decides to measure different things, there is a risk that the circular economy will only be implemented in ways that do not mitigate environmental and social burdens, but instead place them in the monitoring blind spots (Brandão et al., 2020).

Second, the availability of data is a clear bottleneck for monitoring the circular economy (Alaerts et al., 2019). Even at the highest level of aggregation, there are obvious statistical gaps that do not allow indicator tracking (OECD, 2020), mainly due to the fact that some of the dimensions of the circular economy have historically not been reflected in statistical databases.

In fact, the two challenges form a vicious circle in which certain indicators are not chosen due to a lack of data availability to support them, while at the same time certain data are not collected because there is no proof of their usefulness for monitoring. However, an indicator needs to be observed over time to prove its utility. An even greater paradox can be observed with regard to waste statistics. On the one hand, the availability of statistics causes the waste sector to be over-represented in monitoring frameworks (OECD, 2020). On the other hand, the quality of waste statistics is highly criticised for its incompleteness and discrepancies when it comes to numbers that are especially relevant to the circular economy (e.g., discrepancies between the amount of recovered and actually recycled materials that replace primary resources) (Mayer et al., 2019).

Although the discussion of the most suitable indicators to monitor the circular economy is very prominent in the research community and policy documents, data availability is only mentioned as a technical necessity. Although researchers agree that to craft a meaningful monitoring framework, multiple data sources need to be integrated and conceptualised together (Elia et al., 2017; Haupt and Zschokke, 2017; Pauliuk, 2018), concrete discussions on statistics regulations and improving data quality for the sake of circular economy monitoring seem to be limited to micro- and meso-levels.

However, setting up new data collection infrastructures and ensuring data quality in terms of interoperability, accessibility, and reusability requires significant time and investment of resources. This is especially difficult when data are collected by different institutions under a multitude of overlapping regulations and frameworks. For example, the current Waste Statistics Regulation was originally proposed in 1999, came into force in 2002 and the first data reports from the Member States were submitted only in 2006 (based on the data of 2004) (Hansen et al., 2002). Recognising this, CEAP suggests that the Circular Economy Monitoring Framework needs to build up as much as possible on existing European statistics without discussing their suitability for the newly defined challenges.

Therefore, this research purposefully takes a different approach, and instead of discussing what *should* be measured in the endeavour of a circular economy transition, it asks - what *can* be measured *already* and what changes could help break the vicious circle of circular economy monitoring.

1.4 WASTE IN THE CIRCULAR ECONOMY

Although the Circular Economy is still often referred to as the Zero Waste Economy, it has been already established that achieving the state of zero waste will not be sufficient to address the problem of resource scarcity (Zink and Geyer, 2017; Krausmann et al., 2018; Korhonen et al., 2018). In fact, the balance of material flow accounting on a scale of the European Union (Figure 1.1) clearly shows that at the current rate of primary resource use even if 100% of all waste mass would be brought back into the economy, it could only substitute 37,8% of the total mass currently used.

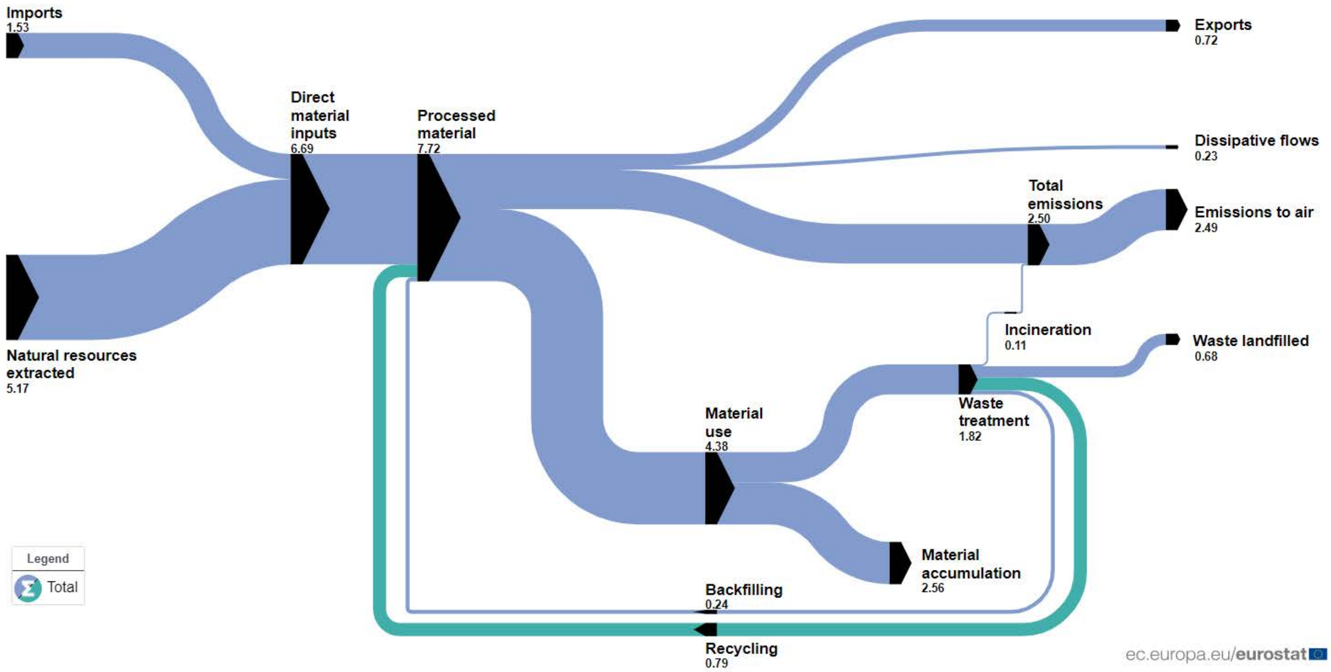


Figure 1.1. Material flows true scale in Gt/year (billion tonnes per year) in 2019, EU27. Source: Eurostat

However, even if recirculating waste back into the economy is not the only strategy that needs to be implemented in light of material scarcity, this strategy is still necessary for at least two reasons. First, waste contains materials and substances that have been once extracted for use for a certain purpose. If the purpose is still relevant, new materials of the same kind will have to be extracted to fulfil it, this way directly contributing to the issue of resource depletion. Second, waste causes pollution and environmental damage by simply being placed out of sight (Alexander and O'Hare, 2020).

Finally, the very concept of closing material loops relies on the assumption that there exists a graspable 'loose end' with which to close the loop. The assumption is born from an image of a landfill where an enormous yet contained pile of materials lies unwanted, causing nothing but visual and odour nuisance and soil pollution. Anybody willing to invest their energy into recovering anything of value out of this pile is simply welcome to do so. However, in developed countries these unowned piles of materials are becoming less and less present as different waste processing methods are introduced for both environmental and economic reasons (Pires and Martinho, 2019; Egüez, 2021). The presence of these methods and the absence of a pile that nobody wants or knows how to handle raises the question, what is waste then? Can it still be considered a 'loose end' if it has already become a commodity, to be traded on a global market?

Ironically, countries that have the highest ambitions for a circular economy have the lowest landfill rates (Figure 1.2). This means their ambitions on closing the loops have to be based rather on redirecting waste from one actor to another

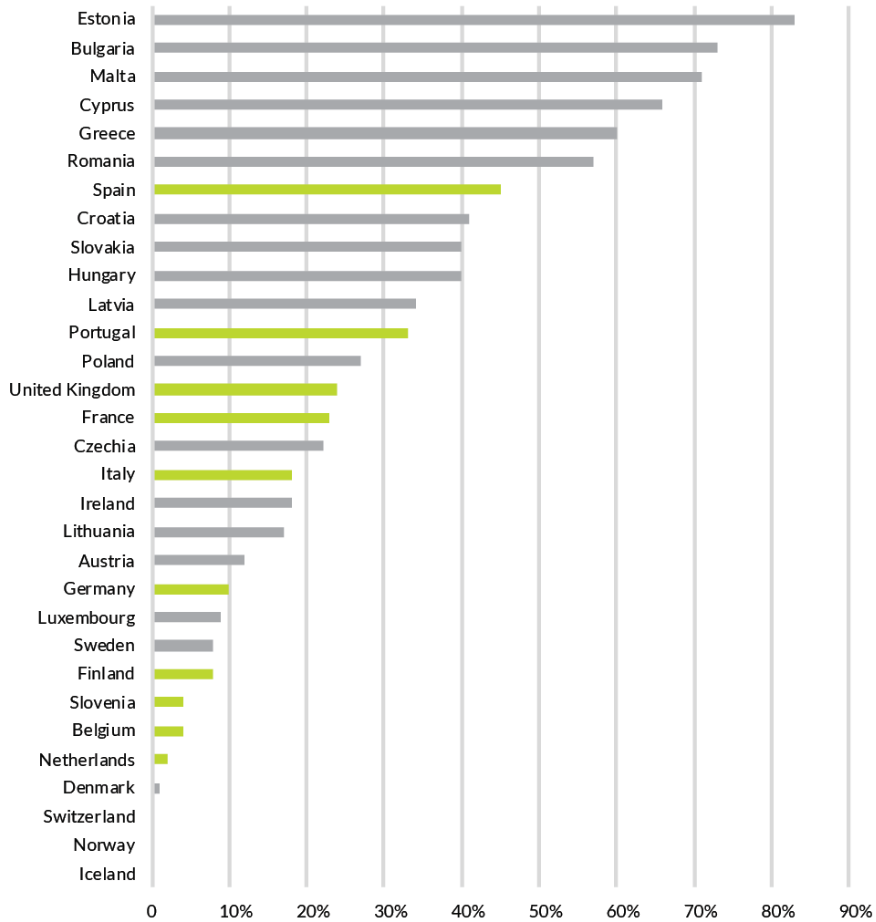


Figure 1.2. Landfill rate of waste excluding major mineral wastes per country, latest available year, source: Eurostat. Highlighted bars indicate countries with initial circular economy monitoring frameworks, source: OECD

instead of utilising absolute discards. According to the definition of the European Union (Waste Framework Directive, 2008/98/EC), waste is 'any substance or object which the holder discards or intends or is required to discard.' The definition involves not only the discarded matter but also the one that discards it, which means that the emergence of waste is ultimately a choice made by the owner of the material (Jorgensen, 2019). Therefore, circular economy strategies based on closing material loops must first and foremost acknowledge and address the complexity of waste and its volatile definition.

Alexander and O'Hare (2020) suggest five methods by which wastes are conjured in and out of view, which are principally temporal, spatial, epistemological, calculative, or rhetorical. When waste is considered a burden, those methods are used to diminish the actual scale of the problem. However, when the narrative is reversed and waste becomes a necessary resource, the same methods are used to increase the potential wins of the new strategies:

Temporal displacements. Past wastes are often discounted as 'not a problem created by us' and at the same time products and systems are designed that will create waste in the future as 'a problem to be solved by the future generations'. Yet within the narratives of the circular economy, 'the future waste is already here, so a real circular economy approach should take into consideration how we deal with massive stocks and the involved secondary materials' (Mavropoulos and Nilsen, 2020).

Spatial displacements. If declaring a substance or objects as waste is merely a choice of its owner, then shifting all waste owners away from a certain area creates a 'waste-free' zone, even if waste is essentially produced in direct relation to the activities happening in that area. At the same time, circular economy strategies are trying to close the loops locally by reclaiming the wastes that are currently exported to foreign economies.

Epistemological displacements. Waste is a product of design, yet engineers and designers are spared from the responsibility due to the 'greater public good' they create. The responsibility of waste production lies with the one that discards the product rather than with those who produce it. For this reason, energy production waste dominates in both the economic and environmental sense, but is much less discussed than consumer waste (Skene, 2018). However, when waste becomes a commodity instead of a burden, credits of its potential value are given in advance to the producer, regardless of possible decisions later on (Schaubroeck et al., 2021).

Calculative displacements. The scale on which waste is considered a problem depends on the unit of measurement. If weight is chosen as a measure, then mineral and industrial wastes are the most prominent ones (Farmer, 2020), while the amount of hazardous emissions caused by waste draws our attention to organic wastes (Sanjuan-Delmas et al., 2021). On the solution side, the calorific value of incineration makes some waste seem less problematic than others. At the same time, the economic value of scarce resources may eclipse the environmental damage caused by recycling them.

Rhetorical displacement. Renaming waste into a 'resource' makes the problem of waste disappear even if it risks creating a lock-in for the future or paradoxically increasing the demand for waste rather than reducing waste volumes (Greer et al., 2021) (e.g., in the case of incineration plants where waste is suddenly framed as an endless source of energy generation). On the other hand, calling something waste grants permission to intervene and take action to eradicate it. For example, a substantial share of waste that is processed by the informal sector is automatically not considered circular (Corvellec et al., 2021).

Being a significant source of environmental pollution, waste is heavily regulated by national and supranational bodies. Especially within the European Union, the EC Regulation No. 2150/2002 on Waste Statistics requires every European country to report biannual statistics on waste generation and treatment per economic activity, treatment method, and population served. The regulation provides general guidelines; however, each country applies a different data collection method. The waste statistics produced due to the given regulation are used (or intended to be used) in circular economy monitoring frameworks across the EU as mandated by the CEAP. Yet the CEAP does not suggest any changes in the Waste Statistics Regulation.

Therefore, the question remains - if the notion of waste is so fluid, how well can the European Waste Statistics provide decision guidance for the circular economy transition?

1.5 GOAL AND SCOPE OF THE RESEARCH

To sum up the previous sections, this research falls under the societal challenge of resource scarcity that for the first time needs to be addressed not within a scale of a limited geopolitical area but as a global risk. The circular economy is gaining traction as a leading concept in policy documents and marketing campaigns, while at the same time causing ongoing academic debates about its scientific coherence. Furthermore, the challenge of resource scarcity must not be addressed in isolation and must take into account the general challenges and megatrends of the 21st century. In line with the rising megatrend of digitalisation, there is a growing demand for the digital macro-level monitoring frameworks that can inform decision-making in pursuit of the circular economy ambitions.

While there is an active ongoing scientific debate about what a CEM *should* be monitoring, there is little debate on what a CEM *can* be monitoring based on the data that is currently available. Even if new data collection requirements can be introduced later to fulfil the needs of a monitoring framework, certain changes in data collection require long-term a-priori efforts. These include changes in conflicting regulations, setting up technical infrastructures, development of appropriate models and taxonomies, quality assurance, and validation.

Instead of being just a technical task, many of the changes require in-depth research grounded in scientific theory. Otherwise, CEM as a decision support tool risks promoting circularity based on the notions of no limits, secondary resources complementing instead of supplementing primary supplies, and governments leaving the responsibility entirely in the hands of businesses and consumers (Corvellec et al., 2021). Therefore, given the scope, speed, and scale of transformation that the circular economy agenda aims at, the challenge must be tackled simultaneously from both sides.

Instead of tackling the full spectrum of circular economy strategies, this research focusses on the most fundamental of them: closing material loops using waste streams. To explain how far we can get with improving waste-related practises and which materials require a different approach to overcome their scarcity, adequate data on waste production, disposal, and treatment are crucial. In theory, such data is already collected by Eurostat under the European Regulation of Waste Statistics. However, in practise, the availability of data remains a key challenge (REPAiR (2016) based on UNECE 2014) for the monitoring and transition of the circular economy.

Therefore, the goal of this thesis is to investigate why European Waste Statistics are currently not able to respond to the key challenge of data availability. The goal is not only to identify the reasons behind the current limitations but also to reveal how the available data collected as mandated by the European Commission can already contribute to circular economy monitoring. To achieve the goal, this research aims to

1. Define the data challenge in circular economy monitoring by developing a theoretical framework to assess decision impacts and guide the process of decision-making;
2. Define data requirements for circular economy monitoring;
3. Provide a detailed account on the possibilities, opportunities, risks and limitations of the waste statistics and their role in circular economy monitoring on a regional scale.

Since the first CEM examples appeared in 2021-2022, it has not been within the scope of this research to review current practises of CEM development. It is also not within the scope of this research to review existing macro-scale monitoring frameworks as this review has been performed by multiple other authors (e.g. Harris et al. (2020); Morseletto (2020); Saidani et al. (2019); Corona et al. (2019); Parchomenko et al. (2019); Korhonen et al. (2018)). They concluded that currently existing frameworks have limited utility due to the suboptimal selection of indicators on the one hand, while technical difficulties of implementation related to the lack of data and tools on the other hand.

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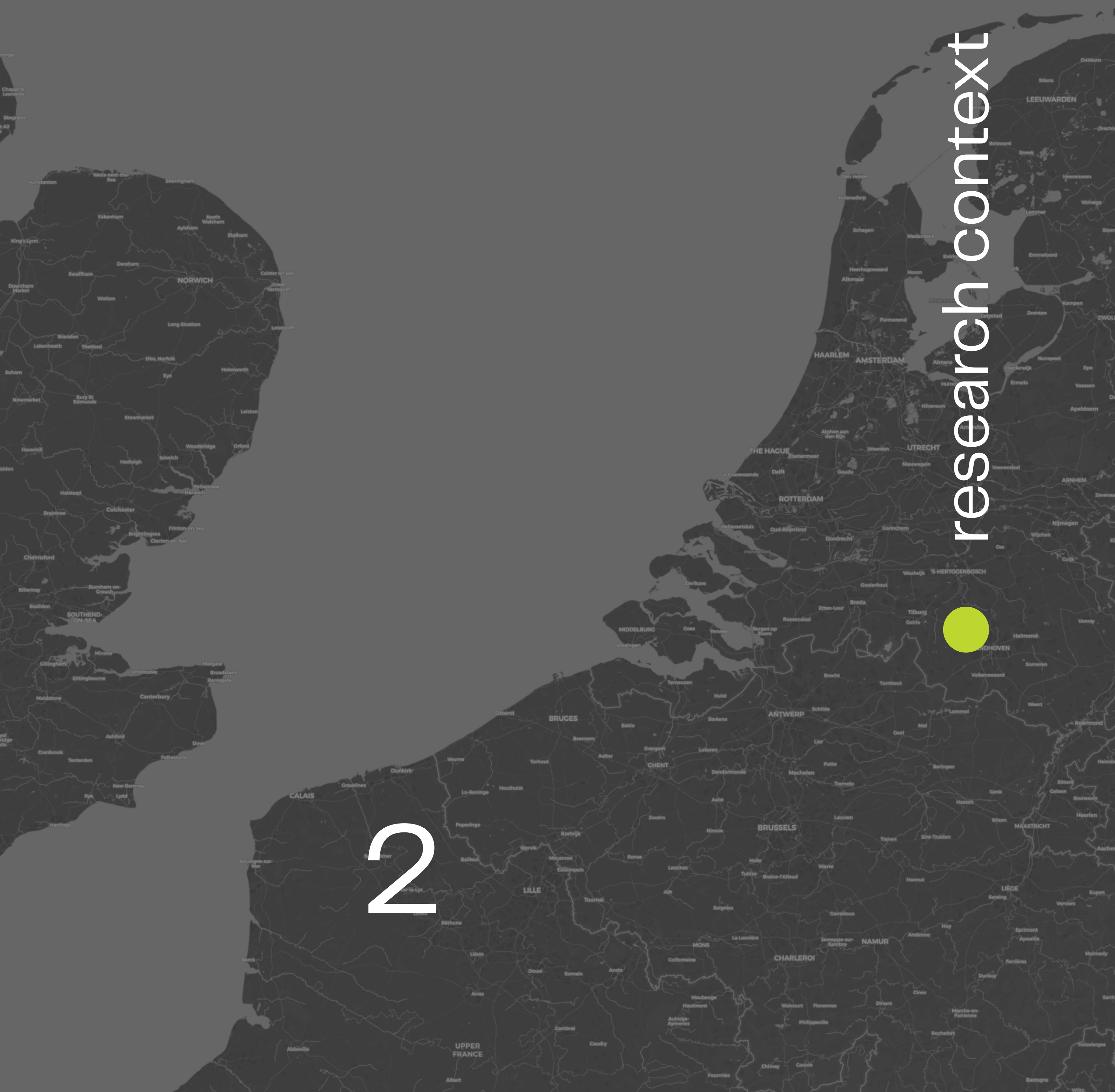

2

research context

research context

2

2.1 AMSTERDAM CITY

Known across the world as the country of trade, characterised by high population density and water-dominated landscape, the Netherlands has realised early on the environmental and economic benefits of sustainable waste management. As a result, it has been ranked among the top countries in the EU in waste management performance (BiPRO, 2012). To reduce the country's dependency, increase resilience, and reduce climate impact, in 2016 the Netherlands announced its ambitious goals towards a circular economy. The country aims to be 'fully circular' by 2050, with an interim target of a 50% reduction of primary raw materials by 2030 (Rijkswaterstaat, 2016). However, at present, the targets are in conflict with economic goals, as many organisations participating in the waste sector have an economic preference for constant or growing waste streams (Arlati et al., 2017).

Approximately once every six years the Ministry of Infrastructure and the Environment (NL: *Rijkswaterstaat*) releases the National Waste Management Plan (NL: *Landelijk Afvalbeheer Plan, LAP*) (ICER et al., 2021). The LAP functions as the assessment framework to grant environmental permissions for waste management related aspects as defined in the Environmental Management Law (NL: *Wet Milieubeheer*). According to this law, local authorities are obliged to adhere to the national policies set by the Ministry. At the same time, they can develop specific waste management policies and set their circularity targets.

Following the country's ambitious goals, Amsterdam, the capital of the Netherlands and one of the key cities in the Northwest-European Delta Metropolis, has set out on a mission to be the leading city in terms of the circular economy. Until the pandemic induced crisis in 2020, it has been the fastest-growing city in the country in terms of inhabitants with an average population increase of 10 000 inhabitants per year (Amsterdam, 2022). The growing number of inhabitants will most probably result in a growth in resource use due to more building activities, higher energy demand and overall consumption. To counteract the growth, the city has created a Circular Strategy 2020-2025 that has been published a year earlier than the European CEAP.

Pioneering is the city's general approach to change and innovation. Policymakers choose the path of experimentation and prioritise action to caution (Prendeville et al., 2018). Following the same attitude, the city has created a monitoring framework as part of its Circular Strategy and is currently on the way to implement a digital Circular Economy Monitor (CEM) (Gemeente Amsterdam, 2020). The CEM will track progress over time towards the set goals, highlight which areas need improvement and estimate target feasibility.

Despite the city's high ambitions and pioneering attitude, a number of barriers still hinder the transition. Campbell-Johnston et al. (2019) and Obersteg et al. (2019) have summarised Amsterdam's challenges as following:

- Knowledge on material quality and quantity;
- Banks reluctant in financing CE business models;
- Up-scaling/mainstreaming pilot projects;
- Low cost of virgin materials relative to secondary ones (linear lock-in);
- Legal definitions of waste being vague but restricting specific subsequent use;
- Global production and material flows going beyond scope of municipal instruments;
- Multi-level policy integration on standards and material regulations;
- Hesitancy/unawareness of companies to integrate CE practices and business models;
- Consumer readiness to pay premiums for circular products;
- City parameters restricting the planning and scope: this requires greater space for the coordination of reverse logistics;
- Presence of polluted or noise-restricted peri-urban wastescapes in port and airport areas;
- Tender and tax procedures not integrating CE principles;
- Knowledge fragmentation within and asymmetry between organisations (intra- and inter-institutional).

CEM is expected to help solve a number of the mentioned issues by providing transparency on the quantity, quality, and frequency of material flow, analysis of circular potentials, environmental savings, and impact of decisions.

The other group of issues, related to the scale and reach of the city's instruments, calls for an expansion of the geographical area considered for monitoring, as well as policies. Therefore, the geographical extent of the Amsterdam CEM extends beyond the municipality's boundaries and considers the Amsterdam Metropolitan Area (AMA, NL: *Metropoolregio Amsterdam, MRA*) a relevant urban region (Figure 2.1).

The AMA forms the northern part of the larger polycentric Randstad region and

Figure 2.1. The position of the Amsterdam municipality and Amsterdam Metropolitan Area in the Netherlands

comprises 32 municipalities, two provinces and the Transport Authority, with Amsterdam municipality located at its geographic centre (MRA, 2022). The region partly overlaps two provinces: North-Holland and Flevoland. It does not fall under a jurisdiction of a single governmental body and has to be understood as rather a partnership between the adjacent municipalities than an administrative unit. However, the region shares a range of policies including economic development, transport, and aspects of spatial planning related to urbanisation, landscape management, and sustainability (MRA, 2022).

When it comes to the management of municipal waste (which is mainly composed of household waste), municipalities in the Netherlands can make direct decisions on its collection, separation, and treatment. However, industrial waste is regulated by the market conditions with companies arranging contracts directly between themselves. However, the mass of industrial waste in the AMA is estimated to be up to 9 times the mass of municipal waste (Gemeente Amsterdam, 2020). Therefore, to reach the ambitious targets the city of Amsterdam has committed to, the industrial waste has to be targeted through partnerships and supporting policy instruments which can be implemented using the AMA as a cooperation platform.

The city has started CEM development in 2020 after the launch of the Circular Strategy. The first online version of the monitor was launched in February 2022. The first version is focusing on providing material input, consumption and waste indicators and an assessment of the related environmental impacts based on the historical data. It focuses rather on defining the current state of material consumption than generating insights into the possible improvements or allowing future impact assessments. The development of these features are prevented by a number of barriers discussed further in this research.

2.2 CIRCULAR ECONOMY MONITOR AND SPATIAL DECISION SUPPORT SYSTEMS

The OECD Report on the Circular Economy in cities and regions (OECD, 2020) distinguishes four key objectives in monitoring circular economy:

1. triggering actions;
2. making the case for the circular economy;
3. monitoring performance and evaluating results; and
4. raising awareness.

The same objectives, although termed differently, are set forward in the Amsterdam CEM (Gemeente Amsterdam, 2020):

1. determining the CE decision-making space;
2. evaluating the feasibility of local CE strategies;
3. assessing the social and ecological impact;
4. and communicating the results to the public.

Although CEM is a new concept, that to date does not have enough precedents to be analysed, similar objectives can be found in systems supporting other topics of public concern such as site selection, resource allocation, network routing, location-allocation, and service coverage (Keenan and Jankowski, 2019).

Circular economy is primarily driven by the agreements between multiple actors to share resources, materials and infrastructure for as long as the physical properties of the resources allow. The process is also facilitated or aggravated by external factors, such as legal requirements and administrative procedures, taxes, the presence of knowledge platforms and infrastructures, and the physical collection, storage, and transportation of the resources. This increases the pool of stakeholders that acting together may create collective strategies to achieve higher benefits to everyone's interests. Although, in theory, mathematical models could be used to optimise the total sum of individual, environmental, social and economic benefits, in practice the system is too complicated to be correctly modelled.

To solve similar ill-defined problems Spatial Decision Support Systems (SDSS) are used. An SDSS can be defined as an interactive, computer-based system designed to support a user or a group of users in achieving higher effectiveness in decision-making while solving a semi-structured problem that has spatial consequences (Malczewski, 1999). Decision Support Systems are meant to support rather than replace human judgements and improve effectiveness rather than efficiency of a process (Uran and Janssen, 2003). This means that a user is expected to utilise the system as an advisory unit that is simply more capable to digest large amounts of data and perform quick computations.

Moreover, modern systems are no longer characterised as purely 'decision support' but rather as 'discussion support' because they have the capacity to evoke and clarify discussions between stakeholders instead of representing optimal results (de Wit et al., 2009). The discussions are supported by explicit assessments of probable impacts during the early stages of spatial planning, policy and business model creation and negotiation. The assessments may vary greatly in their accuracy, precision and complexity ranging from back-of-the-envelope calculations to extensive models involving digital twins (dos Santos et al., 2022) or artificial intelligence algorithms (Vitorino de Souza Melaré et al., 2017). In either case it is expected that a-priori assessments of decision impacts and of their significance may help to prevent irreversible damages and lock-ins, encourage creation of solutions with smallest negative (or largest positive) impact, and reduce financial risks.

Depending on their time synchronisation and user locations, SDSS can fall into four categories that define their characteristics (Sun and Li, 2016): *same time / same location, same time / different location, different time / same location*, and *different time / different location*. A GDSE developed during the REPAiR project falls into the category of *same time / same place* SDSS where all participants in a discussion are

Asynchronous distributed SDSS tasks	**Circular Economy Monitor tasks**	
Describe and assess current system and its performance	Present current and past statistics, indicators and their environmental, economic and social impact	
Formulate objectives	Present CE targets	
Generate alternatives	Present upcoming policies and regulations	Allow modelling resource flow changes
Model decision impacts	Present which parts of the system the upcoming policies will affect	Present which parts of the system the potential changes will affect
Assess decision impacts	Present how policies and other changes will contribute to the targets and what environmental, social and economic impacts they will create	
Communicate results	Present changes using data visualisation methods and raw numbers	
Collect and register feedback	Allows users to express their doubts, questions, suggest changes and report errors	

Table 2.1. Correspondence between the tasks of an asynchronous distributed SDSS (adapted from Ferretti and Montibeller (2016) and Simao et al. (2009) and tasks of a CEM

located around a single screen in a workshop setting. A CEM - if considered as an SDSS- , however, would fall under the category of *different time / different location* SDSS where users are expected to get the supporting information for their tasks and provide feedback at any time and from any location. An asynchronous distributed SDSS is essentially a web application that can perform a number of tasks to support the decision-making process without the need to perform real-time modelling or simulations (Table 2.1).

Given the similarities between the two types of systems, the risks that apply to the effective usefulness of an SDSS should also be taken into account when designing a CEM. The most common ones have been repeated in multiple SDSS reviews from Uran and Janssen (2003) to almost two decades later by Carneiro et al. (2021):

Expressiveness: Sufficient semantic granularity, relevant criteria, scope and extent, and appropriate expertise levels that allow the system user to express their concerns and interests and see them sufficiently reflected in a model;

Representativeness: acknowledgement that a model is only capable of representing certain parts of reality and all goals and intentions cannot be captured in it; therefore, the system has to allow other than structured and numerical ways of representation;

Interaction: ease of use, user-friendliness, and clear communication strategies suited for the level of expertise of users.

At the same time it is important to acknowledge that CEM is not entirely an SDSS. While the two systems do share a number of similarities, there also exist critical differences between the two.

First, an SDSS has clearly defined system boundaries, input variables, and output indicators. The system parameters and models are typically static and represent a certain period of time. However, the CEM is regarded as a knowledge base where new information can be added as it is acquired, therefore constantly expanding on the boundaries, variables and indicators. Furthermore, a CEM aims to affect stakeholders so that they can make individual decisions that together would push the system in the direction of a circular economy transition. Unlike in the case of an SDSS, there is no single decision-making body and no single responsible institution for the final result. Therefore, a CEM, differently from an SDSS, has additional requirements:

1. to support knowledge base growth,
2. to monitor changes over time instead of representing a single snapshot, and
3. to trace capture the effects of decisions made in the past based on the changing data.

2.3 EUROPEAN WASTE STATISTICS REGULATION AND GOVERNANCE

Regardless of the global waste network, there is no international legislation related to waste statistics (Motuzka, 2020). The supranational legislation that includes the biggest pool of countries is the EU policy on waste. It has developed largely over the last half a century, driven by the aim to harmonise waste policy and this way prevent distortion in competition (Hansen et al., 2002). The development of EU waste policies has been motivated mostly by environmental concerns, therefore emphasising waste prevention, eliminating landfilling, and strictly controlling hazardous waste.

There are three ways in which the EU influences waste management in its Member States (Costa et al., 2010):

Regulations that are laws applied in each member state;

Directives that set binding objectives for member states even though the objectives can be incorporated in the national legal systems considering local distinctiveness;

Decisions that bind particular individuals, firms or member states, to perform or refrain from an action, confer rights or impose obligations.

> Waste policies are addressed through a number of directives, which explains why waste management and statistics are approached differently by each country resulting in different policies and legislation.

Waste policies in EU are expressed through a series directives of which the most relevant to this research are:

Waste Framework Directive 2008/98/EC, which defines the general waste management requirements, among which the waste hierarchy and the general principles of Precaution, Proximity, and Polluter-Pays;

Regulation (EC) 2150/2002 on Waste Statistics, which obliges member states to report statistical data on generation and processing of waste in compliance with the European Waste Classification for Statistics (EWC-Stat);

Manual on Waste Statistics, Guidance on EWC-Stat Waste Categories, and Supplement to the Manual for the Implementation of the Regulation (EC). No. 2150/2002 on Waste Statistics, which is intended to provide assistance to statistical data reporting and statistical data users in data interpretation.

Commission Decision 2000/532/EC, which defines the List of Waste (LoW) for administrative purposes, that is, for issuance of permissions, supervision of waste generation, and waste management. The list specifies 839 types of waste, defined by 20 sections.

Regulation (EC) No 1013/2006 on shipments of waste; which requires member states to take into account the principles of proximity, priority for recovery, and self-sufficiency at the community and national levels.

Waste Statistics are reported to Eurostat bi-annually by each member state using a special form. Each member state is responsible for collecting and combining the statistics using its own methods and sources. The guidance document is not binding as it only provides advice for the collection process. As a result, there are significant differences in the quality and consistency of the waste reporting between the member states (Deloitte, 2017). The differences are partly due to the different methods using which the statistics are combined, i.e. some member states use detailed waste registries where waste producers, collectors and treatment facilities submit detailed reports about each waste movement, while others perform sample surveys which are later statistically extrapolated.

However, the other part of inconsistencies owe to vague definitions of shared terms and nomenclatures. For example, waste amounts are reported according to the EWC-Stat categories, which have official correspondence with the List of Waste (LoW) categories. In practise, some countries use EWC-Stat categories, others LoW, and some proceed with their own classification systems. Conversions between the different classifications are not always performed in a consistent manner as waste can be classified by source of generation, process of generation, composition, characteristics, type of generation and collection (Motuzka, 2020). Furthermore, the same terms are often used to denote different concepts, e.g., municipal, solid, and household waste being used interchangeably, processing methods aggregating to different groups, etc. Finally, Eurostat reports inconsistencies due to mass losses due to dehydration, double accounts of waste when it goes through two or more phases of processing, exports and imports of waste, and the lag of time between waste generation and processing (Motuzka, 2020).

Senatore and Teofili (2021) name the following reasons behind the named inconsistencies:

- Insufficient verification of the data at the EU and national level and a lack of incentives for accurate data reporting;
- Delays in the implementation of digital waste data reporting systems; and
- Delays in the improvements of the EU-wide specifications of definitions, criteria, targets, and standards for data verification.

Aside from the statistical shortcomings, EU Waste Directive has been criticized for failing to address as following (Bartl, 2014; Motuzka, 2020; Senatore and Teofili, 2021):

- Conflicts of interest in the waste management sector as any successful waste prevention decreases the turnaround and profit of waste collectors, recyclers, incinerators and landfill operators;
- Decoupling of waste generation from economic growth without burden shifting behind the European borders;

- Measuring waste prevention, increasing product durability, promoting repairability and eliminating planned obsolescence which at the moment are formally encouraged but practically not monitored nor rewarded;
- Illegal waste management which includes imports, exports, collection, trade, burial and sorting by registered and unregistered entities in the private sector.

It must be, however, mentioned that the CEAP (2020) acknowledges the four points of criticism and aims to address them in the upcoming EU policies. Yet the statistical inconsistencies are not mentioned.

While most Member States collect waste data using sample surveys, the Netherlands employs a consistent waste registration from every company that has a waste permit. Since 2006, this data is centrally collected through a written survey and organized through the register for *Afval Meldingen Informatie en Communicatie Electronisch,* in short AMICE-register, at the Waste Registry Division of the Dutch Ministry of Infrastructure and Public Works (NL: *Landelijk Meldpunt Afvalstoffen (LMA)*). This means that Dutch cities have very detailed and complete data available for the monitoring.

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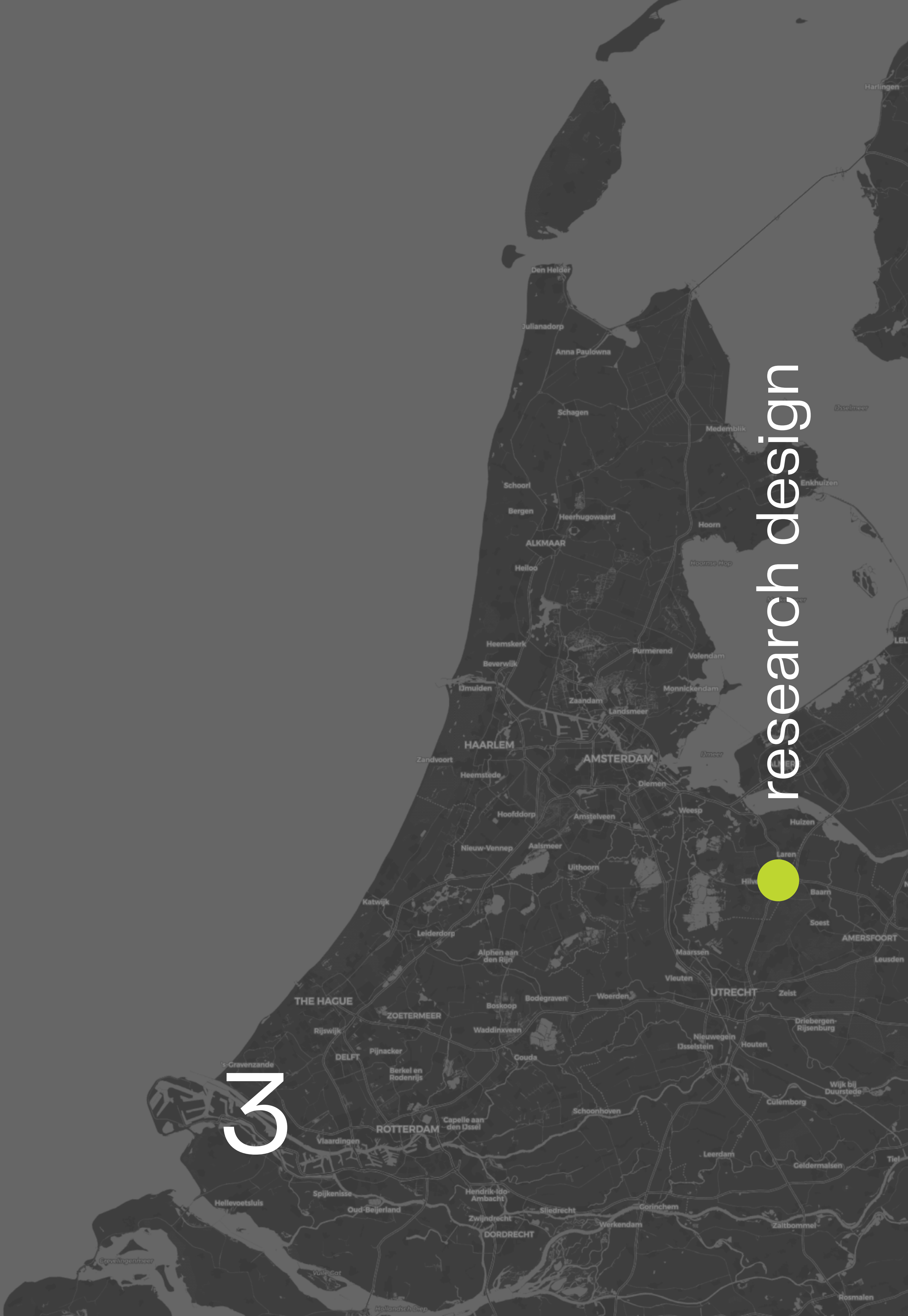
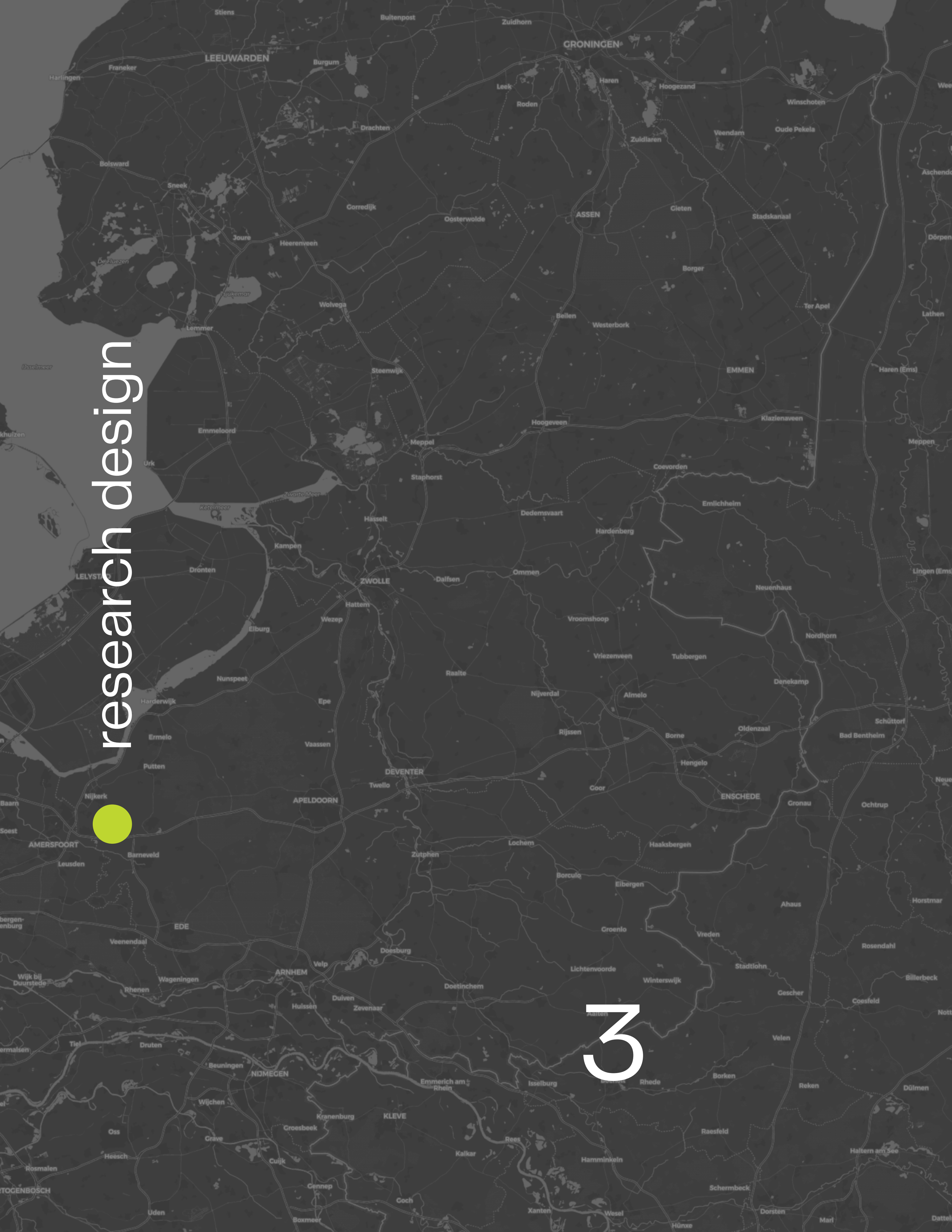
3 research design





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3

3.1 RESEARCH QUESTIONS

The answer to the main research question naturally requires that recommendations are provided on how European waste statistics can be improved to respond to the challenge and sufficiently support the transition towards a circular economy.

Based on the research goals and context described in the previous chapter, the overarching research question is:

Why is European Waste Statistics not responding to the key challenge of data availability to advance the transition towards a circular economy?

The following subquestions are posed to investigate different aspects of the main question using data from the Dutch National Waste Registry in the Amsterdam Metropolitan Area as a case study:

1. A How can policy decisions be assessed in pursuit of a circular economy?
   B What data requirements are set out by the need to assess decision impacts?
2. A What are the expectations and requirements for the circular economy monitoring in the Amsterdam Metropolitan Area?
   B On what theory should circular economy monitoring be based on?
   C How can user expectations and theory be aligned with available data and tools?
3. A How does the Dutch National Waste Registry correspond to the expectations and requirements for circular economy monitoring set in the previous chapters?
   B How does the European Waste Statistics Regulation influence data characteristics?
4. A How can the data from the Dutch National Waste Registry help assess the impacts of decisions in the pursuit of a circular economy in the Amsterdam Metropolitan Area?
   B Which data limitations hinder monitoring and transition towards a circular economy?
   C How can the European Waste Statistics Regulation be improved to better support the transition?

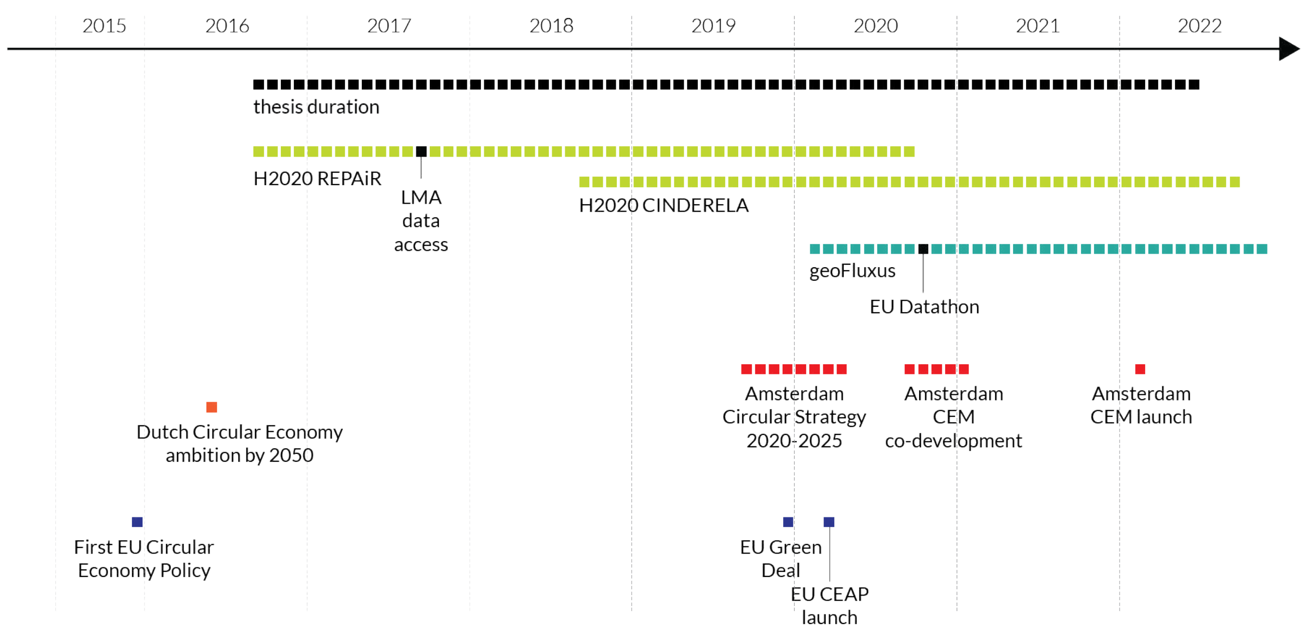


Figure 3.1. Timeline of projects, policies and events that closely relate to this thesis as explained in this section

3.2 RESEARCH SETUP: REPAiR, CINDERELA AND GEOFLUXUS

This research has been conducted under the framework and in close collaboration with two H2020 projects and further continued as an academic spin-off geoFluxus, cofounded by me and a fellow Ph.D. student Arnout Sabbe.

Furthermore, the research is funded by the Amsterdam-based joint TUD (Delft University of Technology), WUR (Wageningen University and Research Centre) and MIT (Massachusetts Institute of Technology) initiative, Amsterdam Institute of Advanced Metropolitan Solutions (AMS), within the research theme Circularity in Urban Regions.

3.2.1 REPAiR: Resource Management in Peri-urban Areas: Going Beyond Urban Metabolism

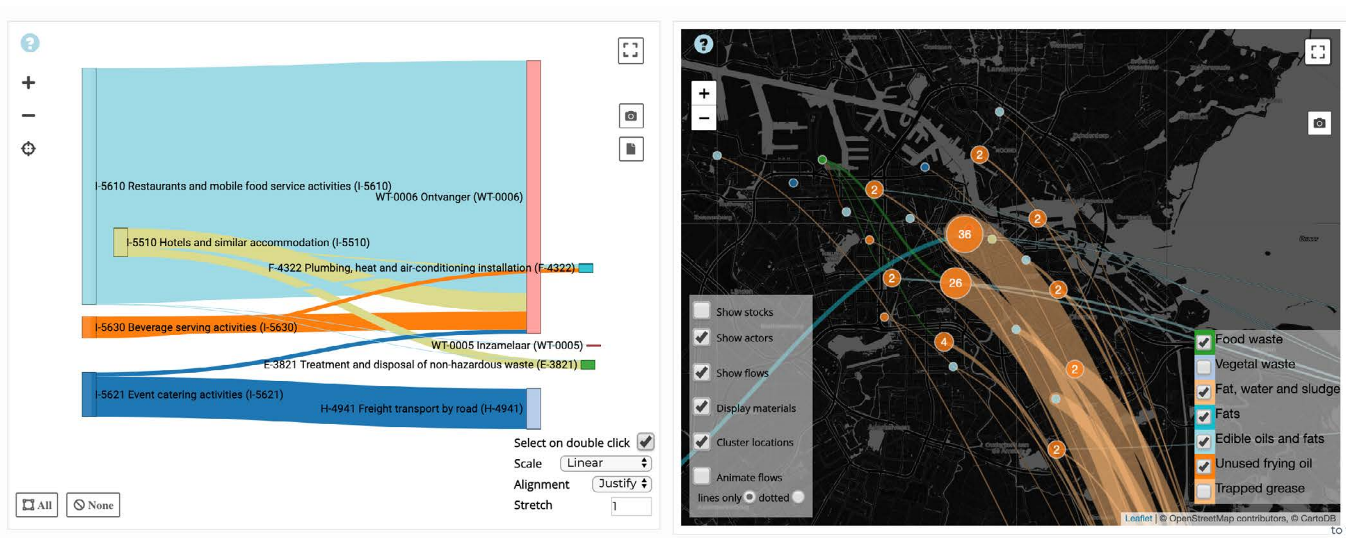
From September 2016 to September 2020 this research has been linked with the H2020 Research & Innovation Action project REPAiR (REsource Management in Peri-urban Areas: Going Beyond Urban Metabolism), grant agreement No. 688920, further referred to as REPAiR.

REPAiR has been tackling the lack of a multidisciplinary approach and concrete tools for European spatial resource management challenges in the 21st century. In four years, the project has developed an online, interactive Geodesign Decision Support Environment (GDSE) that integrates models and methods from, among others, the environmental, geographic, and economic sciences with design and spatial planning methods, both on a software- and process-level for local and regional stakeholders. The project has been running in six European regions: Amsterdam (the Netherlands), Naples (Italy), Gent (Belgium), Hamburg (Germany), Łódź (Poland) and Pécs (Hungary).

The following elements of this research have been developed under the REPAiR framework:

Geodesign Decision Support Environment (GDSE). GDSE is an open source web application prototype created to support Peri-Urban Living Lab (PULL) workshops in the six case study regions of the REPAiR project. The application is based on the six steps of the geodesign methodology (Steinitz, 2012) incorporated into a Living Lab approach (Steen and Van Bueren, 2017). PULLs are based on public-private-people-partnerships, as citizens and local associations are considered an important source of place-specific innovations (Amenta et al., 2019). The exploration of geodesign process models is supported by Material Flow Analysis (MFA) methods (Brunner and Rechberger, 2016; Furlan et al., 2020) and evaluation models are created using the Life Cycle Assessment (LCA) methodology (Guinee, 2002; Taelman et al., 2018). GDSE has been described in detail by Arciniegas et al. (2019) and Arciniegas et al. (2020).

GDSE has been used as a basis for the Amsterdam CEM. All maps presented in this research are produced using this GDSE tool.



Activity-based Spatial Material Flow Analysis (AS-MFA). AS-MFA is an extension of the classic MFA method, which allows exploring spatial and economic aspects of the material flows in a single frame of interactive visualisations. MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time. Although MFA studies always have explicit spatial and temporal boundaries, what happens within those limits is considered as a black box, where materials flow from inputs to outputs through a selected set of nodes. Nodes are typically represented as certain processes, economic activities, or locations. The AS-MFA extension of the analysis makes use of the specific geographic locations where materials are reported either as flows or stocks. The locations are then grouped according to their economic activities. Both locations as activities are simultaneously represented in an interactive frame that contains a map and a Sankey diagram as in Figure 3.2.

The AS-MFA method has been used to analyse and represent waste statistics throughout this research.

Figure 3.2. AS-MFA module in the GDSE. The Sankey diagram on the left represents material flows between different economic activities, and the map on the right represents the same flows on a map. The flows can be toggled on and off by using the interactive Sankey diagram (source: GDSE, REPAiR 2018)

Dutch National Waste Registry (NL: Landelijk Meldpunt Afvalstoffen, LMA). The REPAiR project is the first academic project that was granted access to the Dutch National Waste Registry further referred to as LMA data. The data set consists of statistics on the supply, composition and processing of industrial waste. Since 2006, these data have been centrally collected at the Waste Registry Division of the Dutch Ministry of Infrastructure and Public Works. The waste reports are gathered under the Waste Statistics Regulation No. 849/2010 of 27 September 2010, amending Regulation (EC) No. 2150/2002 of the European Parliament and of the Council on Waste Statistics. The database can provide the most complete data on the reported waste collection from companies in The Netherlands. As waste disposal data can be considered sensitive to some companies, the database is not publicly accessible and should only be used under high standards of data security.
LMA data is the fundamental data set used in this research.

Amsterdam Metropolitan Area (AMA). Amsterdam is one of the two leading pilot case studies of the REPAiR project. Therefore, the city and its region have been selected as the case study for this research. The case study is described in more detail in Section 2.1.

Knowledge transfer and research validation. The exercise of mapping waste flows using the AS-MFA module of the GDSE has been performed in every case study city of the REPAiR project. The results of the exercise allow for partial discussion about the transferability of these research results to other European regions. Transferability is discussed in further detail in Chapter 8.

3.2.2 CINDERELA: New Circular Economy Business Model for More Sustainable Urban Construction

Since September 2018 this research has been partly linked with a H2020 project, New Circular Economy Business Model for More Sustainable Urban Construction, grant agreement No. 776751, further referred to as CINDERELA. CINDERELA is based in part on the GDSE tool developed within the EU H2020 REPAiR project. It focusses on the construction sector, the concrete implementation of business cases, and a platform to support the continued uptake and innovation related to the developed demonstrations.

While the European construction sector consumes roughly half of all extracted materials and generates about a third of all EU waste, its wastes contain valuable Secondary Raw Materials (SRMs) that are currently not exploited. As a solution, CINDERELA has been developing and piloting new circular business models for the waste-to-resource opportunities of SRMs. It has developed a pan-European pool of knowledge and showcased good practises essential to help construction companies build circular economy business models. The Activity-Based Spatial Material Flow Analysis (AS-MFA) tool and Greenhouse Gas Emissions calculation module developed by the geoFluxus & REPAiR teams has been used to develop 6 demonstration projects that are now being implemented across 6 European regions: Amsterdam (the Netherlands), Maribor (Slovenia), Trento (Italy), Bilbao (Spain), Umag (Croatia) and Katowice (Poland).

The following elements of this research have been developed under the CINDERELA framework:

Further development of the GDSE and AS-MFA methodology. CINDERELA project has been using the AS-MFA module to analyse construction and demolition waste flows in the six cities. The project required further adaptations of the web-application, in particular, the ability to render the map not only on the basis of economic activities but also on the basis of the flow material content.
Several maps used in this research make use of the adapted AS-MFA module.

Transfer of knowledge and research validation. The exercise of mapping waste flows using the AS-MFA module of the GDSE has also been performed in every case city of the CINDERELA project using construction and demolition waste flows. The exercise results allow for a partial discussion of the transferability of these research results in case of five additional European regions than initially validated by the REPAiR project. Transferability is discussed in further detail in Chapter 8.

Greenhouse Gas (GHG) Emission Calculation. An additional GDSE module has been developed under the CINDERELA framework that allows tracing AS-MFA links between two locations on a simplified road network using the shortest path algorithm (Figure 3.3). The total driving distance is then related to the most likely type of vehicle for material transport. Distance, vehicle type, and material mass allow estimating the total amount of GHG emissions from transport expressed as CO_2 equivalent. The calculation is discussed in more detail in Chapter 7.

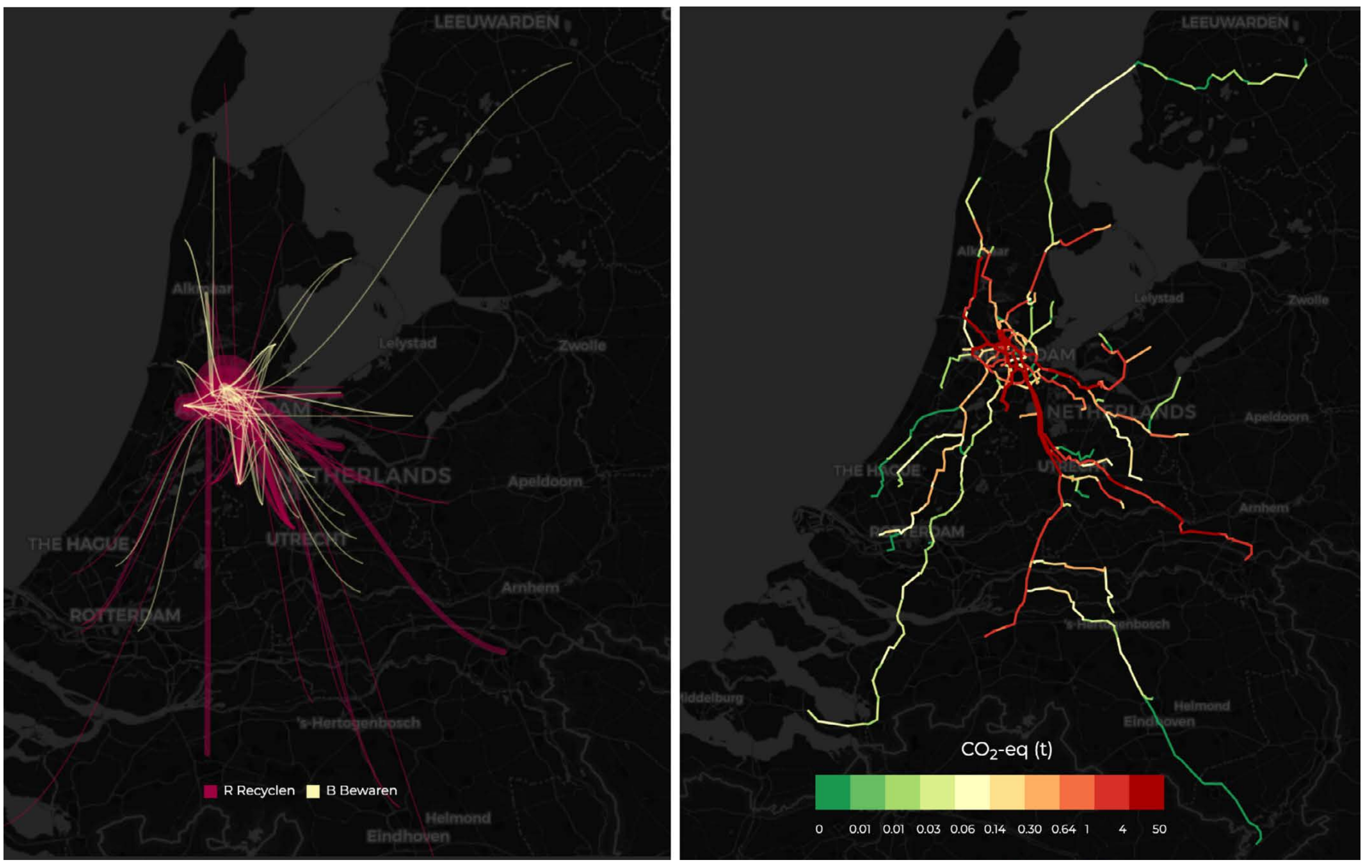


Figure 3.3. All flows of ceramic waste produced in Amsterdam in 2018. Left: flow map that represents the applied waste treatment method. Right: waste transport impact in CO_2-eq. per road segment.

3.2.3 geoFluxus

Since 2019 this research has developed into an academic spin-off co-founded by me and Arnout Sabbe. The spin-off is predominantly based on the AS-MFA module of the GDSE that has been used in both the REPAiR and CINDERELA projects. The spin-off continues to develop the application according to the needs of local and regional governments. The application remains open source, as intended by the H2020 Openness of Research Results policy. Therefore, it remains accessible for both government and research purposes.

The AS-MFA module has been used for the first time outside of the scope of the two H2020 projects by the City of Amsterdam to kick start the CEM as part of the Circular 2020-2025 strategy (Gemeente Amsterdam, 2020). Initially as a traditional paper report, in 2022 it was launched as an interactive online dashboard that helps to develop, implement, and monitor sustainable resource management practises in the Amsterdam Metropolitan Area. In the first stage of collaboration, geoFluxus has been commissioned by the Municipality of Amsterdam to provide insights into the entire downstream waste chain, including its geospatial network, participating actors, involved economic activities and their potential for valorisation. In the second stage of collaboration, geoFluxus has developed an automated data processing pipeline for raw data collected under the European Waste Statistics Regulation and an exploratory analysis to link waste data with import-export data sets provided by the Port of Amsterdam.

In 2020 geoFluxus became the winner of the EU Datathon 2020 European Green Deal challenge. The open-source platform has showcased waste flow analytics based on data sets from the REPAiR and CINDERELA projects. It has demonstrated how EU open data allows estimating GHG emissions of waste transport using the same methodology in different regions of the EU. The presented platform provides governments with data-based evidence on the economic sectors, materials, and locations with the highest potential for reducing waste and emissions.

Since February 2020 geoFluxus is a private limited company registered in The Netherlands providing analysis, research, and development services to governments and companies that require circular economy monitoring frameworks.

The following elements of this research have been developed under the geoFluxus framework:

Collaboration and user interviews with the Municipality of Amsterdam. The Amsterdam CEM project has been developed in close collaboration with the Chief Technology Office of the Amsterdam Municipality. The user interviews described in more detail in Chapter 5 are one of the results of the collaboration.

Port of Amsterdam data access. The port import and export data have been provided to the Municipality by the Amsterdam Port Authority to build the Amsterdam CEM. The data set registers all imports and exports of goods and waste that occur through the port. The data set is intended to help monitor extractive resources that are not locally available, as well as resources that leave the country as materials, products, or waste. This research used the port registration data schema as explained in Chapter 5.

Semantic reclassification of materials found in waste. European Waste Statistics classify waste content using a European Waste Classification (EWC) system. However, EWC codes rarely contain information on the actual resources and materials that a waste stream contains. This makes certain important estimations impossible, e.g., which goods would eventually become which type of waste, or which wastes could be up-cycled to produce which new goods. To provide these insights for the Amsterdam CEM, semantic reclassification of EWC codes has been performed manually for the 200 largest EWC streams in terms of mass.
This research has used the reclassification to demonstrate the potential of the waste statistics for the CEM, as explained in Chapter 7.

3.2 RESEARCH METHODS AND DATA

Being positioned in a rapidly developing yet at the same time highly contested research paradigm, this thesis navigates between the societal and policy-implementation pressures and scientific theories. The overall nature of this research lies in computational methods for the built environment as it combines (geographical) information science with urban policy and decision-making to analyse how European Waste Statistics can be used to monitor and therefore advance the transition towards a circular economy in the Amsterdam Metropolitan Area.

This research consists of five parts that can be best understood through a funnel metaphor. The initial parts are broad and more general, and every subsequent part is more specific to the defined case and data set. The last part discusses to what extent research findings can be transferred to the other c ases. Each part takes into account the results of the previous one and builds upon them.

Theoretical framework

Introduction: Research background and position
Methods: Policy, media & scientific literature review

__1.__ A. How can policy decisions be assessed in pursuit of a circular economy?

Chapter 4: Assessing decision impacts in pursuit of a circular economy
Methods: Scientific literature review, ontology development

B. Which data requirements are set out by the need to assess decision impacts?

User needs

Chapter 5: Circular Economy Monitor for the Amsterdam Metropolitan Area
Methods: Scientific literature review, ontology development, user interviews, data structure analysis

__2.__ A. What are the expectations and the requirements for the circular economy monitoring in the AMA?

B. Which theory should circular economy monitoring be based on?

C. How can user expectations and theory be aligned with available data and tools?

Data quality and availability

Chapter 6: European Waste Statistics Data
Methods: Scientific literature review, data analysis, hypothesis testing, algorithm development

__3.__ A. How does the Dutch National Waste Registry correspond to the expectations and the requirements of circular economy monitoring set forward in the previous chapters?

B. How does European Waste Statistics Regulation influence data characteristics?

Data suitability

Chapter 7: European Waste Statistics Data for a Circular Economy Monitor
Methods: Scientific literature review, data analysis, data query based experiments

__4.__ A. How can the Dutch National Waste Registry data help to assess decision impacts in pursuit of a circular economy in the Amsterdam Metropolitan Area?

B. Which data limitations hinder monitoring and transition towards a circular economy?

C. How can the European Waste Statistics Regulation be improved to better support the transition?

Dutch National Waste Registry Dataset

Amsterdam Metropolitan Area

Validation and evaluation

Chapter 8: Research transferability to the other European regions
Methods: Comparative analysis

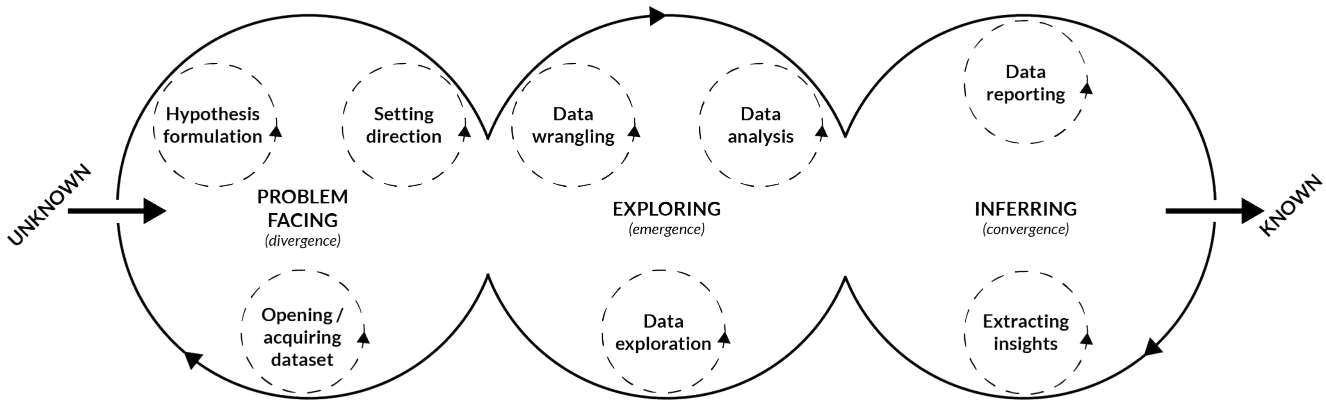
Although the main data set considered for this research is the Dutch National Waste Registry, additional data sources are used to support the analysis. The necessary data are collected using a variety of methods, including user interviews with intended CEM users within the Amsterdam municipality, algorithm design to enrich waste data by the national trade registry, and reusing data sets from REPAiR and CINDERELA projects. No specific data collection is performed solely for the purpose of this research.

As the main goal of this dissertation is to support the development of a CEM, the methods behind the investigation follow the design methodology for designing a data-intensive web-application. As pointed out by Howard et al. (1999), the cognitive fit of a system design task requires that 'the characteristics of the methodology being used should match the characteristics of the application to which it is applied'. For example, if the key aspect of an application is based on complex data structures, it would seem best that the design methodology would place strong emphasis on the importance of first developing correct data models.

In contrast to older data-centred and process-centred application design approaches, Klein et al. (1997) have introduced a decision-centred design approach that is considered the guiding principle for this research. The approach is based on the observation that data-centred applications are suitable for informative purposes, such as archive look-ups or marketplaces, while process-centred applications are suitable to assist routine tasks, such as accounting, manufacturing, scheduling, etc. However, systems created for the purpose of decision support are of a different type as they require not so much of an easy process or data querying, but support in judgement and interpretation. Decision-centred application design is based on Cognitive Task Analysis (CTA), which consists of 5 steps:

1. Understanding the domain;
2. Identifying the people to interview;
3. Eliciting the knowledge used by the subject-matter experts to make critical and difficult judgements and decisions;
4. Representing the knowledge as decision requirements; and
5. Applying the decision requirements to design.

After defining the requirements for the CEM, a data exploration step is performed to understand whether the requirements can be fulfilled by the given data set. Alspaugh et al. (2018) have described Exploratory Data Analysis (EDA) as 'Exploration is opportunistic; actions are driven in reaction to data, in a bottom-up fashion, often guided by high-level concerns and motivated by knowledge of the



domain or problem space.' Kun et al. (2020) have further incorporated EDA into a Data Exploration for Design (DEfD) method depicted in Figure 3.4.

The dissertation combines CTA and DEfD methods into the following five parts, each of which is described in a separate chapter. The following descriptions discuss only the key aspects of the applied methods. A detailed description of methods and data is provided at the beginning of each chapter:

Figure 3.4. The outline of the DEfD method, following the three conceptual stages from the EDI methodology. The different conceptual stages process in sequential order, but iteratively (Kun et al., 2020)

Theoretical framework corresponds to the step 'understanding the domain' in CTA and 'setting direction' in DEfD. The first two parts represent a theoretical framework for research based on a review of the literature. First, the research background and position in the scientific debate is presented in the Introduction (Chapter 1) of this thesis. Given the wide scientific and political debate in which the concept of CE can be found in recent years, the introductory chapters analyse not only the scientific literature but also policy documents and wider mentions of CE in media communications. The Introduction chapter positions this research in the paradigm of resource scarcity and explains its relation to the CE concept.
The second part of the theoretical framework is based on a structured review of the scientific literature and establishes a framework for assessing impact significance. The framework is meant to be used to guide the decision-making in the CEM and, therefore, outline the requirements for the monitoring.

Exploration of user needs includes CTA steps 2) identifying the people to interview; 3) eliciting the knowledge used by the subject-matter experts to make critical and difficult judgements and decisions; and 4) representing the knowledge as decision requirements and 'hypothesis formulation' in DEfD. The central method used to perform the mentioned steps is the development of a formal ontology. To elicit user knowledge and requirements, prospective CEM users from the Municipality of Amsterdam have been interviewed using written surveys. Their answers have been used to develop a user-centred ontology that later has been merged with 3 other ontologies. A theory-centred ontology has been reused from the relevant literature. A tool-centred ontology has been based on the prototype GDSE tool developed in the REPAiR project. Finally, a data-centred ontology has been derived from the waste and port import-export data sets. The final ontology has been used to formulate a hypothesis and several assumptions for data analysis. The method has exposed conflicts and ambiguities between monitor users, developers, and data providers.

Data quality and availability part formulates a hypothesis that the elicited knowledge can be represented as a decision requirement using the Waste Statistics data (CTA step 4). Data wrangling, analysis, and exploration (DEfD) are used as methods to test the hypothesis that 'linking waste producers in the Dutch National Waste Registry to their trade details provided by the Dutch National Trade Registry allows assessing which economic sectors should be first targeted to achieve circular economy goals'.

An algorithm is developed to match the data entries in the National Waste Registry with the data entries in the National Trade Registry. The algorithm adapts best practises of digital entity linking, which are modified to better fit the specifics of both data sets. Successful and validated matches are then compared against the guidelines for Waste Statistics Regulation to test if waste is registered by the companies belonging to those economic sectors which are expected to produce given types of waste.

Data suitability part tests if the decision requirements can be applied to the design (CTA step 5) using the Waste Statistics data. DEfD method describes this step through the processes of extracting insights and data reporting. Four sample queries are used to set up experiments with Waste Statistics data based on the requirements elicited in the ontology development process:

Experiment 1. Determining the CE decision-making space in terms of geographical scope and scale by mapping all waste generated within the Amsterdam Metropolitan Area;

Experiment 2. Determining the CE decision-making space in terms of stakeholders by identifying which economic sectors are responsible for waste production;

Experiment 3. Evaluating the feasibility of local CE strategies by identifying which secondary materials are present in the area and have the potential to be reused;

Experiment 4. Assessing the current carbon emission impact of waste transportation.

The observations made during the experiments are used to report on the opportunities and limitations of the data to correspond to the user requirements.

Solution and evaluation part does not specifically correspond to the CTA and DEfD methods; however, it is intended to reflect on the results by providing recommendations to the CEM design and verify that the insights and results of the previous steps can also be applied in different contexts. Verification is carried out through comparative analysis of different regions across the EU.

Each chapter based on a journal publication (Chapters III, IV, V, and VI) has a dedicated section for the research methods and data used in that part. Because of this set-up, some overlap among those chapters occurs occasionally. Each chapter starts with a preamble that explains its relation to the research questions and summarises the main findings.

Several disciplines have been considered in carrying out this research. Geographical Information Science is the leading discipline placing spatio-temporal considerations of each circular economy aspect at the centre of this research. The majority of methods originate from GIS: SDSS theory is used for the CEM development, the geodesign approach is investigated as a decision making framework, the spatial differentiation tests by Goodchild (2001) are used to determine whether the significance assessment must be spatially varying, and, finally, the waste statistics are analysed using a series of spatial algorithms: geolocation, shortest path analysis, spatial entity mapping, etc. Such methods as formal ontology development or text similarity algorithms are typically found in computer science discipline, although also often used in GIS.

Although the methods used for this research are mostly computational, they are strongly grounded in theories coming from environmental disciplines, especially socioeconomic metabolism, industrial ecology, and environmental management. The theoretical framework is based on, among others, methods of Environmental Impact Assessment and Life Cycle Analysis. The core concepts for the ontology development are borrowed from the discipline of socioeconomic metabolism. The queries used to analyse waste registry data use environmental assessment methods and semantic classifications typically developed by the industrial ecology discipline.

Finally, data analysis is linked to policy analysis both in the introduction of the study and in the conclusions and recommendations. The analysed policies are strongly connected to sustainable development and planning, which can be understood as an overarching discipline for this research.

3.4 RESEARCH REPRODUCIBILITY

FAIR - Findable, Accessible, Interoperable, and Reusable

Reproducibility is an important challenge for research based on computational analysis. Not following good practises leads to a lack of transparency, missing openness, very little reusability, and potentially untrustworthiness of scholarly manuscripts. During this research, a 'reproducibility crisis' has been observed and discussed in several scientific disciplines such as economics (Ioannidis et al., 2017), medical chemistry (Baker, 2017), neuroscience (Button et al., 2013), and for scientific studies in general, across various disciplines. Especially in computational sciences, lack of reproducibility leads to redundant research where the same algorithms are implemented over and over again while researchers could easily build on each other's work. Although plenty of systems have already been developed for similar purposes, their sustainability is heavily hindered by the lack of FAIR-ness. At the same time, research reproducibility ensures research transparency and sufficient documentation, increasing the trustworthiness of the research results (Nust et al., 2018).

Being part of the computational research community, in 2017 I joined an initiative started by Daniel Nust from the University of Muenster to increase research reproducibility in geospatial sciences. In 2018, we showed in an assessment of papers published at the annual AGILE conference (Association of Geographic Information Laboratories in Europe) that overall reproducibility is low and pointed out ways to improve the situation (Nust et al., 2018). In the same year, the AGILE council awarded our initiative to implement one of the core means to improve the situation: the development of new author and reviewer guidelines for AGILE conference submissions.

The guidelines are built around the 'Data and Software Availability' section, which should become an obligatory part of every scientific paper submission in the future. In this section, the authors explicitly report on what data and software are available and where they can be found for reproductions by third parties. The guidelines include concrete examples from the geospatial science domain that relate to common concerns. They aim to accommodate a variety of skill levels towards full openness and reproducibility. The guidelines are meant as a living document that will be further developed by the Reproducible Research (RR) initiative based on community feedback.

The created guidelines, reports, and all related documents are published on OSF:

https://10.17605/OSF.IO/PHMCE

To show a good example, this research fully follows the reproducibility guidelines; therefore, every published paper includes the 'Data and Software Availability' section even if it is not required by the publishing journal. Given that this research is based on a data set that is considered sensitive and, therefore, cannot be made public, all relevant materials are preserved following the principles 'as open as possible, as closed as necessary.'

REPRODUCIBILITY CHECKLIST

For all **datasets** included/produced in the paper, check if data:

- ❏ Is provided in a non-proprietary format
- ❏ Is documented for third parties to reuse
- ❏ Is accessible in a public repository and has an open data license

For all **software tools/libraries/packages** and **computational workflows** included/produced, check if:

- ❏ Reproduction steps are explained in a README (plain text file), flowchart, or script
- ❏ Computational environments (including hardware) are documented or provided
- ❏ Versions of relevant software components (libraries, packages) are provided
- ❏ All parameters and expected execution times for the computational workflow are provided
- ❏ Software developed by the authors is available in a public repository and has an open license
- ❏ There is a clear connection between **tables, figures, maps, and statistical values** and the data and code that they are based on, e.g., using file names or documentation in the README

In the **Data and Software Availability section**, check if you include:

- ❏ Data and software statements (see examples below)
- ❏ The reasons, if any, for not being able to share (parts of) data or code

For all **data and software** check that:

- ❏ All datasets and code (used or mentioned) are assigned DOIs
- ❏ Datasets and code are cited throughout the paper

After acceptance in the **camera-ready paper** check that:

- ❏ If data has been shared privately or anonymously for peer review, they are updated with all metadata and accessible via a DOI and referenced from the paper
- ❏ If a reproducibility review report will be published for your paper, a DOI URL in the Data and Software Availability section is included using the following template:
  A reproducibility report for this paper is available confirming that [considerable parts of the computational workflow / all results / Figures 1 and 4] could be independently reproduced, see https://doi.org/link_to_report.

Figure 3.5. Reproducibility Checklist created as part of the Reproducibility Guidelines for the AGILE conference, version 1.

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4 theoretical framework

theoretical framework

4

ASSESSING DECISION IMPACTS IN PURSUIT OF A CIRCULAR ECONOMY

Research questions:

A How can policy decisions be assessed in pursuit of a circular economy?

B What data requirements are set out by the need to assess decision impacts?

Based on:

Sileryte, R., Gil, J., Wandl, A., van Timmeren, A. (2018),

Introducing Spatial Variability into Impact Significance Assessment

Published in: Geospatial Technologies for All. Lecture Notes in Geoinformation and Cartography, 1863-2351, part F3. Springer International Publishing, pp.189–209

ISBN 978-3-319-78207-2

DOI 10.1007/978-3-319-78208-9_10

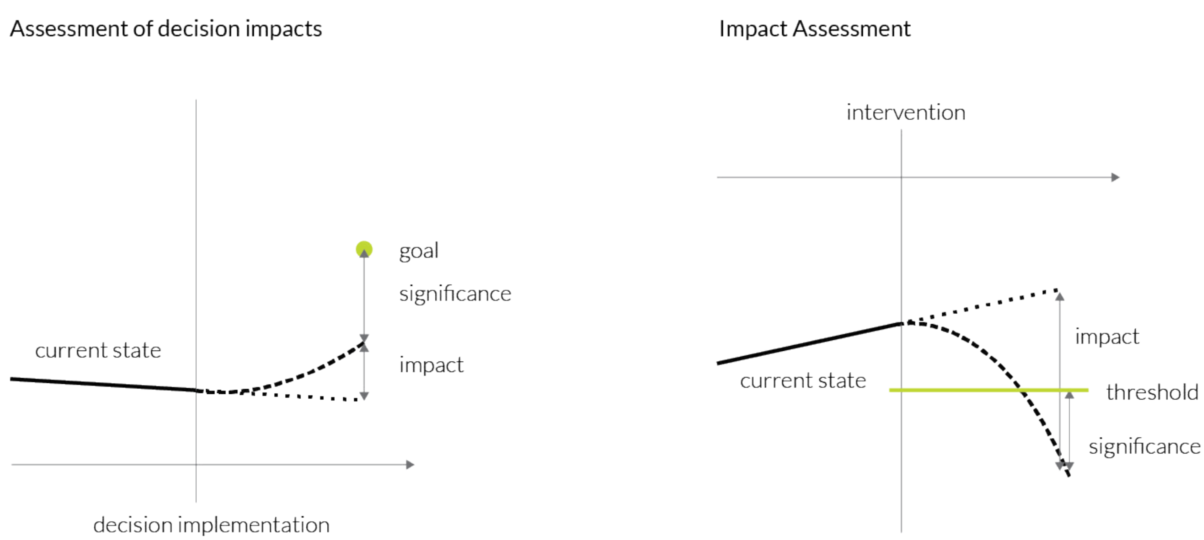
PREAMBLE

Significance can be described as "the quality of being worthy of attention" and as such necessarily requires a subjective viewpoint of a user. The act of decision-making is closely associated with social and political conflicts and deeply held values that reflect cultural, historical, and social norms rendered acceptable by the community Jones and Morrison-Saunders (2016). Therefore, considering the magnitude of the impact significance instead of the magnitude of an impact allows individual or group judgement to be part of the decision-making process.

Significance assessment is not only a part of a decision-making process that allows prioritising alternatives in cases of project appraisal, granting permissions, deciding upon financing, etc. It is also a useful measure in a design process, as it allows assessing what difference a new design brings and how it can be optimised for the best positive impact. And finally, it is a tool for the direction of current policy, a tool for the past evaluation, and a tool for monitoring the future.

In the following publication, significance is discussed as part of an *Impact Assessment* process, while the research question is pertaining to *the assessment of decision*

Figure 4.1. Left side: conceptual representation of significance assessment of decision impacts. Right side: conceptual representation of impact significance assessment.



impacts. There is a slight difference between the two terms, as can be seen in Figure 4.1:

Impact Assessment (IA) is a formal methodology that accounts for all impacts that are directly caused, maintained, or indirectly influenced by a certain intervention. In that case, the Impact Significance Assessment requires a definition of a threshold for each of the relevant aspects. Impacts that fall below the threshold are generally considered insignificant and impacts above the threshold are generally considered significant.

In contrast, **the assessment of decision impacts** means assessing whether a certain decision brings the situation closer to the predefined goals compared to the other possible decisions. Significance assessment in this case requires the definition of a goal or a target given the chosen values. The significance of impacts can be compared in relation to the set goal. In this case, not all impacts are necessary to assess, but only those that are relevant to the predefined goal.

Another difference between the two methods of assessment lies in the direction of the impacts. Impact Assessment is strictly concerned only with the impacts that a decision is going to have on the aspects of importance. However, the assessment of decision impacts can also work in the opposite direction, as the context in which a decision is made can also have an effect on its impact. For example, if the question at hand considers the optimal location for placing a new waste processing plant, then Impact Assessment would be concerned with as wide a spectrum of positive and negative impacts that the processing plant will have on its surroundings. However, the assessment of decision impacts would be considered with the impact that the placement would have on the goals set. The goals can be set both considering the impact on the environment (e.g. noise levels, energy production potential, increased transport loads) and the impact to the project success of the project surroundings (e.g. NIMBY syndrome, employment potential, amount of waste to be treated.) (Figure 4.2).

Furthermore, Impact Assessment is typically concerned only with negative or

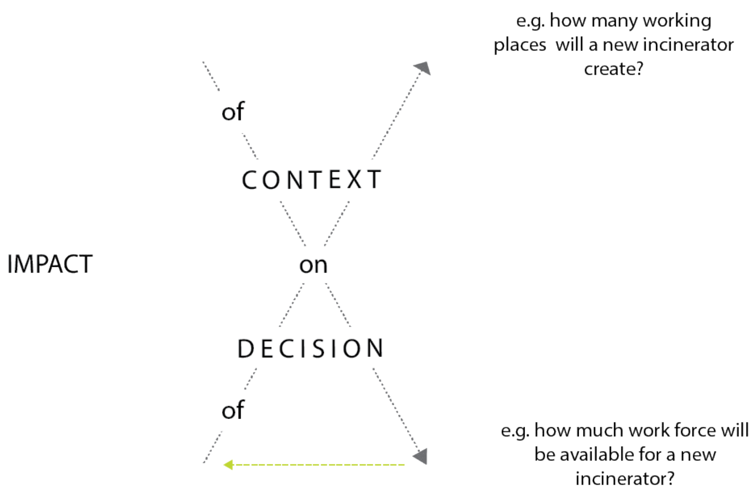


Figure 4.2. Impact can be assessed in two directions: either as the impact that the context will have on the decision or as the impact that the decision will have on the context.

unwanted impacts. However, assessment of decision impacts is related to set goals and targets which typically have a positive aspect. Therefore, the goal of Impact Assessment is to prevent or mitigate significant impacts, and the goal of assessing decision impacts, especially in the context of circular economy policy and decision-making, is to promote those policies and decisions which lead to significant impacts.

Impact Assessment and assessment of decision impacts are not mutually exclusive and can be performed simultaneously. Although it is more likely that assessment of decision impacts is performed first to evaluate, confirm, and discard certain alternatives before a more in-depth investigation of Impact Assessment is performed. In both cases, the significance assessment can be quantitative and qualitative. The theoretical framework described in the publication can be equally applied to both scenarios - Impact Assessment as well as the assessment of decision impacts.

The theoretical framework within which further analysis is developed is built on the assumption that a CEM is a decision support tool as described in Chapter 2 Section 2.2. Due to the research setup explained in Section 3.2, a Geodesign Decision Support Environment (GDSE) is the primary tool considered for the theoretical framework.

The key difference between a GDSE and a CEM is that a GDSE is a synchronous centralised system, while a CEM is an asynchronous decentralised system. Both systems are meant as discussion rather than decision support tools where its users are not expected to arrive at a final conclusion while using the system but to inform their decision-making process and foster collaboration. Ultimately, the goal of both systems is to accelerate the transition towards the circular economy. Given that acceleration cannot be achieved with only positive impacts in all aspects, and that the transition should be viewed as an ill-defined problem which is too complex to model, the notion of significance is of high relevance to both systems.

While in some cases an impact of the proposed change may be considered equally significant under all circumstances (e.g. increase of carbon emissions as a main contributor to the global climate change), many impacts may change both their direction and the extent of significance depending on their context (e.g. land consumption may be positively evaluated if applied to abandoned territories or negatively if a forest needs to be sacrificed). The geographical context (i.e. its sensitivity, vulnerability, or potential) is commonly assessed by Spatial Decision Support Systems. However, currently these systems typically do not perform an actual impact assessment because impact characteristics remain constant regardless of location. Similarly, relevant Impact Assessment methods, although gradually becoming more spatial, assume their context as invariable. As a consequence, impact significance so far is also a spatially unvarying concept. However, current technological developments allow us to rapidly record, analyse, and visualise spatial data.

Therefore, the following chapter introduces the concept of spatially varying impact significance assessment, by reviewing its current definitions in the literature, and analysing to what extent the concept is applied in existing assessment methods. It concludes with a formulation of spatially varying impact significance assessment that answers how policy decisions can be assessed in pursuit of a circular economy (RQ1). The requirement of spatial variability is one of the requirements formulated as an answer to RQ2.

4.1 INTRODUCTION

The shift towards circularity will require changes in design, production, logistics, and consumer behaviour. The sustainability of these systems is highly dependent on their geographical contexts, such as location and availability of resources, presence of a skilled workforce, economic, environmental, and transport geography (Accorsi et al., 2015). Policies and tools supporting the shift cannot be applied uniformly across the territory because economic, social, environmental, and institutional situations differ not only on a national level, but also locally, on a community level. These instruments should include contextualised place-based significance assessments of probable impacts, with Geographic Information Systems (GIS) as their basis.

In the context of sustainability pursuit and transition to CE, this article proposes that both impact and its context assessments cannot be applied uniformly, and that the significance of impacts is a spatially varying measure. The article is organised as follows. First, the general concept of impact significance is reviewed, setting the theoretical framework of this study. Then the need for spatial differentiation is discussed, defining the analytical framework that is later applied to four methods of impact assessment considered the most relevant in the context of this research. Recommendations for spatially differentiated impact significance assessment are given in the fifth section. Finally, conclusions are drawn, followed by discussion of future work.

4.2 THEORETICAL FRAMEWORK

'Impact Significance Assessment' or 'Impact Significance Determination' is not commonly explored as a separate subject, as a combined query in Scopus returns merely 11 distinct results (Query 1, Table 4.1). Reducing the query to 'Impact Significance' results in a significantly larger number of 92 documents (Query 2). Keyword analysis reveals that impact significance is most commonly associated with topics such as Environmental Impact Assessment (47/92 documents, Query 3) and decision-making (10/92 documents, Query 4). Spatial Analysis or GIS are among the keywords in only 5 of 92 documents (Query 5).

Impact significance assessment may serve two purposes (Zulueta et al., 2017): 1) identification of significant impacts to trigger authoritative actions after conducting an impact assessment of a certain project; and 2) impact significance assessment for the purpose of comparison between multiple alternatives as a support to the decision-making process. The latter purpose is considered in the context of this article.

The way in which impact significance is assessed differs considerably between different jurisdictions, as there is clearly an absence of a legal definition for the concept (Jones and Morrison-Saunders, 2016). Wood (2008) describes impact significance as a dynamic, contextual, and political concept, characterised by uncertainty. The need for greater transparency, clarity, and understanding of the significance determination process has been recognised in the literature for decades. However, there is little apparent progress evident as the latest publications on the topic, such as Retief et al. (2016); Ehrlich and Ross (2015); Jones and Morrison-Saunders (2016), still mention the same issues related to significance assessment, i.e., lack of guidelines, vague terminology, high lexical and process uncertainty, and low consistency and coherence.

The act of decision-making is closely associated with social and political conflicts and deeply held values that reflect cultural, historical, and social norms rendered

No.	Query	Platform	Date
1	TITLE-ABS-KEY ('Impact Significance Assessment' OR 'Impact Significance Determination')	Scopus	15 Sep 2017
2	TITLE-ABS-KEY ('Impact Significance')	Scopus	15 Sep 2017
3	TITLE-ABS-KEY ('Impact Significance') AND (LIMIT-TO (EXACTKEYWORD, 'Environmental Impact Assessment') OR LIMIT-TO (EXACTKEYWORD, 'Environmental Impact') OR LIMIT-TO (EXACTKEYWORD, 'Environmental Impact Assessments') OR LIMIT-TO (EXACTKEYWORD, 'EIA') OR LIMIT-TO (EXACTKEYWORD, 'Environmental Impact Assessment (EIA)') OR LIMIT-TO (EXACTKEYWORD, 'Environmental Assessment') OR LIMIT-TO (EXACTKEYWORD, 'Environmental Impact Significance Assessment'))	Scopus	22 Nov 2017
4	TITLE-ABS-KEY ('Impact Significance') AND (LIMIT-TO (EXACTKEYWORD, 'decision-making'))	Scopus	22 Nov 2017
5	TITLE-ABS-KEY ('Impact Significance') AND (LIMIT-TO (EXACTKEYWORD, 'GIS') OR LIMIT-TO (EXACTKEYWORD, 'Geographic Information Systems') OR LIMIT-TO (EXACTKEYWORD, 'Spatial Analysis')	Scopus	22 Nov 2017
6	'GIS AND 'multi criteria' AND 'decision support' AND (collaborative OR participatory OR cooperative) AND sustainability AND urban YEAR > 2015'	Google Scholar	1 March 2017

Table 4.1. A list of literature queries

acceptable by the community (Jones and Morrison-Saunders, 2016). When the primary objective of the significance assessment is sustainability, the focus shifts from minimising damage to maximising long-term gains (Gibson et al., 2005). The considered time period is longer to include future generations, and more attention is paid to assessing cumulative impacts (Lawrence, 2007c). Both negative and positive impacts are addressed, in contrast to assessments that are only aimed at project approval. The impact of a proposed action is considered negatively significant if it inhibits sustainability. It is considered positively significant if it makes a durable contribution to the achievement of sustainable visions and strategies compared to the baseline scenario (Barrow, 2000).

To investigate what supplements impact magnitude to determine impact significance, several scientific publications have been reviewed. In addition to the publications returned by Query 1, additional studies have been chosen based on the summary made by Cloquell-Ballester et al. (2007), namely Table 1: Criteria to determine the significance of environmental impacts according to different authors (p. 64); and some related citations in recent publications (Table 4.2).

Table 4.2. A list of literature used for the review on impact significance assessment

List of references	
Duinker and Beanlands (1986)	Wood (2008)
Thompson (1990)	Ijäs et al. (2010)
Canter and Canty (1993)	Gangolells et al. (2011)
Antunes et al. (2001)	Briggs and Hudson (2013)
Bojórquez-Tapia et al. (2002)	Zulueta et al. (2013)
Cloquell-Ballester et al. (2007)	Ehrlich and Ross (2015)
Lawrence (2007a)	Jones and Morrison-Saunders (2016)
Lawrence (2007c)	Zulueta et al. (2017)
Lawrence (2007b)	

One statement that researchers and reviewers seem to agree on is that impact magnitude and impact significance are essentially different concepts that should not be confused (Thompson, 1990; Lawrence, 2007a; Wood, 2008; Ehrlich and Ross, 2015). Furthermore, there is general agreement that subjectivity cannot be avoided in the process, although it can be well informed by science and be maximally transparent (Briggs and Hudson, 2013). Thus, all reviewed publications seem to agree that there are two sides of impact significance - the rather objective side related with the impact's assessment and the rather subjective one related to the values of importance given to that impact. Table 4.3 gives an overview of how different authors define significance and its two main components.

In its essence, the determination of impact significance is a multi-criteria problem (Cloquell-Ballester et al., 2007). What the different authors (as well as official regulations) do not seem to agree on is which factors exactly characterise impacts and which ones characterise importance. Generally, there is a lot of inconsistency in how the arguments are classified by the authors. For example, Bojórquez-

Publication	Objective (impact) measure	Subjective (judgement) measure
Duinker and Beanlands (1986)	Magnitude and spatiotemporal distribution of change, reliability of prediction	Importance of environmental attribute to project decision-makers
Canter and Canty (1993)	Impact intensity	Impact Context
Antunes et al. (2001); Wood (2008)	Impact magnitude	Context sensitivity
Bojórquez-Tapia et al. (2002)	Interaction intensity	Environmental vulnerability
Lawrence (2007a)	Impact characteristics	Characteristics of the receiving environment
Cloquell-Ballester et al. (2007)	Project activities	Environmental factors
Ijäs et al. (2010)	Scale of importance, magnitude of change	Permanence, reversibility, cumulativity, context susceptibility
Gangolells et al. (2011)	Impact severity	Concerns of interested parties
Zulueta et al. (2013, 2017)	Impact characteristics	Expert judgement
Briggs and Hudson (2013)	Impact on a receptor	Value of the receptor
Ehrlich and Ross (2015)	Impact adversity	Threshold of acceptability
Jones and Morrison-Saunders (2016)	Impact characterisation	Impact importance

Table 4.3. Variables of impact significance according to different authors

Tapia et al. (2002); Cloquell-Ballester et al. (2007) regard synergic and cumulative effects as properties of impact intensity, while Antunes et al. (2001); Lawrence (2007b); Wood (2008) regard cumulative effects as properties of the impact receiving context. Institutional arrangements are often viewed as constraints or background to significance determination procedures (Briggs and Hudson, 2013; Ehrlich and Ross, 2015) rather than context properties (Lawrence, 2007a; Wood, 2008). Ijäs et al. (2010) classify impact permanence and reversibility of impact on the same side as context susceptibility and Ehrlich and Ross (2015) regards everything as impact properties, while decision-makers are responsible for setting a subjective threshold value to determine how all of these properties qualify for significance.

Moreover, there does not seem to be a consensus between the authors on who is responsible for providing value judgements to determine the significance. Although some authors attribute this responsibility to experts and scientists (Antunes et al., 2001; Cloquell-Ballester et al., 2007; Zulueta et al., 2017), others suggest asking for public opinion (Antunes et al., 2001; Gibson et al., 2005; Gangolells et al., 2011; Briggs and Hudson, 2013) or leaving it in the hands of decision-makers as advocates of society (Duinker and Beanlands, 1986; Ehrlich and Ross, 2015).

The focus of this article is on adding a spatial dimension to the objective procedure of impact assessment and to the subjective procedure of judgement. To offer a clear definition of the two, the arguments collected during the literature review were classified into two groups (Table 4.4), one for the arguments given based on the characteristics of the impact and the other for the arguments given based on the context of the impact received, according to the following definitions.

Impact Characteristics refer to all characteristics that would be calculated using the same formula if the same intervention was moved to a different context. For example, if odour from a new facility affects the radius of 1000 m around the facility, then moving the facility to a new location would not change the radius.

Context Characteristics refer to all characteristics that would be calculated with the same formula if an intervention with different impact were placed in the same context. For example, if a habitat is negatively affected by odour, then placing a facility with a smaller odour radius would not change the habitat's sensitivity.

Arguments for significance

Examples	References
Magnitude or intensity	
Noise levels, odour intensity, amount of pollutants, amount of required resources, amount of employment	All
Extent of potentially affected factors	
Amount of affected population, volume of polluted water, 'the greatest good for the greatest number'	Duinker and Beanlands (1986); Canter and Canty (1993); Antunes et al. (2001); Lawrence (2007a); Ijäs et al. (2010); Briggs and Hudson (2013); Zulueta et al. (2017)
Economic considerations	
Costs for certain institutions, revenue potential	Wood (2008)
Spatial patterns	
Spreading distance, density, affected area, fragmentation, inclusion	Duinker and Beanlands (1986); Bojórquez-Tapia et al. (1998); Antunes et al. (2001); Lawrence (2007a); Wood (2008)
Temporal patterns	
Duration, frequency, periodicity, swiftness	Duinker and Beanlands (1986); Canter and Canty (1993); Bojórquez-Tapia et al. (1998); Antunes et al. (2001); Lawrence (2007a); Wood (2008); Ijäs et al. (2010); Briggs and Hudson (2013); Zulueta et al. (2017)
Reversibility	
Depletion of fossil fuels, erosion of tropical forests, human toxicity	Canter and Canty (1993); Antunes et al. (2001); Ijäs et al. (2010); Briggs and Hudson (2013); Zulueta et al. (2017)
Reliability	
Certainity, probability, predictability	Duinker and Beanlands (1986); Canter and Canty (1993)
Social and ethical importance	
Child labour, public controversy, public priority, 'the greatest good for the least advantaged'	Duinker and Beanlands (1986); Canter and Canty (1993); Bojórquez-Tapia et al. (1998); Lawrence (2007a); Wood (2008)

Ecological sensitivity	
Species extinction potential, resilience, recovery capacity	Canter and Canty (1993); Bojórquez-Tapia et al. (1998); Wood (2008)
Cultural sensitivity	
Proximity to scientific, cultural or historic resources, aesthetic effect in scenic landscapes	Canter and Canty (1993)
Competition for resources	
Groundwater depletion, agricultural land use	Duinker and Beanlands (1986)
Socioeconomic sensitivity	
Accessibility, employment, agricultural production	Antunes et al. (2001); Canter and Canty (1993)
Institutional arrangements	
Legal noise thresholds, target recycling rates, political targets	Duinker and Beanlands (1986); Canter and Canty (1993); Lawrence (2007a); Wood (2008)
Cumulative effects	
Current pollution rates, synergy, spatiotemporal crowding of effects, induction potential, precedent setting, feedback resistance, biomagnification	Canter and Canty (1993); Bojórquez-Tapia et al. (2002); Lawrence (2007a); Wood (2008); Ijäs et al. (2010); Zulueta et al. (2017)

Table 4.4. Arguments for significance determination, based on impact characteristics and context characteristics.

Based on the literature review, it has been concluded that Impact Significance can be defined as a function between Impact Characteristics and Context Importance (Equation 4.1), where impact characteristics are provided by an objective assessment procedure and context importance is provided by subjective judgement.

$$IS = f(I, C) \tag{4.1}$$

where:

IS = Impact Significance,

I = Impact Characteristics,

C = Context Importance.

4.3 SPATIAL VARIABILITY

It has been noticed almost three decades ago 'that methodologies which proceed through full aggregation of impacts to a 'final score', should not be used as an assessment technique, the results of which are intended for use by the decision-maker. Such an approach would remove the decision from those appointed or elected for that purpose and place it in the hands of the study-team.' (Thompson, 1990).

Based on the reviewed literature, it seems that although a 'final score' is avoided for the clarification of various impacts, the significance of impacts is still spatially invariable. Spatial extent and spatial patterns are used only as one of the impact-defining characteristics. For example, the Spatial Impact Assessment Methodology (SIAM) proposed by Antunes et al. (2001) is mainly aimed at performing an aggregation of impacts in the spatial dimension. However, the spatial differences between the alternatives are not communicated to the decision-makers.

> There are multiple reasons why impact significance should not be a spatially uniform measure. First, by stripping the spatial dimension, local impacts either are completely absorbed by the impacts on the larger scale or are wrongly given the same weight (Antunes et al., 2001). Second, impacts of different nature can accumulate in space and time and that way synergistically affect not only environmental but also social or economic sustainability. Third, impact assessment practises 'will increasingly have to deal with significance judgements in relation to new proposals where existing thresholds, even without the proposal, have already been exceeded for various valued components' (Retief et al., 2016).

Furthermore, concerns of affected communities can differ from place to place (Gangolells et al., 2011). Therefore, using values from one community may not fit the judgements of the neighbouring one. In the event of large-scale changes that involve national or regional policies, each of the multiple affected communities would take the changes differently. For example, a small development proposal in an ecologically sensitive environment may have a more significant impact than a much larger development located in a more robust setting. Similarly, a community dominated by high unemployment may be more supportive of controversial development proposals than comparable areas with full employment (Wood, 2008).

Finally, two conditions must be controlled to accept a judgement as well-founded: consistency and consensus (Cloquell-Ballester et al., 2007). Although consistency refers to the standard deviation of individual judgements, a study by Janssen et al. (2015) has shown that associating individual stakeholder values with particular locations helped to arrive at a consensus that could not be reached otherwise.

Having spatial variability in impact significance assessment requires a spatially explicit model. Goodchild (2001) suggests four tests to determine whether a model is (or should be) spatially explicit:

The Invariance Test considers a model spatially explicit if its outcomes (rankings or orderings of decision alternatives) are not invariant under relocation of the feasible alternatives. This implies that a change in the spatial pattern of feasible alternatives results in changes in their rankings.

The Representation Test requires that the decision alternatives are geographically defined. Such alternatives consist of at least two elements: action (what to do?) and location (where to do it?).

The Formulation Test declares a model spatially explicit if it contains spatial concepts such as location, distance, contiguity, connectivity, adjacency, or direction.

The Outcome Test checks if the spatial form of the outputs is different from the spatial form of its inputs. For example, the input values of spatial decision problems may be assigned to various spatial objects, while the output maps would represent the overall values associated with each location using raster data format.

4.4 ANALYSIS OF IMPACT SIGNIFICANCE ASSESSMENT METHODS

Although rarely considered a subject on its own, impact significance assessment is an intrinsic part of Impact Assessment methods and Decision Support Systems. Based on the review in Section 4.2, impact significance assessment is a procedure that can rank or classify impacts taking into account both impact characteristics and the importance of the context where they occur. To determine the current state-of-the-art of spatial variability in impact significance assessment, four methods have been selected as the most relevant in context of transitioning towards CE: Environmental Impact Assessment (EIA), Life Cycle Assessment (LCA), impact assessment in Geodesign and Spatial Decision Support Systems (SDSS). These methods were evaluated using spatial variability tests (Goodchild, 2001). The results of the analysis (Table 4.5, 4.6, 4.8, 4.9) have shown that the spatial variability of impact significance corresponds to one of the two equations (Equations 4.2 and 4.3).

$$IS_{(x,y)} = f(I_{(x,y)}, C) \tag{4.2}$$

where:

$IS_{(x,y)}$ = Impact Significance at location (x, y),

$I_{(x,y)}$ = Impact Characteristics at location (x, y),

C = Context Importance.

$$IS_{(x,y)} = f(I, C_{(x,y)}) \tag{4.3}$$

where:

$IS_{(x,y)}$ = Impact Significance at location (x, y),

I = Impact Characteristics,

$C_{(x,y)}$ = Context Importance at location (x, y).

4.4.1 Environmental Impact Assessment

Spatial variability test	Impact Characteristics	Context Importance
Invariance	+/- Subject to change based on the project relocation	- No requirement for spatially differentiated environmental sensitivity or public judgement values
Representation	- Decision alternatives may not be associated with project relocation	- No requirement for spatially differentiated environmental sensitivity or public judgement values
Formulation	+ Project and its impacts must be associated with particular geographical location	- No requirement for geographic definition of environmental sensitivity or public opinion
Outcome	+/- Spatial extent must be provided, but there is no defined format	- No required format for the description of environmental sensitivity

Table 4.5. Spatial variability of impact significance assessment in EIA.

Environmental Impact Assessment (EIA) is a procedure used to provide an analysis of the potential significant environmental effects associated with major development proposals and to communicate this information to decision-makers and the broader public (Wood, 2008). As there are many different methodologies for impact identification and assessment, it is characterised by diversity in its practise and by associated ambivalence (Pope et al., 2013). The latest review on the state of the art EIA by Zelenakova and Zvijakova (2017) describes EIA as a seven-step procedure: scoping, impact identification, description of environment, impact prediction, impact assessment, decision-making, and communication of results. Although impact significance assessment is not explicitly mentioned as a separate step, it should intrinsically be a part of decision-making.

The analysis of spatial variability has been made on the basis of Directive 2011/92/EU as amended by Directive 2014/52/EU (known as the 'EIA Directive'). The main principle of the EIA Directive is to ensure that plans, programmes, and projects that are likely to have significant effects on the environment are evaluated and their implications made public prior to their approval or authorisation (European Commission, 2014). The Directive indicates the rules for reporting the carried EIA; however, it does not appoint a single method of assessment. Nevertheless, the Directive provides a list of impact characteristics that need to be considered, among which is spatial extent. A description of the location of the project is also required, with particular regard to the environmental sensitivity of geographical areas likely to be affected.

According to the EIA Directive, 'Member States may set thresholds or criteria to determine when projects need not undergo [...] environmental impact assessment' European Commission (2014). The public interested in environmental decision-making should also be informed and allowed to express comments and opinions. However, the Directive does not require project developers to collect either the importance judgement of the public or institutional judgements, which would later be juxtaposed with the predicted impacts.

Based on the analysis results in Table 4.5, it appears that according to the EIA Directive, Impact Significance in a particular location is determined by the Impact Characteristics in that location and spatially non-differentiated values of Context Importance as in Equation 4.2.

4.4.2 Life Cycle Assessment

LCA is especially relevant in the context of the transition to CE, as it can tell whether the achieved circularity of a certain resource would actually enhance overall sustainability (Haupt and Zschokke, 2017). LCA is 'primarily a steady-state-tool' that does not consider temporal or spatial information and mostly has no relation with the context. In fact, this information is often lost due to aggregation (Udo de Haes, 2006). The comparison between impacts is instead done by employing a functional unit (e.g. treatment of household waste produced in the city of Amsterdam during one year) and aggregating all the emissions into indicators that can be compared directly, or at midpoint or endpoint levels. Although LCA is able to provide a complete picture of all impacts associated with a

Spatial variability test	Impact Characteristics	Context Importance
Invariance	+/- May be subject to change on relocation of alternatives in both spatial and non-spatial LCA	+/- Typically not spatially differentiated, although precedents exist
Representation	+/- The decision alternatives may have both a choice of actions and locations, although typically on a coarse granularity	+/- Typically not spatially differentiated, although precedents exist
Formulation	- Spatial concepts are not included in impact assessment	- Spatial concepts are not included in characterisation
Outcome	+/- Impacts may be geolocated based on processesses as objects in different spatial form (e.g. grid cell assignment)	- Spatially differentiated characterisation factors typically do not change spatial form

Table 4.6. Spatial variability of impact significance assessment in LCA according to the selection of literature as in Table 4.7

product or process, communication of results usually requires an expert audience (Elia et al., 2017).

Although LCA was developed as a spatially independent approach, spatial attempts of LCA associated with every stage can be found in the literature (Nitschelm et al., 2016; Moncaster et al., 2018). The significance of impacts in LCA is typically determined by impact indicators and characterisation factors. Both impact inventory and characterisation factors can be spatially differentiated. In fact, Moncaster et al. (2018) have demonstrated that varying the methodological choices in terms of temporal boundaries, data coefficients, and spatial boundaries can change the results by an alarming factor of 10 or even more. Their analysis shows that the impact of difference in methodology can be higher than the impact of alternative decisions using the same methodology.

The spatial variability of the impact significance assessment is analysed based on the selection of recent publications (Table 4.7). Based on the results of the analysis in Table 4.6, it appears that the significance of the impact in a particular location is typically determined according to Equation 4.1, although Equations 4.2 and 4.3 are also possible for spatial LCA.

List of references	
Haupt and Zschokke (2017)	Nitschelm et al. (2016)
Hiloidhari et al. (2017)	Kim et al. (2015)
Maier et al. (2017)	Smetana et al. (2015)
Escamilla and Habert (2016)	Hellweg and Mila i Canals (2014)

Table 4.7. A list of literature used for the review on Life Cycle Assessment

4.4.3 Geodesign

Spatial variability test	Impact Characteristics	Context Importance
Invariance	+ All alternatives are of a spatial nature, thus the ranking of impacts directly depends on them	- The stakeholder values are not spatially defined
Representation	+ The decision alternatives consist of actions and geographical locations	- Stakeholder values are associated with actions but not particular locations
Formulation	- Impacts are not characterised by spatial concepts	- Stakeholder values are not characterised by spatial concepts
Outcome	+/- Output is not presented in spatial format, but as a matrix	- Output is not presented in spatial format, but as a matrix

Table 4.8. Spatial variability of impact significance assessment in geodesign methodology

Geodesign has been chosen as the leading methodology for the decision support environment in the REPAiR project (REPAiR, 2016) as it is a design and planning method that closely couples the creation of design proposals with impact simulations informed by the geographical context. Impact Assessment is the 4th step of the geodesign methodology (Steinitz, 2012) and refers to the question 'What differences might the changes cause'? The impacts are then assessed by experts and stakeholders using simple assessment matrices that assign values from 'very bad' to 'very good' to each scenario of change for each of the valued factors. Impact significance is determined based on a consensus between the workshop participants considering their judgement and expertise.

The results of the analysis in Table 4.8 reveal that the significance of impact in geodesign is generally not spatially differentiated because the importance of the context is not spatially explicit. Furthermore, although impact characteristics are spatial in nature and are determined by spatial alternatives, impact significance is assessed uniformly for the entire study area. This would lead to Equation 4.2 being the most suitable for describing the determination of impact significance in geodesign. However, workshop participants may implicitly assume spatial variability and, accordingly, adjust their ratings of the alternatives without formally expressing them.

4.4.4 Spatial Decision Support Systems

Spatial variability test	Impact Characteristics	Context Importance
Invariance	- Uniform throughout the study area	+ Expressed per spatial unit in means of sensitivity, vulnerability or potential
Representation	- Location varies among alternatives, but actions and thus their impacts remain spatially constant	+ Decision alternatives are associated with context characteristics that define its importance
Formulation	- Not spatially defined	+/- Mostly limited to location, but may also include distance, adjacency, direction, etc.
Outcome	- Not spatially defined and therefore not output in spatial format	+ May be based on different spatial form than decision alternatives

Table 4.9. Spatial variability of impact significance assessment in SDSS according to the selected literature as in Table 4.10

An SDSS can be defined as an interactive computer-based system designed to support a user or group of users to achieve greater effectiveness in decision-making while solving a semi-structured problem that has spatial consequences (Malczewski, 1999). Decision Support Systems are meant to support rather than replace human judgements and improve effectiveness rather than efficiency of a process (Uran and Janssen, 2003). This means that a user is expected to use the system as an advisory unit that is simply more capable of digesting large amounts of data and performing quick computations.

An increasing number of scientific articles related to SDSS are published every year to solve an increasing variety of spatial decision problems that follow rather distinct methodologies (Ferretti and Montibeller, 2016). To investigate current practises and how they approach impact significance assessment, a small set of 12 relevant publications was chosen according to Query 6 (Table 4.10).

Evidently, none of the studies has conducted a real impact assessment. Instead, impact significance has been decided solely on the basis of the importance of the context. For example, the presence of ecosystem services increases access to green spaces. Therefore, ecosystem services should be located in a cell where access to green spaces is lowest (Meerow and Newell, 2017). In some studies, impacts refer not to the impacts a project would cause to the environment but to the impacts the environment would have on the project's success. For example, more transport infrastructure is better for urban development. Therefore, urban development should be located where the transport infrastructure is the best (Grêt-Regamey et al., 2016). Equation 4.3 is the most suitable to describe how impact significance is determined in a particular location in SDSS.

List of references	
Meerow and Newell (2017)	Corral et al. (2016)
Bonzanigo et al. (2016)	Janssen et al. (2015)
Jeong and Garcia-Moruno (2016)	Dapueto et al. (2015)
Rovai et al. (2016)	Bojesen et al. (2015)
Ottomano Palmisano et al. (2016)	van Niekerk et al. (2015)
Grêt-Regamey et al. (2016)	Erfani et al. (2015)

Table 4.10. A list of literature used for the review on Spatial Decision Support Systems

4.5 RECOMMENDATIONS FOR SPATIALLY DIFFERENTIATED IMPACT SIGNIFICANCE

According to Equations 4.2 and 4.3, for Impact Significance to be spatially differentiated it is sufficient that either Impact Characteristics or Context Importance is spatially differentiated. However, if only one variable in the equation is spatially differentiated and the other is spatially constant, the value of impact significance does not account equally for both impact characteristics and context importance. Instead, it aligns with the variability of the spatially differentiated one. Spatial variations of both impact characteristics and context importance should be taken into account to conduct a spatially differentiated impact significance assessment, as per Equation 4.4.

$$IS_{(x,y)} = f(I_{(x,y)}, C_{(x,y)}) \tag{4.4}$$

where:

$IS_{(x,y)}$ = Impact Significance at location (x, y),

$I_{(x,y)}$ = Impact Characteristics at location (x, y),

$C_{(x,y)}$ = Context Importance at location (x, y).

Several recommendations are provided to achieve spatially differentiated impact significance that reuse elements of existing methodologies, following the four tests defined by Goodchild (2001).

The Invariance Test on Impact Characteristics. Impact characteristics should be subject to change if the location of an object or action is changed, e.g. if a decision needs to be made upon which neighbourhood to place a compost park, and one of the considered impacts is 'increased accessibility to green spaces', then the number of people able to access the new park needs to be calculated for each of the neighbourhoods.

The Invariance Test on Context Importance. The values of context importance should also vary between different locations. For example, following the same example of locating a compost park, context importance may depend on the demographics of the neighbourhood with higher preference for young families and lower for students, which will vary from neighbourhood to neighbourhood.

The Representation Test on Impact Characteristics. If decision alternatives involve both the choice of actions and their location, the characteristics of impacts must be changed accordingly. For example, if a choice needs to be made between locating a compost park in an existing green space or in a newly created one, then impact assessment should describe the impact of the new and adapted park depending on the location characteristics, as some of them might be more favourable for adaptation while the others for a new green space.

The Representation Test on Context Importance. When decision alternatives involve both the choice of actions and their locations, importance should be given not only on the basis of the preferred action but also considering the different possibilities of locations. For example, the acceptability and usage of a compost park can depend on the social composition of a particular neighbourhood, while the need for greater access to green spaces can depend solely on the demographics of the neighbourhood.

The Formulation Test on Impact Characteristics. Those impact characteristics that change depending on the context characteristics should be formulated with spatial concepts. Although impact characteristics such as reversibility or duration may depend only on the chosen action and do not vary in different contexts, impact magnitude may be well associated with the context characteristics. For example, the possible odour from the composting facilities may affect different areas by different intensities depending on the wind patterns.

The Formulation Test on Context Importance. Distance, adjacency, connectivity, or direction can also serve to define context importance. The importance does not always have to be bounded to specific cells, but expressed as adjacency to certain facilities or sensitive habitats, a function of distance from risk inducing object, accessibility over a network, or gradually decreasing while moving north or south due to climate or cultural variations.

The Outcome Test on Impact Characteristics. To evaluate the impact on each value component, it is necessary to identify receptors and describe the impact pathways that affect these receptors (Antunes et al., 2001). The receptors will eventually have a spatial dimension (e.g. population density, species distribution, location of resources). However, the spatial form of an impact may be different from that of the receptor.

The Outcome Test on Context Importance. Similar to the impact characteristics, the importance of the context can be expressed in a spatial form different from the significance assessment. Context importance may be based on e.g. topography, network centrality or administrative boundaries, while impact significance may be assessed per individual neighbourhoods.

The four tests help to determine whether the assessment is or could be spatially differentiated and on what grounds. Passing one of the four tests is sufficient to qualify for the spatially differentiated impact significance assessment; however, a balance between spatial differentiation in impact characteristics and context importance needs to be retained, i.e. if Impact Characteristics are spatially explicit, then Context Characteristics must also be spatially explicit.

The need for spatial differentiation in impact significance should also be critically evaluated on the basis of its added value. As Nitschelm et al. (2016) have noted, 'the debate about whether spatialised LCA reduces uncertainties in LCA studies remains open. The amount of local data needed for spatialised LCA studies can indeed increase uncertainties in the LCI phase.' The same observation holds true not only for LCA but also for impact assessment and decision support methods, in general. However, the evidence from SDSS demonstrates that the judgement of context characteristics is spatially varying, while Impact Assessment studies prove the same about impact characteristics. This suggests that accounting for both components of the significance assessment should lead to a more informative and just result.

4.6 CONCLUSIONS AND FUTURE WORK

Review of the literature on impact significance assessment has revealed that although the process is commonly performed during impact assessment and decision-making, there is no single method that could be followed. Significance assessment is required by legal documents such as the EIA Directive, but there is a lack of a legal definition or standardised method. What different authors agree on is that impact significance assessment is a double-sided procedure that involves objective assessment of impacts and subjective judgement of their importance. However, there is no consensus on what exactly characterises impacts and who needs to provide judgement of importance and how. The review provides an overview of how different authors describe the two components of impact significance and what arguments are used to support the judgement.

> As a result, this research suggests that the assessment of impact significance should be viewed as a function between impact characteristics and the importance of the context in which the impact occurs. While impact characteristics can be estimated using objective measures, context importance requires judgement of importance that may be provided by stakeholders, decision-makers, public opinion, or institutionally.

Until now, publications on impact significance regard spatial aspects only as possible impact characteristics and not as a separate dimension of assessment. However, when decision-making involves local impacts whose significance is highly dependent on the characteristics of the context, the assessment requires spatial differentiation. Following this assumption, three main challenges must be overcome: 1) probable impacts must be characterised according to their geographical context; 2) the geographical context must be evaluated for its relative importance; and 3) finally, the values must be combined to represent impact significance that may have spatial variability dependent on both components.

Environmental Impact Assessment, Life Cycle Assessment, Geodesign, and Spatial

Decision Support Systems, all employ impact significance assessment prior to comparison of decision alternatives. Although alternatives often have spatial form and cause impacts that can be represented spatially, the four spatial tests of Goodchild (2001) have revealed that spatial differentiation is mainly based on impact characteristics or context importance, but not both simultaneously. As a result of this study, recommendations have been provided to overcome this gap in future impact significance determinations.

The recommendations drawn from the analysis are further tested and refined in practise during the development of a Geodesign Decision Support Environment. Future work still includes providing clear unambiguous definitions of the used terms (e.g. context vs. impact) and demonstrations of how the devised theory can be implemented in decision support. The frameworks and tools created aim to be sustainable and exceed the specifics of a single case study (Circular Economy).

REFLECTION ON THE FINDINGS

The most important finding that is taken further into account in the following research steps is the distinction between impact and the context in which impact occurs. This requirement for CEM as well as for GDSE sets the corresponding requirements for the waste statistics. To fulfil the requirements, waste statistics are expected to provide sufficient granularity and coverage in spatial and, potentially, other dimensions to allow distinguishing between the (spatial) alternatives in circular economy strategies.

Given that the significance assessment is not a computational method, but a cognitive process, "sufficient granularity and coverage" cannot be evaluated in numerical terms. Following the theoretical framework, granularity and coverage can be considered sufficient when both variables (impact characteristics and context importance) can be compared using the same cells without losing critical information.

To give an example, if the question at hand considers changes in waste exports, the result of the impact assessment may be that there will be reduced negative impacts "abroad" without being able to specify further details. If decision-makers do not assign varying importance to where abroad the impact is reduced, then the coverage of both variables is matching. However, if decision-makers consider it more important to reduce the negative impact in countries outside the EU rather than in countries inside the EU, then the spatial coverage of impact characteristics is insufficient for the significance assessment.

If impact characteristics are spatially differentiated between the different continents, while context importance varies per country, then impact characteristics do not have sufficient spatial granularity. When the situation is reversed and impact characteristics distinguish between the countries while importance is not given to each country separately, the question should be asked whether the importance is effectively uniform or insufficiently defined.

Impact characteristics are measured, modelled, or simulated; therefore, their granularity and coverage are clearly defined. However, context importance is a rather subjective that is more often qualitative and based on judgement, therefore, its granularity and coverage are not always easy to define and, therefore, compare. A method that is able to provide an interface and, therefore, enable comparison between the computational models and human judgement is based on formal ontologies, as explained in the following chapter.

DATA AND SOFTWARE AVAILABILITY

No data, software or computational workflow has been used for this st udy. All queries used for literature review are included in Table 4.1.

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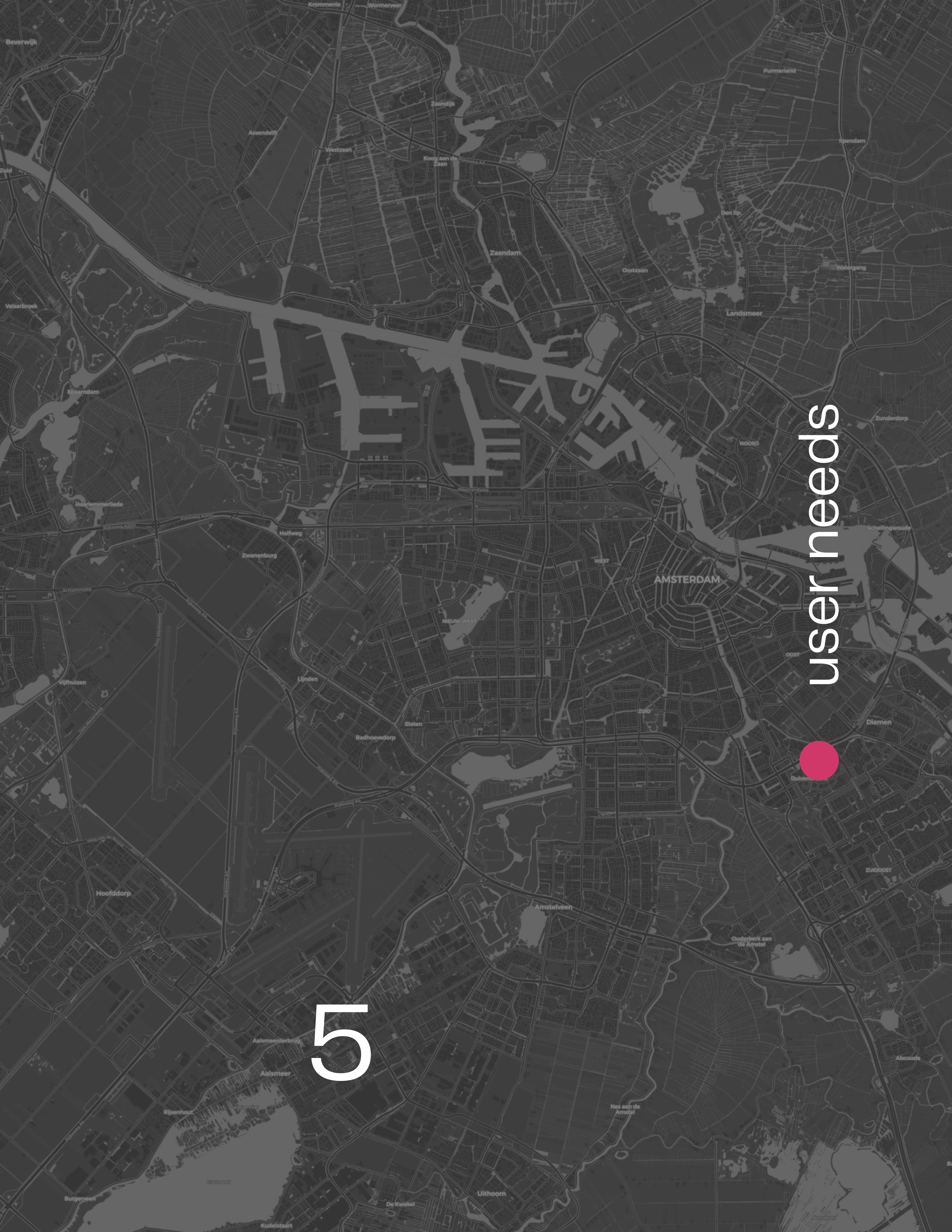

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Watergang
Velserbroek
Landsmeer
Spaarndam
Zunderdorp
NOORD
Haarlemmerliede
Halfweg
Schellingwoude
Zwanenburg
WEST
AMSTERDAM
NIEUW-WEST
Vijfhuizen
Lijnden
OOST
Diemen
ZUID
Sloten
Badhoevedorp
Duivendrecht
ZUIDOOST
Hoofddorp
Amstelveen
Ouderkerk aan de Amstel
Aalsmeerderbrug
Abcoude
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De Kwakel
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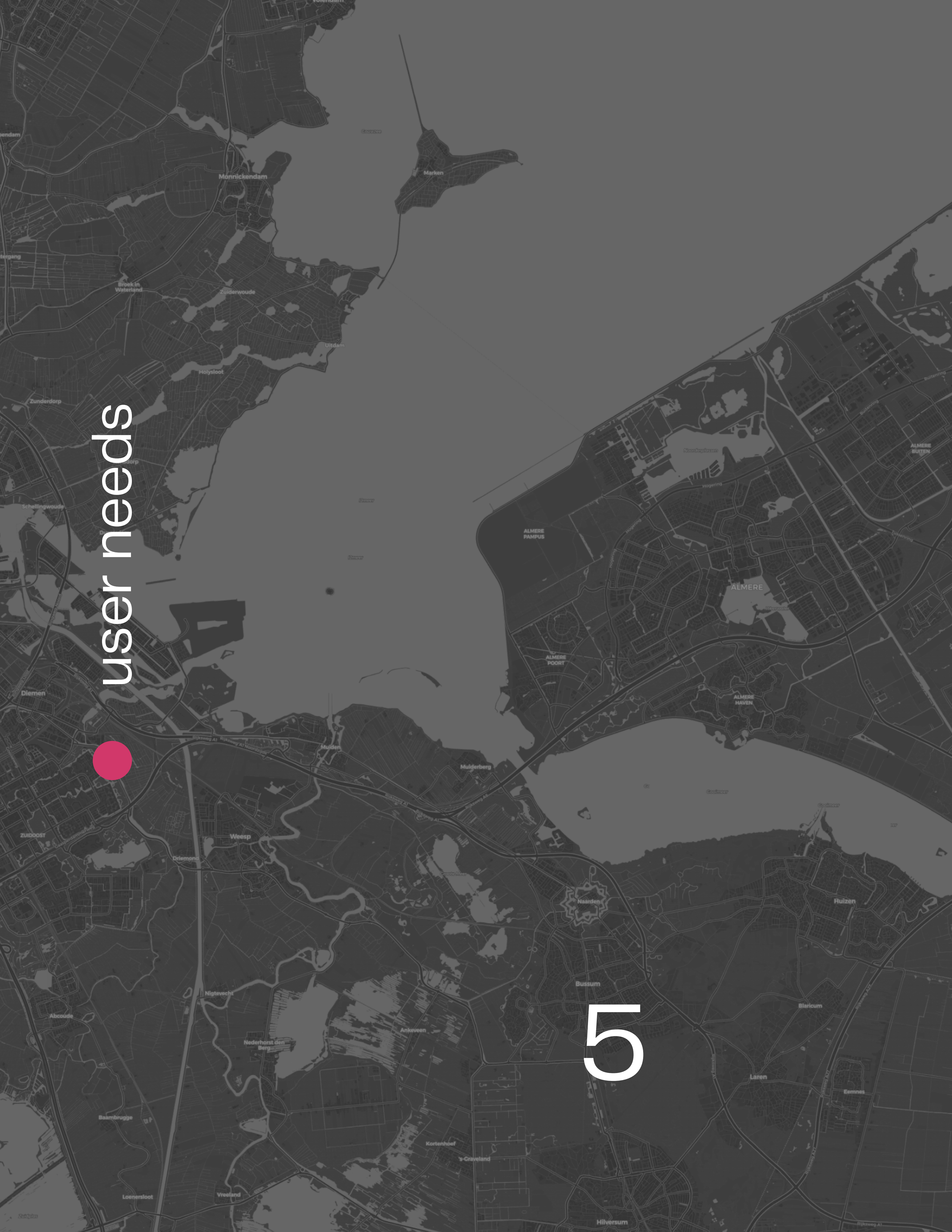
5

user needs

5 user needs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's-Graveland
Baambrugge
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Hilversum

CIRCULAR ECONOMY MONITOR FOR THE AMSTERDAM METROPOLITAN AREA

Research questions:

- A What are the expectations and requirements for the circular economy monitoring in the Amsterdam Metropolitan Area?
- B On what theory should circular economy monitoring be based on?
- C How can user expectations and theory be aligned with available data and tools?

Based on:

Sileryte, R., Wandl, A., & van Timmeren, A. (2021).

A Bottom-up Ontology-based Approach to Monitor Circular Economy: Aligning User Expectations, Tools, Data and Theory.

OSF Preprints, Accepted for publication in the Journal of Industrial Ecology.

DOI 10.31219/osf.io/sqcdv

PREAMBLE

This text has been published in Fothergill J, Murphy J (2021) ***The Circular Economy and Impact Assessment. A primer*** *International Association for Impact Assessment (IAIA), pp. 25*

The city of Amsterdam aims to be the global forerunner in the transition toward a CE. In 2019, as part of its Circular Strategy 2020-2025, it started developing a monitoring dashboard: a web application accessible to both policy makers and the general public.

As the city adopted Kate Raworth's acclaimed 'doughnut economy model' as its main vision for sustainable development, the monitoring dashboard aims to effectively measure the impact of the city of Amsterdam by visualising the input, throughput and output of the material streams of the city. The monitoring dashboard zooms in on material flows from resource extraction to meet city consumption to all residual flows of materials that become waste and the environmental impacts they cause both locally and globally.

The doughnut model presents an aggregated image of how far the city is from its targets, but the Monitor allows zooming in on multiple indicator lenses: geospatial, temporal, materials, and the contribution of both different economic activities and waste processing methods. Instead of only emphasising positive change and presenting existing circular initiatives, the Monitor's dashboard helps to ask 'what still needs to be solved'.

The dashboard consists of highly granular data, combined from different governmental sources (industrial waste reports, registries of the Chamber of Commerce, international trade data, etc.). It also exposes existing data gaps and proxies used in decision-making, encouraging users to contribute higher-quality data.

To capture the full scope of impacts caused by changes in material flows, a combination of impact assessment methodologies is necessary:

Life cycle assessment (LCA) supported by a material flow assessment (MFA), the standard approach risks being too contextually/locationally agnostic, thus lacking key social and ecological variations that influence impact significance.

Environmental Impact Assessment (EIA) enables this specific site definition, but this tends to mean that wider material flow (indirect) impacts can be missed.

The Monitor itself is not an impact assessment tool; however, it provides information to support both methods:

1. Material consumption and waste quantities and known site-specific emission factors related to the waste collection and processing methods necessary for LCA inventories.
2. Existing (residual) flows in a data structure that enables project- and plan-level IAs to rapidly identify where precisely social and ecological boundaries have already been crossed and the opportunity to contribute to return to desired levels by a specific project in a specific site.

Case study authors:

Rusne Sileryte and Arnout Sabbe developed the waste mapping part of the Monitor as part of their doctoral thesis (Delft University of Technology). They now run a spin-off on an open source project (geoFluxus). Amsterdam Monitor is being developed in close collaboration with Juan-Carlos Goilo (Project Leader - Amsterdam City Innovation Office), who is currently writing his doctoral thesis on the conceptual framework of monitors at the University of Amsterdam.

5.1 INTRODUCTION

The global megatrend of resource scarcity in combination with rapidly changing demographics is reflected in the growing number of policy documents that place CE high on the agenda: from national and supranational plans (The European Commission's Circular Economy Action Plan ((Commission, 2020), Circular Economy Promotion Law of the People's Republic of China (PRC, 2008)) to city scale strategies (e.g. Amsterdam Circular Strategy 2020-2025 (Gemeente Amsterdam, 2020), London's Circular Economy Route Map (London Waste and Recycling Board, 2017)). The next step after the targets are set and actions are listed is tracking progress and monitoring their effectiveness.

However, current monitoring frameworks are widely criticised for being too aggregate and therefore generic (Haberl et al., 2019), disconnected from environmental impacts, unable to measure reduction or prevention (Harris et al., 2020), and not related to concrete goals or accompanying policies (Friant et al., 2020). Moreover, top-down macro-frameworks require standardised data collection and reporting systems that involve multiple stakeholders and are often too hard to implement (Harris et al., 2020). The process of decision-making and monitoring of success is further exacerbated by the lack of agreement on what exactly the transition to CE is supposed to achieve (Kirchherr et al., 2017; Corona et al., 2019) and what can and should be achieved through policy interventions (Friant et al., 2020). Policy decisions on resource management do not only affect the place and time where and when policies are made, but extend far beyond the chosen territory and time frame due to existing networks of resource flows (Furlan et al., 2020; Korhonen et al., 2018).

To overcome the challenges that top-down monitoring frameworks face at this stage of the transition, we suggest beginning with a bottom-up approach and first consolidating the available data, existing theory, and practical concerns of decision-makers in a specific monitoring context. We argue that aligning terminology, capabilities, and expectations helps to expose and therefore overcome the limitations of current monitoring frameworks.Therefore, the objective of this publication is to demonstrate how an ontology creation process can facilitate the exposure of data and knowledge gaps and potential conflicts.

A use case from the city of Amsterdam in the Netherlands has been chosen to evaluate and demonstrate how the available data, tools, user expectations, and theories behind a circular economy monitor (mis-)align with each other. The city has a moonshot ambition "to be 100% circular by 2050, with an intermediate target of a 50% reduction in primary raw materials consumption by 2030" (Gemeente Amsterdam, 2020). To measure the progress towards its goals, Amsterdam is currently building a Circular Economy Monitor (CEM) which should serve as a powerful data infrastructure for CE transition monitoring and decision support. Given that a 100% material circularity is not possible from the thermodynamic perspective, to date it remains unclear what the achievable ambition is. Different sources refer to the full circularity in a range of definitions from 'economy that requires no raw materials' to 'waste-free economy' The ambiguity of the goal further emphasises the lack of semantic integrity in the circular economy policy.

5.2 THEORY

The most prominent remark repeated in multiple reviews of macro-level monitoring frameworks is the lack of consensus on CE terminologies and definitions among scholars, politicians, and practitioners (Homrich et al., 2018; Kirchherr et al., 2017). Harris et al. (2020) noticed that some scholars regard the main aim of CE as achieving economic prosperity, followed by environmental quality, while others perceive the aim in the opposite order. Parchomenko et al. (2019) have made an attempt to list all relevant CE elements and found that neither the list of elements can be robustly grounded in the existing literature nor the precise meaning and distinction between them. Korhonen et al. (2018) take the field's critique even further by stating that "the scientific and research content of the CE concept is superficial and unorganized. CE seems to be a collection of vague and separate ideas from several fields and semi-scientific concepts."

The other group of remarks is related to technical challenges. While the existing macro-level frameworks (or their modifications) together are likely to be able to answer all CE goals, there is no single integrated methodology that can integrate all required parts (e.g., assessing scarce resource input, emission levels, material losses, product durability, local jobs, etc.) into a single study (Corona et al., 2019). At the same time, the vast majority of macrolevel CE indicator frameworks are not linked to any tool capable of calculating them and remain mostly described textually (Saidani et al., 2019). And eventually, the requirements cannot be met by the data available to support the frameworks (Harris et al., 2020).

> Unlike the authors who suggest that "constructs involved in the CE literature still need to be further refined and a more homogeneous nomenclature should be applied" (Homrich et al., 2018), we suggest that at this stage of the transition all efforts to systematise knowledge (and thus monitor progress) must strive for maximum flexibility and adaptability to new findings and improved definitions.

The technology to support this heterogeneous approach is, in principle, available and can be based on Semantic Web standards, ontologies, shareable linked data repositories, and other e-Science technology. To support this technically, it is necessary that distant communities of practise use semantic metadata (Scheider et al., 2017). One of the key technologies for organising a conceptual world is ontology engineering (Kumazawa et al., 2009).

An ontology in its basic sense can be understood as a controlled vocabulary in which a certain world, domain, or model is described. It provides names to the most important concepts, their synonyms, and antonyms, and describes which properties are allowed and expected, and how these concepts relate to each other. It is an intermediary of information technology that can be understood both by people and computers. Formalising a concept into an ontology makes it machine readable, which facilitates data exchange, allows automated reasoning, and ensures concept, data, and metric reusability and interoperability.

Every model implicitly uses an ontology, but few of them are explicitly formalised beforehand. Every data collection is based on its implicit ontology and is often recorded as explicit metadata. Monitoring applications typically make use of a relational database that can be converted to an ontology (Zedlitz and Luttenberger, 2012; Munir and Sheraz Anjum, 2018). In turn, humans who use data and relational databases have specific questions in mind that are expressed using domain-specific terminology. The terms used may have explicit definitions grounded in theory and shared between all domain experts or they may be used interchangeably and change meaning depending on the context.

If domain knowledge is well grounded in theory and well established, the implicit ontologies of data, tools, and users are also implicitly aligned. However, if a research field is still emerging or highly contested, there is a risk of misalignment that leads to a multitude of problems (Kumazawa et al., 2009). Even the most comprehensive tools are not to be used if users do not find how the information provided helps answer their specific questions. If a database structure does not align with the semantics of the data, the data are at risk of losing utility during processing and conversion. Not using terms that are grounded in theory causes the systems to be short-lived, due to their low interoperability and replicability in different contexts. Finally, if the lack of alignment is overlooked, wrong conclusions can be drawn based on conflicting terminology.

Since Holsapple and Joshi (2002) have suggested an ontology development process as a means of supporting collaboration between different disciplines, it has been used in a variety of settings, including the water-energy-food nexus (Kumazawa et al., 2009), defining projects and scenarios for an integrated assessment modelling of agricultural systems (Janssen et al., 2007), knowledge management within electronic government services (Fraser et al., 2003), integrated highway planning (France-Mensah and O'Brien, 2019), and a multitude of others.

Although the body of literature on Circular Economy has been growing since

Brundtland's report (1987) and since 2010's (Calisto Friant et al., 2020) increases exponentially, the use of formal ontologies is rarely included in the discourse. While a SCOPUS search for the term "Circular Economy" returns 9195[1] results, only 28 of them mention the word "ontology" in the title, keywords or abstract, and only 11 of them actually focus on describing, developing, or evaluating ontologies (Table 5.1). To date, no published attempts have been made to use formal vocabularies in constructing circularity metrics. Likewise, to the best of the authors' knowledge, no ontology exists that aims to support policy decisions in the transition towards a CE.

Although ontologies are often discussed in substance without explicitly stating them, for practical reasons they are excluded from this review. An article that does not explicitly discuss an ontology would first have to go through a machine-readable ontology development process, which would have to be done by the authors of this paper and would likely lead to a biased result.

It is important to note that none of the reviewed ontologies (except the European Waste Classification Taxonomy) has been published in a machine-readable format along with a scientific paper that describes them. This automatically prevents their reuse and further development. However, reusing existing ontologies from the same or even adjacent disciplines is the most common advice in the ontology development literature.

The ontology proposed by Pauliuk et al. (2016) aims to provide a practical, mutually exclusive and collectively exhaustive ontology that can accommodate data from any interdisciplinary model of socioeconomic metabolism (SEM) study domain. Analysis tools developed for studying SEM flows can inform CE efforts on how quickly material stocks grow, when and how materials become available for reuse, and how much recovered resources can contribute to maintaining the necessary stocks by closing the loops. The ontology is concerned only with the physical flow aspects of the material in SEM studies, that is, the properties of the physical material, the locations, quantities, and the processes that change them. It is a high-level ontology that aims to be as domain agnostic as possible, providing a

[1] as of 5th March, 2021

minimal required amount of classes to support interdisciplinary research. For these reasons, their ontology is more suitable to be used as a theoretical basis for this paper than the other reviewed ontologies, all of which are specific to a certain domain.

Table 5.1. Overview of all publications returned by SCOPUS that focus on describing, developing or evaluating ontologies in relation to a circular economy.
A - Waste-to-resource recommender system;
B - Internet of Things;
C - Product or material passport;
D - CE business model support;
E - Data and information exchange.

Domain and publication	Purpose					Available for reuse	Scale
	A	B	C	D	E		
European Waste Catalogue (Capelleveen et al., 2021)	+					Yes	-
Waste Treatment Processes (Pacheco-López et al., 2020)	+					No	Meso
Product life cycle monitoring (Mboli et al., 2020)		+		+	+	No	Micro
Nannochloropsis gaditana microalgae (Fernández-Acero et al., 2019)	+					No	Micro
Product passport (Gligoric et al., 2019)		+	+	+	+	No	Micro
Building material passport (Sauter et al., 2018)	+		+		+	No	Micro
Eco-industrial parks (Martín Gómez et al., 2018)	+			+	+	No	Meso
Product passport for textiles (Sauter and Witjes, 2017)			+		+	No	Micro
Socioeconomic metabolism (Pauliuk et al., 2016)					+	No	Macro
Product-service systems (Vasantha et al., 2015)				+	+	No	Meso
Equipment maintenance (Olivier et al., 2015)					+	No	Meso

5.3 METHODS AND DATA

Holsapple and Joshi (2002) have described 5 general ontology development frameworks: inspirational, inductive, deductive, synthetic, and collaborative. The frameworks differ in terms of the starting point (seed) for the ontology creation. Even if the domain and purpose of the ontology are the same, depending on the method used to create them, it may deliver radically different results. Therefore, a hybrid and iterative approach is recommended until the ontology is considered application-ready.

For this paper, four different ontology creation approaches have been used based on the Amsterdam CEM use case: user-centred (collaborative), data-centred (inductive), tool-centred (inspirational), and theory-centred (synthetic). The four created ontologies are then compared and merged with each other in an iterative manner to arrive at a single ontology that would satisfy all requirements as closely as possible. Ideally, all four should be easily mapable to each other. That would mean that there is a clear correspondence between what the users of a circular economy monitor wish to know, what a circular economy monitoring and decision support tool is able to provide, which data is available, and what is backed up by scientific theory.

> The more overlapping concepts can be found between the four initial ontologies, the better they are aligned. Therefore, the notes on ontology mapping, alignment, and merging of concepts are used to discuss CE terminology, underlying assumptions, data, and knowledge gaps.

The first iteration of an Amsterdam CEM builds on two baseline data sets that represent the major part of the linear economy: the national industrial waste registry and port import/export declarations. The web application used as a basis for the CEM originates from the H2020 project REPAiR (Resource Management in Peri-Urban Areas). The Geodesign Decision Support Environment (GDSE) is a prototype web application in which different stakeholders in CE strategies can assess their environmental and spatial impacts (Arciniegas et al., 2018; Remøy et al., 2019). The main intended users of the early stages of the Amsterdam CEM are policy and strategic advisors, and programme managers within the Municipality.

The CE ontology resulting from the described development process is an open source initiative that is used as part of the Amsterdam CEM currently under development by the Amsterdam Municipality CTO Innovation office and geoFluxus BV. The ontology is tailored to the Amsterdam case and, therefore, would need to be revised and adjusted to fit a different decision-making context with different underlying data sets and different circular economy goals and ambitions.

5.3.1 Data-centred / inductive approach

A data-centred ontology is created based on the analysis of the data XML schema, available metadata, and interviews with data set providers. Similarly to relational databases, implicit data set ontologies tend to be flat. Data analysis and discussions with the data set authors tend to reveal additional semantic rules that are not made explicit in the schema or metadata. Another challenge arises from using multiple data sources, all of which have their own ontologies, which may or may not be overlapping or supplementary.

Two data set schemas have been used as a basis for the data-driven ontology creation:

The waste data registry has been used both in the REPAiR project and for the Amsterdam CEM. The data set consists of waste statistics on the supply, composition, and processing of industrial waste. Since 2006, these data have been centrally collected through a written survey and organised through the register for *Afval Meldingen Informatie en Communicatie Electronisch*, in short, the AMICE register, in the Waste Registry Division of the Dutch Ministry of Infrastructure and Public Works (NL: *Landelijk Meldpunt Afvalstoffen (LMA)*. The waste reports are collected under the Waste Statistics Regulation[2]. The

[2] Commission Regulation (EU) No 849/2010 of 27 September 2010, amending Regulation (EC) No

database can provide the most complete data of reported company waste collection in the Netherlands and therefore plays a substantial role in monitoring secondary resource flows and their changes in the transition towards the circular economy. As waste disposal data can be considered sensitive to some companies, the database is not publicly accessible and should only be used under high standards of data security.

Port import and export data has been provided to the Municipality by the Amsterdam Port Authority for building the Amsterdam CEM. The data set has not been used in the REPAiR project; therefore, the REPAiR relational database is not necessarily suitable to accommodate port data. The Amsterdam CEM aims to also include those resources that are imported into the region by various means of transport (rail, water, road, etc.) as they help monitor extractive resources that are not locally available, as well as resources that leave the country as materials, products, or waste.

5.3.2 Tool-centred / inspirational approach

The tool used as a prototype for the Amsterdam CEM originates from the H2020 project REPAiR, Resource Management in Peri-Urban Areas, Going Beyond Urban Metabolism. Since 2016, the REPAiR project has been connecting geodesign (Steinitz, 2012), Living Lab (Amenta et al., 2019), Material Flow Analysis (Brunner and Rechberger, 2016) and Life Cycle Assessment (Guinee, 2002) methodologies in order to create a Geodesign Decision Support Environment (GDSE) where different stakeholders in CE strategies would be able not only to create solutions, but also assess their environmental and spatial impacts (Arciniegas et al., 2018; Remøy et al., 2019). The project has been running in six urban regions in the EU and has involved stakeholders from research and higher education, regional and local governments, industry partners and local civil society.

Amsterdam, one of the REPAiR pilot case studies, has used the GDSE web application for data analysis used to kickstart the CEM as part of the Circular 2020-2025

2150/2002 of the European Parliament and of the Council on waste statistics strategy (Gemeente Amsterdam, 2020). For this reason, the tool-centred approach considers the relational database of the GDSE as a starting point of the ontology.

Instead of starting with the development of a formalised ontology, a tool prototype was created, which includes a relational database to support its functionality. The prototype has been loaded with the available data from the six case studies and further developed based on the use of stakeholders. The database structure has been iteratively adjusted to support the data and newly developed features. The main difference between the tool-based and data-based approach is that, on the one hand, the available data sets may not serve all functions of the tool which asks for data set modelling and enrichment. However, not all information available in a data set is relevant for tool functionality, although it may still be relevant to tool users.

Although automated transformation of a relational database into an ontology is possible (Zedlitz and Luttenberger, 2012; Munir and Sheraz Anjum, 2018), the resulting ontology typically has the same flat structure (i.e., classes and instances) as the original relational database (i.e., relations and columns) (Munir and Sheraz Anjum, 2018). At the same time, database constraints can only be partly represented by the assertions available in the ontology language. Therefore, it is impossible to translate relational models into ontologies and vice versa without loss or corruption of information unless all implicit (default) information is made explicit (Kiko and Atkinson, 2005). Since the goal of the ontology creation process is to identify semantic inconsistencies, for this experiment, the transformation has been performed manually.

5.3.3 Theory-centred / synthetic approach

The goal of the Amsterdam CEM is to represent the past, current and future material flows and stocks and their relevance to the transition towards the circular economy. Therefore, the theoretical basis for the monitor stems from the socioeconomic metabolism (SEM), which is an adjacent domain to the Circular Economy. Analysis tools developed for studying SEM flows can inform CE efforts how fast material stocks grow, when and how materials become available for reuse, and how much recovered resources can contribute to maintaining the necessary stocks by closing the loops.

Based on the review of existing ontologies in the CE domain (described in the main document), the one developed by Pauliuk et al. (2016) has been selected as the most suitable for reuse as an initial input. The ontology proposed by Pauliuk et al. (2016) aims to provide a practical, mutually exclusive, and collectively exhaustive ontology that can accommodate data from any interdisciplinary model of the SEM study domain, allowing efficient data and knowledge exchange between different studies.

5.3.4 Combined Ontology

The four ontologies that have resulted from the theory-, tool-, user-, and data-centred approaches have been combined into one by performing the following steps:

1. All entities and axioms from the four ontology approaches have been copied, retaining their original IRI in an empty ontology file. This way those entities that had the same short names did not get merged into the same entity.

2. Entities that have the same short names have been investigated to decide whether they are indeed the same entities and can be merged into one or if they need to be renamed to distinguish between the different concepts. For example, `Activity` from the tool-based ontology and `Activity` from the data-based ontology actually refer to two non-overlapping concepts and therefore the latter has been renamed into `HarbourActivity`).

3. Entities that do not have the same short names but anyway refer to the same concept have been aligned in the hierarchical order by subsumption or equivalence. Entities that after alignment became subclasses of broader classes were checked for the integrity of the inherited axioms.

4. Entities that refer to opposing concepts have been disjoint. *Part-of* relationships have been introduced by `contains` and `belongsTo` object properties.

5. Similar entities that describe neighbouring concepts have been grouped together by making them subclasses of a single superclass. If any of the axioms available on the subclass level were true to the superclass level, they were moved to the superclass and automatically inherited by the neighbouring concepts.

6. Finally, a HermiT 1.4.3.456 reasoner has been used to debug the ontology, and it has been confirmed to be coherent and consistent.

The alignment process was carried out by the authors of this paper in consultation with the data providers, tool developers, and representatives of the Amsterdam municipality. The consultations took the form of informal discussions.

5.4 RESULTS

The alignment process has resulted in a coherent and consistent ontology that hosts 161 classes, 64 object properties, 87 data properties, and 781 axioms. Not all classes in the ontology could be defined with the same level of detail, even after consulting their creators. The resulting ontology is not application-ready and rather describes the first attempt of alignment, which requires further iterations, as described below.

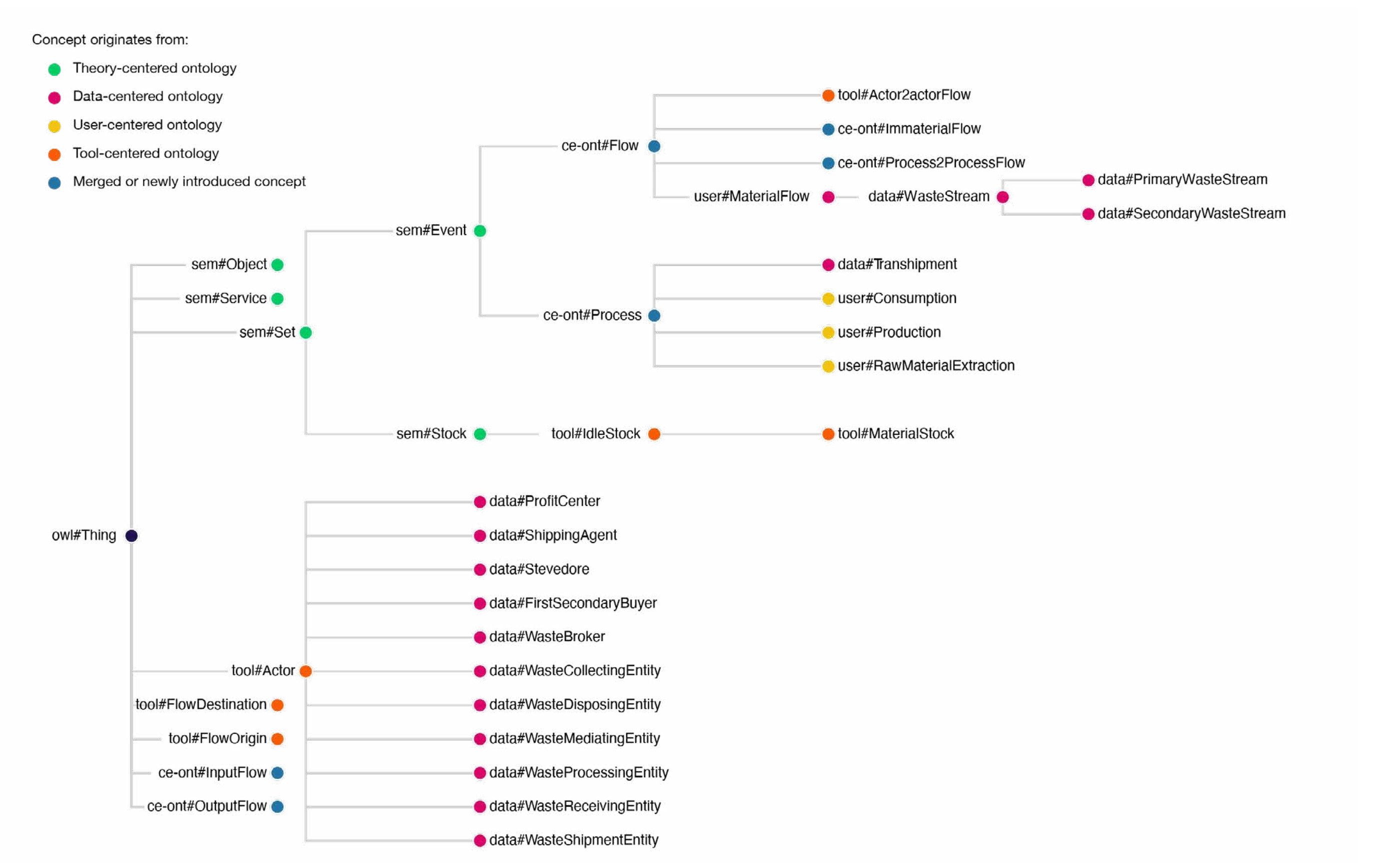
In general, four categories of classes could be distinguished depending on the process that is required to define them and on which related steps are still missing before the ontology can be used to support the Amsterdam CEM. Those four categories closely relate to the different types of knowledge gaps and ambiguities that could be identified during the ontology alignment process. The following is a short description of each of the four categories.

5.4.1 Core Concepts

Core Concepts are those classes that describe the informational and data structure as the basis of the CEM. Core Concepts can be found in all four of the underlying ontologies even if they are named differently (e.g., the tool-centred ontology assumes that flows connect actors instead of connecting processes as in the case of the theory-centred ontology). The definitions of these concepts are strongly grounded in theory and can be aligned with the available data. They are well understood and requested by users, and therefore their entities can be explored using the CEM tool.

The goal of the CEM is to represent past, current and future material flows and

Figure 5.1. The zoom-in on the core concepts of the merged ontology. Each concept is colour-coded according to the approach it originates from.



stocks and their relevance to the transition to the circular economy. Therefore, the core concepts provide a minimal amount of concepts necessary to describe material dynamics. The core concepts are definite, explicit, and exhaustive. The combined ontology extends the core concepts defined by Pauliuk et al. (2016). In addition to having the concepts of `Flow`, `Process`, `Stock`, and `Service`, it introduces the core concepts of `Actor`, `Destination`, `Origin`, `InputFlow`, and `OutputFlow`. Figure 5.1 summarises which classes of the combined ontology are considered the `Core Concepts`.

Actor - an institution, organisation, company, group of people (e.g. households), etc. that participate in processes and services and whose behaviour and decisions need to be influenced to change the content and context of flows, processes, and stocks. Actors have a context (location) that determines which institution is able to change the context conditions or policies to change the behaviour of an actor. Actors may own stocks.

The most important addition is an `Actor` class The need arises from 1) lack of specifications in data about what processes certain actors perform; 2) the need to know who is responsible for the decision-making regarding the content and direction of output and input flows.

In addition to the different goals to achieve and the benefits to reap, different actors may have influence on the different spheres and aspects of CE. For example, an industry player is able to invest in changing the design of its products to be easier repairable, a local government can support the repair by allocating physical space, but a consumer may still choose to throw a broken product away, even if it is cheaper and more convenient to repair it. Due to these differences, every group of actors needs specific feedback and monitoring mechanisms to understand to what extent their decisions help to achieve the set targets. Each actor belongs to an activity that describes the reason that an actor is involved in a flow. An activity may be unknown if it is not specified in the data. The activity itself is a debatable property.

Flow is a description of a particular type of event, where objects are preserved and move from one set A to another set B (Pauliuk et al., 2016)

We adapt this definition of flows and extend it by allowing flows to connect either actors (`Actor2ActorFlow`) or processes (`Process2ProcessFlow`). Each process may have one or more actors, or an actor may carry out one or more processes. If each process has exactly one actor and each actor carries out exactly one process, then `Actor2ActorFlow` and `Process2ProcessFlow` is the same flow. Just how a flow can connect groups of processes, it can connect groups of actors that all share some common characteristics (e.g. an activity or a geographical area).

Flows may be material or immaterial, meaning that they can change the location or ownership of a physical stock (in which case they can also be modelled as processes or only provide a certain service (e.g. brokerage). In some cases it is not possible to tell from the data whether an actor provides a process or a service, therefore the core concepts of the ontology have to allow modelling flows without the necessity to make this assumption. Allowing flows between actors instead of processes solves this problem.

In the SEM definition, stocks can be involved in events, while the tool-centred ontology describes a stock as the amount of materials that have not changed their location in a given period of time (in case of the GDSE the period is a calendar year). Therefore, to align the ontologies, the tool-centred definition of a stock is considered a subclass of `sem#stock` and has been renamed into an `tool#IdleStock`, defined as a set of objects that have not been involved in any event given a chosen period of time.

Stock is a set of objects of interest (Pauliuk et al., 2016)

From a theoretical and data perspective, a concept that is not mentioned by users and is not implemented in the tool is a service. Pauliuk et al. (2016) define services as phenomena 'where the changes of the consuming unit are small compared to the energy and material throughput of the producing activity'. Although not directly involved in material flows, services (e.g., transshipment or brokerage services) do have influence on where the material flows are directed, which processes are applied, and what is the size and composition of the participating stocks.

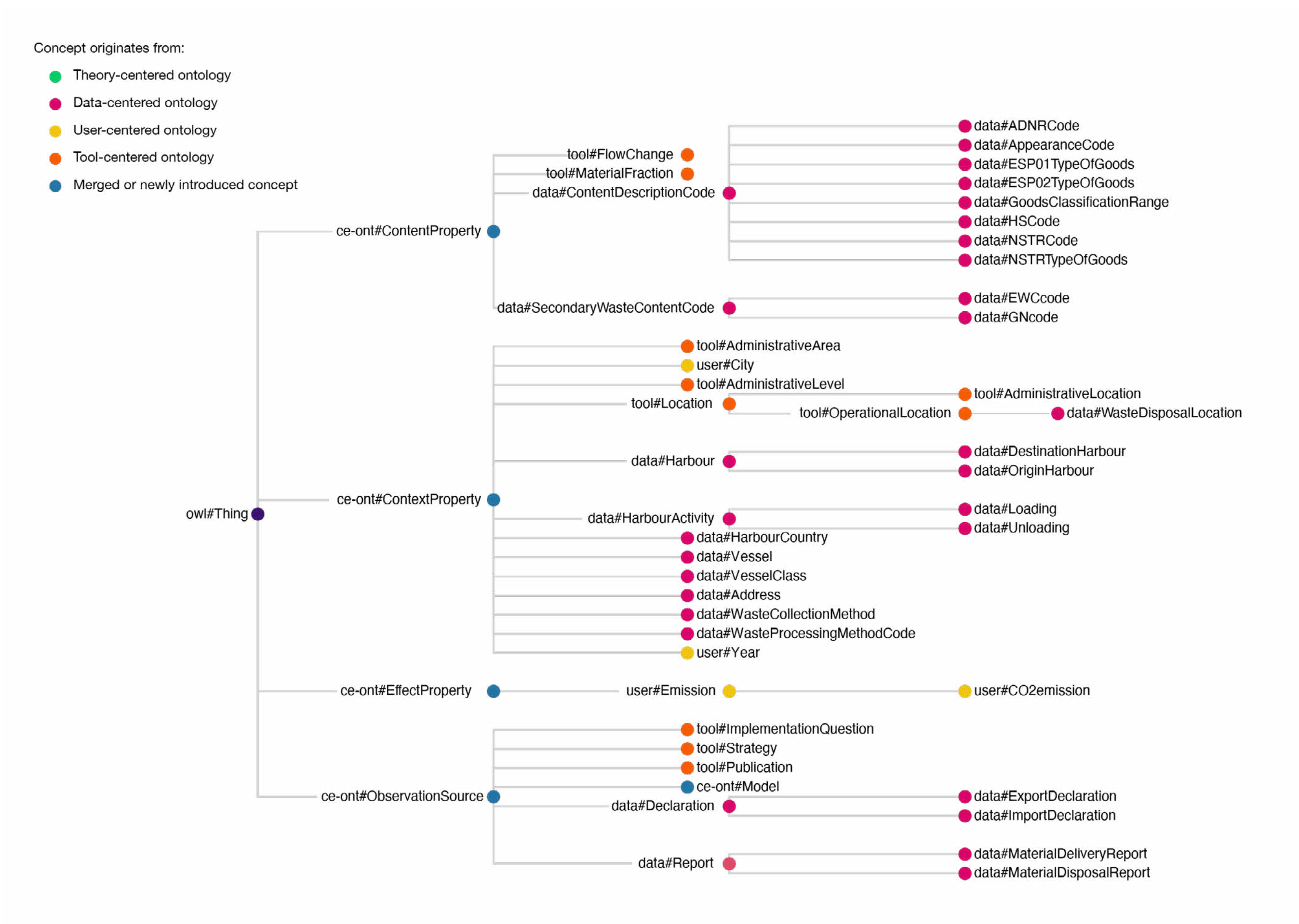
5.4.2 Observational Properties

Observational properties are those classes that describe the properties of core concepts and have intrinsic values and relationships. They are axiomatic and therefore not disputable and definite. Although their values may be disputable, the meaning of the properties themselves is neither questionable nor ambiguous, e.g. geographical locations, city or harbour names can only refer to certain sets of values.

Like the name suggests, observational properties refer to the values that can be observed (e.g. stock or actor location, material content or quantity, observation source). They can be registered using different units and may differ under different conditions, but a conversion to another unit or measure is always possible if the conditions are known (e.g., flow content can be expressed on product, material, or substance level of detail if enough information is provided). Observational properties can always refer to the source of an observation. If an observation does not have a direct source and has been extracted by combining different data sources, it can refer to a model that has been used to obtain the value.

Figure 5.2. The zoom-in on the observational properties of the merged ontology. Each concept is colour-coded according to the approach it originates from.

Observations may be part of either an objective biophysical reality that exists independently of the individual observer, or a social-legal reality that is constructed by humans (Spash, 2012; Fischer-Kowalski and Weisz, 1999). When the data used



to study material flows and stocks come from legal registries and reporting systems, the observations are always social-legal and might or might not reflect the biophysical reality as well.

Observational properties can belong to one of the four subclasses dependent on the properties of the core concepts they are describing: content, context, effect, or an observation itself. Figure 5.2 summarises which classes of the combined ontology are considered an `Observational Property`. Classes that describe observational properties were mostly found in the data-centred ontology.

Qualitative content properties tend to be described as ontology classes (e.g. product codes), while the quantitative properties are described using data properties instead of classes (e.g., mass, hazardousness). Context can be changed after a stock participates in either a process or a flow. The context of an idle stock does not change over a defined period of time. A class of vessels or a waste collection method describes the container in which a stock participates in a flow.

Content properties describe the content of a stock which can change if a stock goes through a process and does not change if a stock participates in a flow.
Context properties define in which context the core concepts exist and are related to either the spatial or temporal boundaries of the concept, or the container in which a concept exists.

Core concepts may or may not share a context: the location of an actor may be the same as the location of a process that the actor carries out. However, there might also be a distinction between operational and administrative locations as in the tool-based ontology, or registered and waste disposal locations as in the case of the data-based ontology. If a flow is material, then it can be assumed that the materials have changed their location from the origin actor or process to the destination actor or process. If a flow is immaterial, the actual location of a stock might be located at a destination, origin, or even in a different context.

Context properties are critical when using the ontology for reasoning purposes and to test whether the available data is capable of answering the required questions. A significant part of the questions formulated by the interviewees refer to at least one context property, mostly temporal or spatial one. If the available data does not have references to the mentioned properties, the ontology prevents reasoning based on the data which may be not representative for the question at hand.

Effects describe what observable changes in the context are caused by the processes.

The most common effect concept that was present in both tool-based and user-based ontologies is the concept of emissions, especially carbon emissions were mentioned by multiple interviewees. Direct emissions occur in the context of the process; indirect emissions can be found by tracking other flows and processes involved in the life cycle of the stock content.

Observation sources explain where a certain observation comes from. An observation must always have a reference to an external source. An external source can be a publication, a declaration, a report or any other data source that has been used. If an observation does not have a direct source and has been extracted by combining different data sources, it can refer to a model that has been used to obtain the value.

5.4.3. Debatable Properties

Debatable properties, different from the observational ones, do not have fixed values or relationships, their definitions may change over time, and cannot be considered axiomatic. Those definitions need to be clearly defined by referencing a certain standard or by creating a set of ontological rules. Examples of typical debatable properties are groupings of other concepts. Such a grouping needs to create or reference a certain taxonomy or classification and decide upon its rules: How will the actors be assigned to each class? Can the classes overlap? Do the classes cover all possible instances? Can new classes be added?

Before (re)using the ontology, the debatable properties should be debated and agreed upon with all relevant stakeholders (domain experts and system users), and their definitions must be made available. Debatable properties can be split into taxonomies and denotations. Both taxonomies as denotations do not have to be invented from scratch and ideally would be reused referencing a definition in an established domain such as macroeconomics, process engineering, industrial engineering, etc.

For example, both tool- and user-centred ontologies use an `Activity` class that is intended to group actors according to their core activities that result in cer-

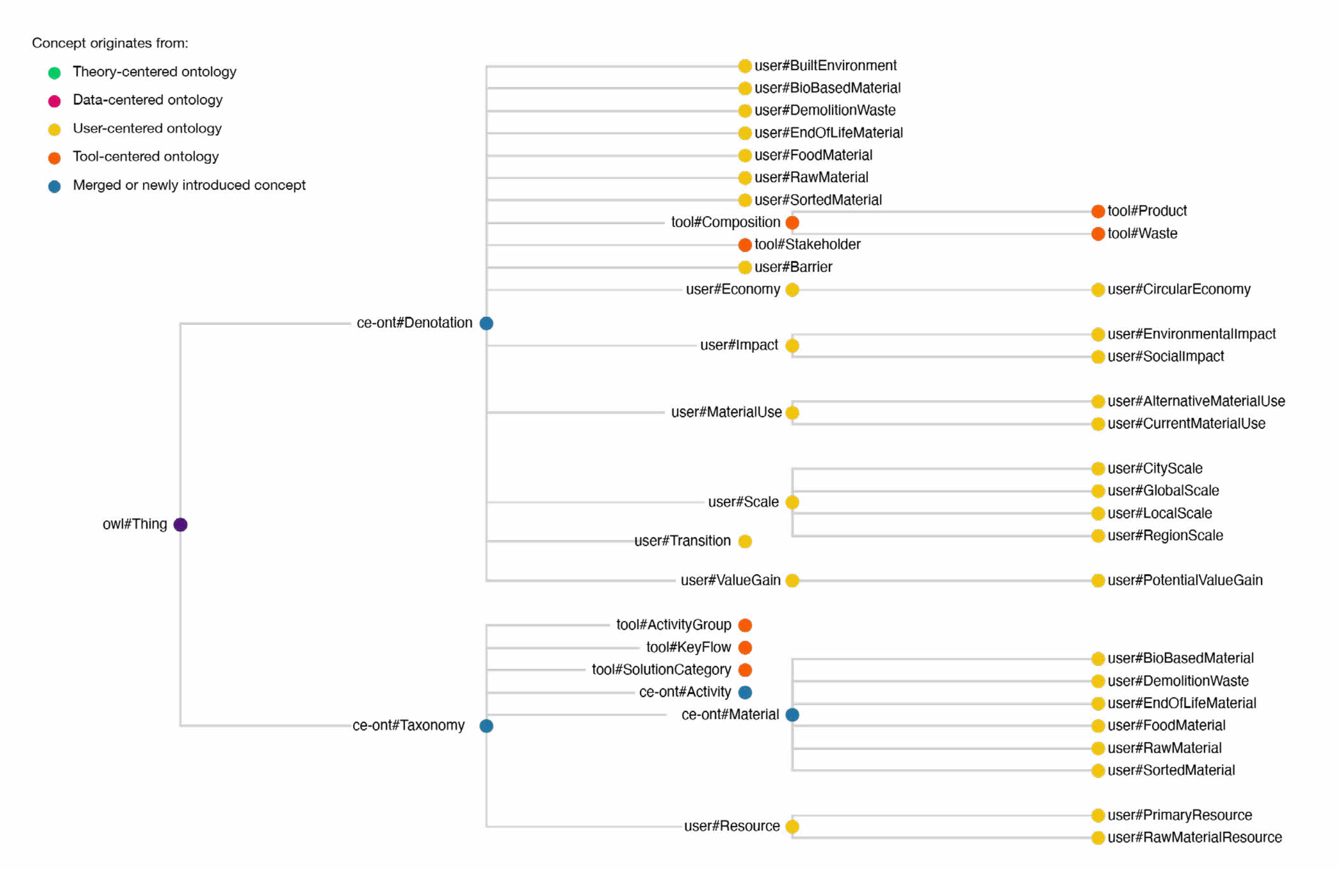


Figure 5.3. The zoom-in on the debatable properties of the merged ontology. Each concept is colour-coded according to the approach it originates from.

tain material demands. The GDSE tool has been using NACE Rev. 2 Statistical Classification of Economic Activities to group actors into activities (Furlan et al., 2020). However, the classification covers only economic activities, therefore actors whose material demands do not arise from an economic activity (household consumption, public infrastructure works, etc.) are not covered by the classification. Moreover, since the purpose of the NACE taxonomy is not related to the circular economy, this grouping can lead to arbitrary aggregations.

Another example of a taxonomy is the European List of Waste (EWC) that is commonly used in European countries (including the LMA data set used for this research) to describe the waste content. However, as concluded by Capelleveen et al. (2021) - the fixed EWC taxonomy does not fit the purpose of identifying CE opportunities not only due to its taxonomic caveats (inefficiency of hierarchical reporting, missing codes, overlaps, etc.) but also lack of semantic content to identify resource reuse opportunities. They suggested that developing a waste folksonomy

Taxonomy is a hierarchical arrangement of multiple terms that specify the same concept in more detail.

would be a better approach for a still immature domain.

Denotation - a term that requires a definition provided by using ontological rules for defined classes.

Without having a strict definition, denotations tend to be understood according to their connotation. For example, classes like `Product` and `Waste` can be disjoint or overlapping, covering or open axioms, dramatically changing the analysis results.

Some classes can have both taxonomy and denotation subclasses. For example, the `Material` class is a property that requires a material taxonomy to be used to describe the content of stocks. However, properties such as `BioBasedMaterial`, `DemolitionWaste`, `EndOfLifeMaterial` are denotations that should refer to certain members of the material taxonomy.

Figure 5.3 summarises which classes of the combined ontology are considered a `Debatable Property`. Classes that describe debatable properties were found mainly in a user-centred ontology.

5.4.4 Specific Properties

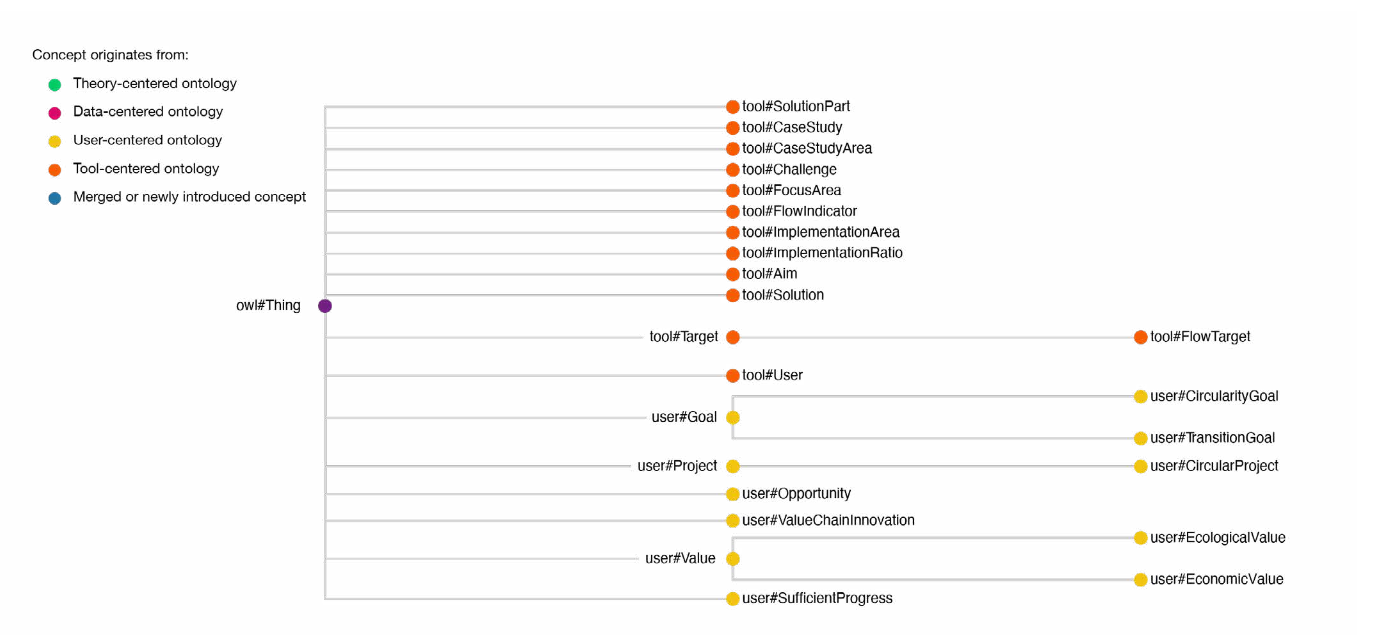
Specific properties are neither observable nor debatable. They are specific to a certain user or a group of users. They describe relationships between classes based on particular non-axiomatic definitions. Since they are based on personal (or group) opinions, they cannot be disputable either. They need to always refer to the author(s) of property values and definitions.

Targets, aims, goals, and challenges are typical examples of specific properties, as different user groups can have different interpretations of both the definition and the value of such a property. Such properties can change with time or when different people take up the same functions, e.g., in the case of governmental targets.

The difference between specific and debatable properties is that debatable properties need an agreement between different groups of users or stakeholders, while specific properties do not need to be agreed upon. Specific properties define variables that can be decided upon - they are like parameters of monitoring and decision support that can be played with. Debatable properties, on the other hand, are variables of the system that should not be changed to get better monitoring results. For example, a target for local food production can be changed to check how easily it can be met, but the boundary of 'local' should not be changed to easier meet the set target.

Figure 5.4 summarises which classes of the combined ontology are considered a `Specific Property`. Classes that describe specific properties were mostly found in user- and tool-centred ontologies, which is expected from the inspirational and collaborative ontology development frameworks.

Figure 5.4. The zoom-in on the specific properties of the merged ontology. Each concept is colour-coded according to the approach it originates from.



5.5 DISCUSSION

5.5.1 Correspondence

Monitoring the transition towards a Circular Economy is first of all concerned with representing material flows and stocks and their relevance to the transition. This assumption can also be confirmed by the observation that the core concepts that are primarily based on this representation have been identified in all four of the underlying ontologies. The core concepts have been aligned by merging repeated concepts into one (specifically `Flow`, `Process` and `Actor`) or by subsumption.

There are a few groups of concepts that are semantically close, but do not have a clear direct correspondence with each other because of lack of definitions and axioms. An outstanding group relates to the material content of stocks and flows. Data-centred ontologies describe the material content of flows using international classifications (taxonomies) of wastes or products that do not always contain a specification of materials that constitute those waste or product streams. However, monitor users ask for information about specific groups of materials (e.g., raw food, bio-based, end-of-life materials). Meanwhile, a tool-based ontology uses a generic `Material` class further enriched by certain properties such as `isAvoidable` and `isHazardous` and a `Composition` class that distinguishes between `Product` or `Waste` subclasses based on the underlying data. Finally, certain stock properties such as chemical structure, heat capacity, elemental composition, etc. suggested in the SEM ontology are not available in the data and are not mentioned by the users.

Another group of close concepts relate to location and geographical extent. Data typically describe the geographic location of actors without explicitly specifying whether that is the actual location of material stocks. Monitor users are interested in comparative statistics that use vaguely defined geographic extents such as local, city-scale, built environment, etc. The tool also allows users to use administrative levels to group actors or flow origins and destinations.

Both material and geographical properties can be aligned between the ontologies if:

1. Experts and users are involved in the ontology creation process and can provide their suggestions for the correspondence between the observational and debatable properties.
2. Providing such a correspondence can easily become a tedious task if each member of the taxonomy needs to be manually matched with their material content. For example, the European Waste Catalogue is made up of approximately 650 different codes, and the Harmonised System Nomenclature used in harbour declarations comprises about 5,000 commodity groups. Therefore, such correspondence tables should be developed as a common effort and shared with the available ontologies by the CEM creators.
3. Data providers are involved in the ontology creation process and can provide sufficient metadata that allows semantic matching of the entities available in the data to those asked by the monitor users.

5.5.2. Terminology Conflicts

Most conflicts could be resolved by renaming classes to better specify how they differ from each other (for example, `t ool#Stock` has been renamed to `tool#IdleStock` and became a subclass of `sem#Stock`, `data#Activity` has been renamed to `data#HarbourActivity` and became a subclass of `tool#Activity`).

Instead of hard terminology conflicts, some semantic heterogeneities (differences in interpretation of the meaning of data) could be found between the ontologies. The most prominent one is the confusion between an activity and a process. The tool-based ontology considers flows as material movements between actors that all carry out a certain (economic) activity. Thus, at an aggregated level, it is possible to analyse material flows between activities and identify how each of them contributes to waste production (Furlan et al., 2020). While some of the activities could be considered processes in the SEM ontology (mining, quarrying, manufacturing, transporting, etc.) others do not describe what happens to the materials, only what causes them to be moved or discarded (catering services, recreational activities, education, etc.). From the user interviews, such terms as consumption, production, raw material extraction, and material use are used to question what needs to be changed to accelerate the transition. None of these terms appear in the data-centred ontology; therefore, without a clear distinction between a process and an activity, those questions cannot be answered.

This confusion could be resolved by making the following distinction between the two concepts:

Process - an event that modifies properties of a participating stock.

Activity - a property of an actor that describes the reason that an actor is carrying out a certain process.

Thus, a process mostly defines what happens to a stock; e.g., a stock of waste is sorted, a stock of food products is transported to another country, etc. In some situations, an activity and a process might be the same if, for example, a transportation company (`Actor`), provides transportation services (`Activity`) to transport (`performsProcess`) some goods (`Stock`). However, if a restaurant discards food waste, then its activity is catering while the process is waste disposal.

5.5.3. Expectation Gaps

Expectation gaps can be observed by analysing the concepts that appear only in one of the four ontology approaches without having close correspondences in the other ones. It is especially relevant to analyse non-corresponding concepts that appear in the user interviews as it means that the chosen data, tools, and theory are not sufficient to answer the questions raised by the ones who need to implement policies to advance the transition. The concepts that could be found only in the user interviews could be roughly divided into two groups:

- Concepts that relate not only to the observation of the state of flows and stocks but also to the interpretation of the values and impacts they actually have: `SocialImpact`, `IndirectEmission`, `EcologicalValue`, `EconomicValue`, `SufficientProgress`. All of these concepts are specific concepts that ask the user to provide one's own interpretation and definitions; however, the entities currently available in the ontology are not enough to provide definitions for the mentioned concepts.

- Concepts related to the means that can accelerate the transition, in particular `Barrier`, `TransitionGoal`, `CircularProject`, `ValueChainInnovation`. These concepts are related to the solutions, aims, and challenges of the tool-centred ontology. However, the tool-centred ontology (and thus the tool itself) provides limited definitions and relations between the concepts, which are left to the free interpretation of a user.

5.5.4 Missing Concepts

The resulting ontology is rather an initial attempt and a representation of Amsterdam case study at a certain point in time than a complete representation of the circular economy domain. The number of entities is limited to those that have been found in the four underlying ontologies. Therefore, every time the ontology is used in a new monitoring and decision-making context, it is expected to be updated to meet growing user needs, a growing knowledge base, tool requirements, and additional data sources.

However, it must be noted that several concepts, referred to as necessary requirements for the validity of circularity metrics in the related literature Morseletto (2020); Corona et al. (2019); Suárez-Eiroa et al. (2019); Kirchherr and van Santen (2019), have not been found in any of the four ontologies. Therefore, future work on Amsterdam CEM should include a discussion of whether excluding the following concepts out of the current monitor scope is meaningful or rather accidental and if they should be included in the upcoming CEM iterations.

- Quality properties that describe the quality of observations, such as granularity of the data, accuracy of the measurements, certainty, and model sensitivity;
- immaterial flows of assets that play an important role in the circular economy, especially financial flows, energy flows, and information flows throughout the entire supply chains;
- concepts related to environmental impacts, especially pollutants and GHG emissions;
- utility and durability of stocks;
- concepts related to social well-being and employment at all skill levels;
- business models and value creation, capture, and distribution;
- fiscal, legal, and organisational contexts.

5.6 CONCLUSIONS

To understand whether an ontology development process can benefit CE monitoring efforts, four approaches have been used to create four separate ontologies that were later compared, merged, and aligned with each other to arrive at a single integrated ontology. Notes taken during the process have been used to provide a detailed discussion of common concepts, identified conflicts, and gaps in monitoring expectations between monitor users, data, tools, and theory. The resulting ontology entities could be divided into four main groups: core concepts and their observational, debatable, and specific properties.

The common concepts identified in all four ontology building approaches have led to the formulation of the core concepts for monitoring the transition towards a circular economy. The core concepts were stocks, flows, and processes, as suggested for the practical ontology of socioeconomic metabolism by Pauliuk et al. (2016) - with actors as an additional core concept as identified in the other three approaches. Although not necessary to model physical material flows and, therefore, typically not mentioned in SEM studies, actors participate in processes and services. Their behaviour and decisions must be influenced to change the content and context of flows, processes, and stocks; therefore, they are of high relevance for policy decisions.

Although acute terminology conflicts have not been identified by aligning the four ontologies, the alignment process has proven to be beneficial for identifying confusing or ambiguous terms. Several classes need a subsequent iteration of ontology development before the ontology can be used in an application. Specifically, debatable properties, such as taxonomies and denotations, need the consensus of monitor users and CE experts on their choice and precise definitions. Especially debatable properties would benefit from reference to existing standards related to the CE domain, e.g., existing ISO standards or established vocabularies of industrial ecology. Specific properties require explicit references to their authors and their definitions.

In addition, the ontology alignment process has revealed that there are gaps in monitoring expectations between monitor users and the data, tools, and theory chosen to support them. Two groups of lacking concepts have been identified: concepts that relate to the interpretation of the value and impact of current flows and stocks, and concepts that relate to the means and solutions that can accelerate the transition. Finally, several concepts have been identified as relevant to the monitoring in the CE literature, but were not encountered in either of the four approaches tested. The missing concepts relate to observation quality properties, immaterial flow of assets, environmental and social impacts, legal, fiscal, and organisational contexts, and the utility and durability of stock.

While the resulting integrated ontology is not yet sufficient to be used directly in a web application (CEM) due to a number of lacking definitions, it has already been used as a guidance to the policy makers for the selection of additionally needed data sources and analysis methods to fill the knowledge gaps. For example, a repeatedly expressed need for the assessment of carbon emissions resulted in conducting a Life Cycle Analysis (LCA) for the materials most commonly found in waste. This, in turn, led to the need for an extended ontology of waste materials to connect the LCA results and the waste data.

Expressing terminology definitions as ontological rules instead of textual definitions has allowed one to compare multiple definitions at the same time. Machine-readable ontological rules have allowed us to employ automated reasoners that could process significantly more complex definitions with a large amount of classes and axioms.

Based on the lessons learnt during the ontology alignment process, we recommend the following points for creating digital tools to monitor the transition towards a circular economy:

- An ontology is better suited than a relational database schema for a highly contested domain. Although a relational data model represents the structure and semantic data integrity, it does not store the domain metadata that can be stored in an ontology.

- Experts and users should be involved in the ontology creation process, specifically to provide their suggestions for the correspondence between the observational and debatable properties. Monitor users, especially if they are policy makers, should be allowed to discuss and agree on which taxonomies should be used and how terms that are open to interpretation need to be defined.

- The underlying properties that led to the denotation of relevant terms should be explicitly recorded to allow monitor users to reclassify stocks and flows and realign system boundaries to produce metrics and indicators that fit their specific questions.

- If monitor users are concerned with flow and stock properties that cannot be directly found in the available data, correspondence rules need to be provided between the data properties and the denotations used by the monitor users. Given that providing such correspondence rules can be a tedious and, therefore, error-prone task, the rules should be published according to the FAIR[3] data principles.

- Data providers should be involved in the ontology creation process to provide sufficient metadata that allows semantic matching of the entities available in the data to those asked by the monitor users.

- Fields that are available in the data but do not fit into the existing data structure of the monitoring tool should not be discarded without discussing their relevance with the domain experts and monitor users.

- Conflicting or overlapping terms can be easier discovered if the concepts are defined as fully as possible; therefore, an ontology that contains only relevant classes is not enough. The terms should be defined using sufficient object and data properties and assertions.

- An ontology needs to be reviewed every time it is being used and all newly added properties need to be critically assessed for one of the three types they belong to. The observational properties need to have their values referenced to the sources, the debatable properties need to reference chosen taxonomies and denotations, and the specific properties need to reference their authors.

- Future work should explore different methods of ontology building that would include more collaborative ontology development and alignment environments.

- New ontologies should contribute to existing ontologies by suggesting updates, aligning new concepts, and publishing the final result as an updated version.

[3] https://www.go-fair.org/fair-principles/

REFLECTION ON THE FINDINGS

The theoretical framework for the significance assessment discussed in Chapter 4 discusses only the spatial variability of impact characteristics and context importance. However, the results of the ontology development experiment have revealed that monitor users (decision-makers) consider context importance in more than just spatial dimension, that is, classes of `Production`, `Consumption`, `Food Material`, `Years` (Duration), `EcologicalValue` refer to elements of importance that are not spatially defined; however, they refer to certain conceptual boundaries.

Following the SEM paradigm, the five dimensions in which relevant values and elements change as suggested by (Pauliuk et al., 2019) are:

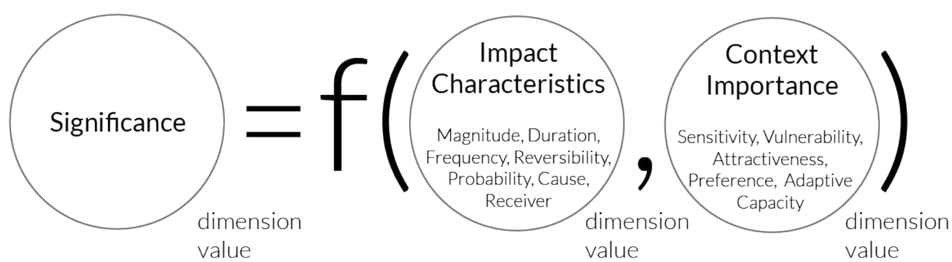
1. The time dimension,
2. the location dimension,
3. the process dimension,
4. the object (substances, materials, goods, products, or commodities) dimension, and
5. the layer dimension (unit).

These five dimensions fully cover all the classes of merged ontologies that relate to the importance of context, as in Table 5.2. Therefore, to fully accommodate user needs, the theory of Significance Assessment formulated in Chapter 4, should be extended to include all the other dimensions.

The Spatially varying Significance Assessment results in a different measure of significance at each location that has diverse values of impact and context characteristics. In principle any of the dimensions (or their combination) can be represented as the extra defining variable - location, time, material, economic activity, etc. If both Impact Characteristics and Context Importance change due to the change of that variable, significance will change accordingly.

Dimension	Merged ontology classes
Time	`Year`
Location	`AdministrativeArea`, `City`, `Location`, `Harbour`, `Address`, `Scale`
Process	`Activity`, `Vessel`, `WasteProcessing Method`, `Demolition`, `MaterialUse`
Object	`ContentDescriptionCode`, `SecondaryWasteContentCode`, `BioBasedMaterial`, `DemolitionWaste`, `EndOfLifeMaterial`, `FoodMaterial`, `RawMaterial`, `SortedMaterial`, `Composition`, `Resource`
Layer	`MaterialFraction`, `Emmission`, `Value`

Table 5.2. Combined ontology classes according to the flow dimension they describe



Several examples can be given to illustrate how significance assessment would work in practise with each of the five dimensions:

1. The significance of increased employment (`Impact`) during the different seasons (`Time`) depends on the increase in relevant (`Impact Characteristics`) and seasonal unemployment rates (`Context Importance`) of each specific season (`Dimension Value`)

2. The significance of decreased noise (`Impact`) in the different brown fields of

Amsterdam (`Location`) depends on the relevant noise decrease (`Impact Characteristics`) and development potential (`Context Importance`) at each separate brown field (`Dimension Value`).

3. The significance of the increase in financial support (`Impact`) for different economic activities (`Process`) depends on the relevant financial support increase
(`Impact Characteristics`) and contribution to the circular economy transition (`Context Importance`) for each separate economic activity
(`Dimension Value`).

4. The significance of the reduced extraction rate (`Impact`) of the different raw resources (`Object`) depends on the relevant reduction (`Impact Characteristics`) and scarcity (`Context Importance`) of each kind of raw material (`Dimension Value`).

5. The significance of reduced transport emissions (`Impact`) of the different pollutants (`Unit`) depends on the relevant reduction (`Impact Characteristics`) and the environmental sensitivity (`Context Importance`) to each pollutant (`Dimension Value`).

The assessment of the sufficient granularity and coverage of the data to support the significance assessment, as discussed in Chapter 4 applies according to the same principle to all dimensions. For example, if decision-makers attach importance to seasonality, but impact characteristics are aggregated or averaged per full year, then its temporal granularity is insufficient for significance assessment. In case of processes, if the data ontology has `Construction and Demolition Process` as one but different importance is attached to `Construction` than to `Demolition`, then the granularity of the process taxonomy should be considered insufficient.

Another important consideration is epistemic uncertainty whether available information belongs to a certain class and to which degree (e.g. if carbon emission values are factually applicable to certain materials and processes or if extraction rates available in the data are representative of the given time period). On the one hand, even if the available data have sufficient coverage and granularity, it is possible that the assessment can point to wrong results due to high uncertainty. On the other hand, missing data or its specific properties often could still be filled by modelling or assuming information based on the neighbouring classes. In this case, it would be important to capture the probability that the information is true. In addition to granularity and coverage Ballatore and Zipf (2015) suggest that one captures the conceptual quality of the data in terms of five more dimensions: accuracy, completeness, consistency, compliance, and richness, all of which help the interpretability of the results of the assessment.

DATA AND SOFTWARE AVAILABILITY

Data supporting the findings of this study are available from the CTO office of the Municipality of Amsterdam in the Netherlands. Restrictions apply to the availability of these data, which were used under licence for this study. Data are not available from the authors and can only be accessed directly from the Municipality of Amsterdam.

Anonymised interviews, ontology alignment rules and machine readable ontology files in OWL/XML format are available in supporting information of the published article and on OSF repository via the following link: `https://osf.io/p7cft/` All four ontologies are also available in a public repository:

`https://github.com/rusne/ImpactOntology/tree/master/ontologies`

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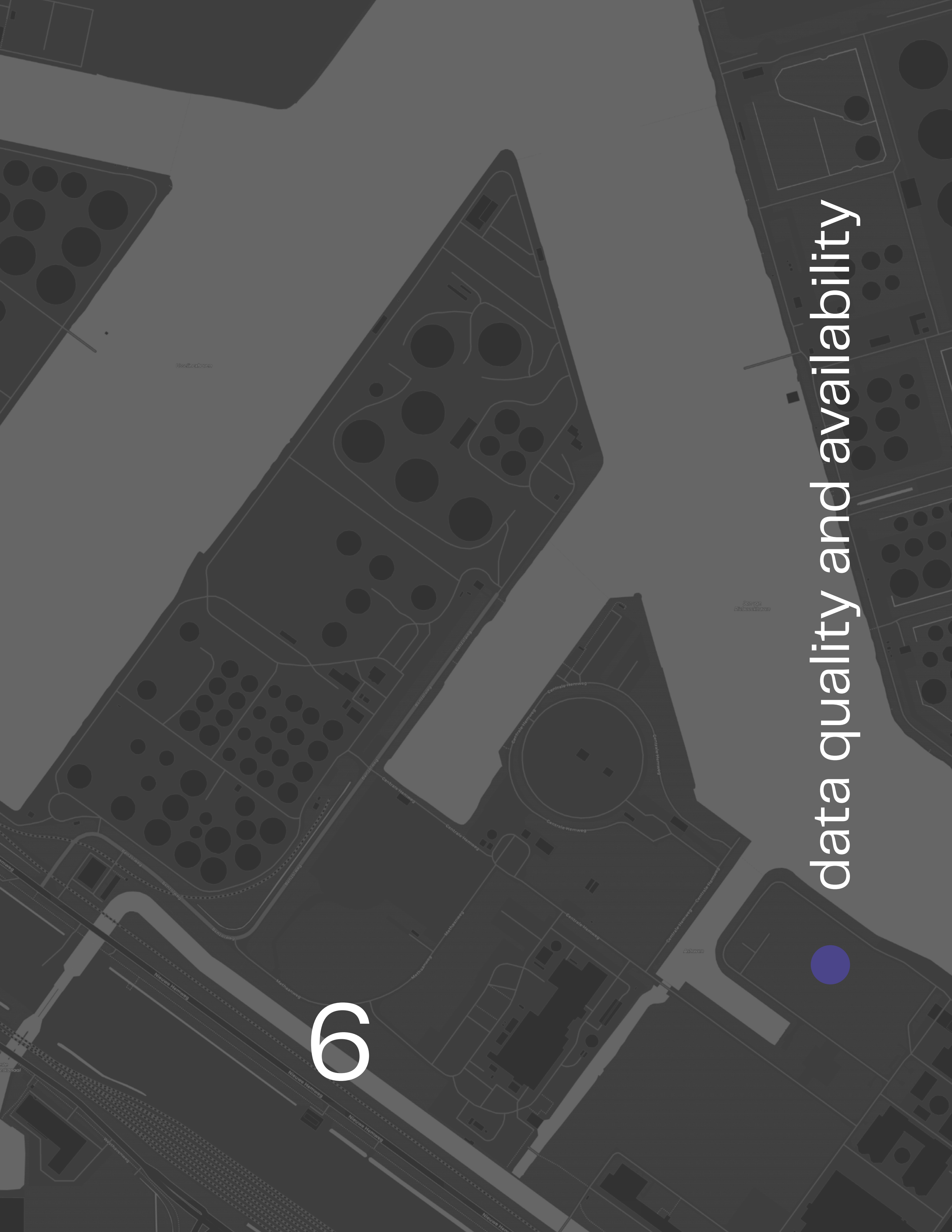

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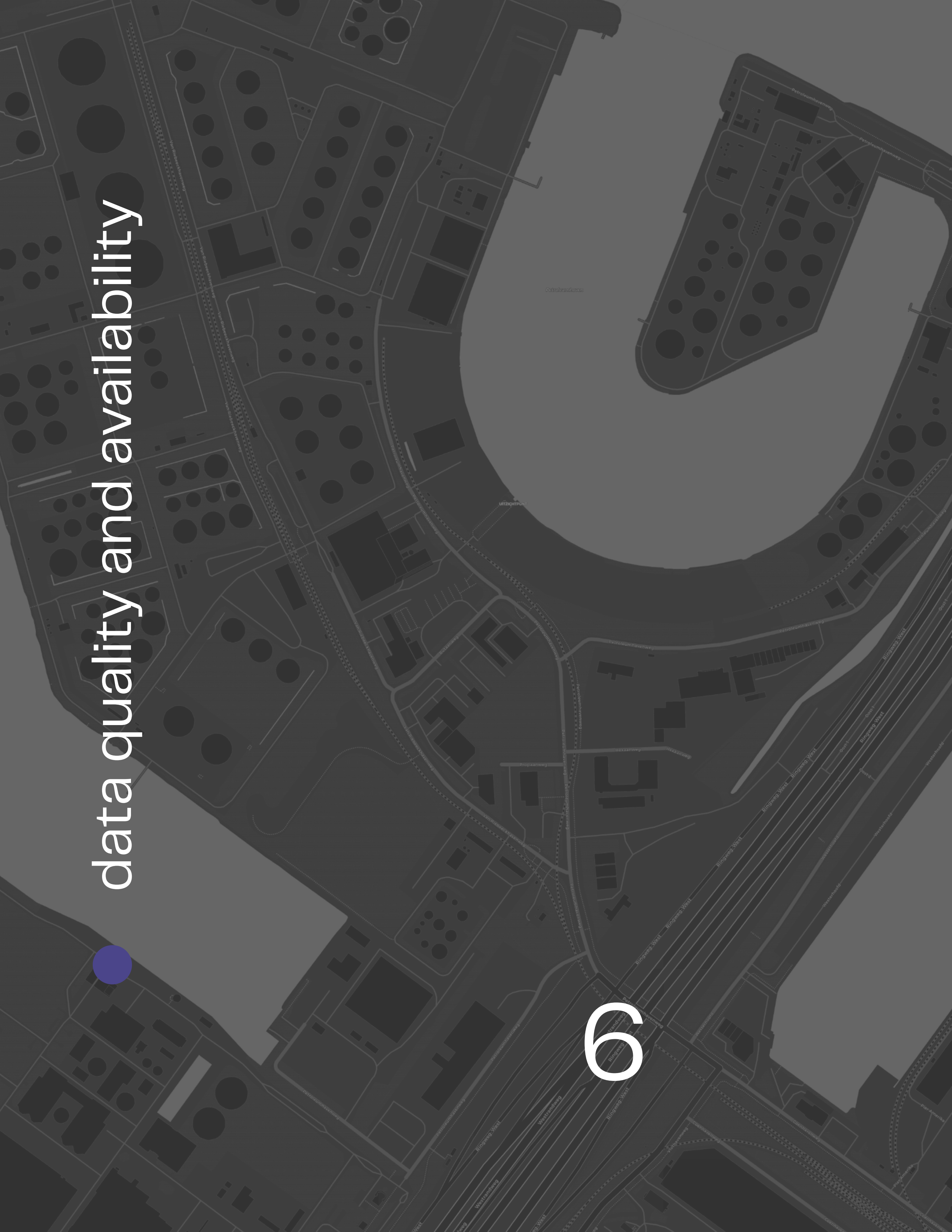
data quality and availability



data quality and availability

6

EUROPEAN WASTE STATISTICS DATA

Research questions:

A How does the Dutch National Waste Registry correspond to the expectations and requirements for circular economy monitoring set in the previous chapters?

B How does the European Waste Statistics Regulation influence data characteristics?

Based on:

Sileryte, R., Wandl, A., & van Timmeren, A. (2021).

The Responsibility of Waste Production: comparison of European Waste Statistics Regulation and Dutch National Waste Registry

Published in: Journal of Waste Management, Vol. 151, pp. 171-180

ISSN 0956-053X

DOI 10.1016/j.wasman.2022.07.022

PREAMBLE

Based on the merged ontology developed as described in the previous chapter, the core concepts of the Amsterdam CEM are Flow, Process, Stock, Service and Actor. The addition of an Actor class to the core concepts was necessary due to the two main reasons: 1) lack of specifications in data about what processes certain actors perform; 2) the need to know who is responsible for the decision-making regarding the content and direction of material output and input flows. Typically SEM studies are not concerned with the specific actors but rather with the processes or services performed by the actors. Registering company names as nodes between which material flows occur, without knowing their core activities, is of little use to the SEM studies.

However, the primary purpose of the Dutch National Waste Registry is not accurate waste statistics but environmental control of waste related activities in the country. The registry is used by the governmental environmental institutions for licenses, permissions, control of air, water and soil pollution originating from waste handling, and other legal aspects related to waste management. Therefore, the process or activity that a waste producing company is performing is not part of the registry. As licenses, permissions and other control mechanisms are handled on a company basis, the relevant activities and processes are not stored in registry's database.

However, processes and activities are still relevant both for Eurostat reporting purposes and for the analysis of socio-economic metabolism and, therefore, circular economy monitoring. As proven by the interviews with the monitor users at the municipality, there is a clear demand for aggregated information about which economic sectors need to be tackled first to achieve circular economy ambitions.

The Eurostat guidelines suggest that national trade registries, such as the Chamber of Commerce, should be used to assign waste producers to their economic activities for the sake of consistency between the different s tatistics. Moreover, the way waste content is registered also provides information on the processes that have caused waste. The European List of Waste chapters are formulated not to describe the waste content but exactly the waste origin, e.g. "01 Wastes resulting from exploration, mining, quarrying and physical and chemical treatment of minerals", "02 Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing", "17 Construction and demolition wastes (including excavated soil from contaminated sites)", etc.

Therefore the hypothesis tested in the following publication reads as following:

Linking waste producers in the Dutch National Waste Registry (NL: *Landelijk Meldpunt Afvalstoffen, LMA*) to their trade details provided by the Dutch National Trade Registry (NL: *Kamer van Koophandel, KvK*) allows assessment on which economic sectors should be targeted first to achieve circular economy goals.

The hypothesis stands on the following assumptions:

- Targeting economic sectors instead of individual companies or otherwise combined sets of companies is easier from the administrative and policy point of view.

- Assessment on which companies should be targeted first can be done on the basis of the waste data, for instance, by assessing its environmental impact from treatment and transport, waste material circularity potential, etc.

- The main overarching circular economy goal as defined by the Amsterdam Circular Strategy 2020-2025 (Gemeente Amsterdam, 2020) is 50% reduction of primary material used by 2025.

The validity of the named assumptions is discussed in the following chapter.

6.1 INTRODUCTION

Waste generation and its treatment is often the starting point for monitoring the transition towards a circular economy (CE) as it represents the final stage of the undesired linear economy.The ability to prevent waste disposal and generate secondary materials for a long time has signified success in preventing material losses and protecting the environment (Melosi, 2004). However, environmental research in the last two decades has exposed that waste recycling alone is not sufficient to achieve a sustainable economy in the light of increasing global resource scarcity (Geyer et al., 2016) putting waste prevention, material reuse and upcycling higher on the political agendas than ever before (Morseletto, 2020).

To date, the EC Regulation No 2150/2002 on Waste Statistics enables Eurostat to collect statistics from member states on 1) waste generation per economic sector and household consumption; 2) waste treatment by waste category and type of treatment and 3) number and capacity of recovery and disposal facilities (per NUTS 2 region) and population served. Each country is free to choose and apply any data collection method as long as it complies to the provided guidelines.

A number of reports aimed at evaluating the transition on the EU level emphasise that significant variations of data quality and the lack of harmonisation in data collection methodologies between the member states hinder effective monitoring and knowledge transfer (Hanssen et al., 2013; Deloitte, 2017; Nuss et al., 2017). At the same time the most common methodology used to provide waste statistics is to scale up data collected from a sample of companies to a whole sector. Waste treatment statistics are often collected directly from the waste treatment facilities and therefore disconnected from the waste producers.

This way of reporting statistics works well within the traditional linear economy where waste is a post-factum problem and needs to be dealt with after it has already occurred. However, promoting and supporting such circular economy strategies as waste prevention, design for reuse, prolonged lifespan, etc. involve companies from the full supply chain. Governments need to create a coherent set of incentives and increase coordination among all relevant stakeholders (OECD, 2021). Therefore as much information as possible is necessary to identify the right stakeholders by understanding which economic sectors they belong to and to understand which interventions can be made to deal with which kinds of waste before it is effectively disposed of. At the moment the expected correspondence between the types of waste and economic sectors that produce them is provided by the 'Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics'. However, it is not known how well these expectations reflect the operational reality of waste production and disposal.

The Netherlands is one of the few member states whose waste data is not based on sample surveys but on consistent waste registration from every company that has a waste permit (Deloitte, 2017). These companies are statutorily required to register all transported waste, including its producer, waste characteristics, transport methods and final treatment. The caveat of the current system is that companies involved in the waste chain are reported only by their name and address without using unique identifiers able to link the available data with other business registries.

The Dutch Chamber of Commerce registry holds information about all companies and their economic activities and could be used to enhance the waste registry with the relevant information. However, there is no key yet that connects both databases. Company names typically have multiple spelling variations, they often have different administrative and operational locations, moreover, multiple companies can be registered at the exact same location. Finally, the waste registry contains spelling and factual errors with regards to companies' names and addresses.

Within this scope this paper explores to which extent the guidelines available in the Waste Statistics Regulation are reflected in the available data and if they can be turned into computational rules to improve the quality of linking. A computational method is used to link waste producers to their economic activities based on name similarity and geospatial proximity. Finally, a discussion is provided on the consequences that legal and operation discrepancies on the waste producer responsibility might have on supporting CE transition.

6.2 RELATED WORK

Linking waste production to the responsible economic sectors is a common subject in Material Flow Analysis (MFA) (Brunner and Rechberger, 2016) studies. Those studies aim to quantify material flows and stocks in a system with strictly defined temporal and geographic boundaries. Regional MFAs typically aim to quantify material supply, export, consumption and disposal over a chosen period of time. MFA follows the law of conservation of mass and can be framed as a mass balancing exercise where bottom-up data is combined with top-down highly aggregated numbers (Gao et al., 2020; Nuss et al., 2017). Input-output tables are used to couple financial information with physical waste data and to link waste with economic activity. However, Salemdeeb et al. (2016) discuss that the used method cannot effectively distinguish between direct and indirect waste generation and being a top-down, economy-wide approach aggregating the whole economy into only 21 industrial sectors, it cannot distinguish sufficiently product groups or individual companies.

Region-wide granular bottom-up data sets that describe material input-output nodes are rare and no published examples could be found that aim to link waste producers to their economic sectors on a legal entity level. Nevertheless, linking diverse registries of legal entities without a common identifier is a common problem arising in various fields. Identifying records that correspond to the same real-world entity appears under the names of entity resolution, linkage, matching, merge, purge or deduplication (Burdick et al., 2015).

A rule-based matching approach using both entity name and address similarity can be found in such domains as the investigation of health-related behaviours dependent on living environments (Hirsch et al., 2020; Mendez et al., 2014), validating names and addresses of transportation and logistic entities (Guermazi et al., 2020), matching observations across financial data sets (Cohen et al., 2018; Burdick et al., 2015), identifying same entities in patent files (Medvedev and Ulanov, 2011; Magnani and Montesi, 2007). Most of them conclude that domain expert knowledge integration improves or would improve matching results (Pilania and Kumaran, 2019; Cohen et al., 2018; Choi et al., 2017; Antoni et al., 2018; Schild, 2016; Mendez et al., 2014; Magnani and Montesi, 2007).

This paper further builds on the existing examples of entity matching using standard computational methods to evaluate name similarity and geospatial proximity between potential matches. Therefore, the novel contribution of this work is not in the domain of entity matching but within the discussion regarding the adequacy of the European Waste Statistics Regulation to support the desired transition towards the circular economy. To date, no published study of the waste allocation to the economic sectors according to the Eurostat method could be identified. The lack of such studies is likely influenced by the high sensitivity of the relevant data sets which are typically not available for research purposes. This study is thus the first one to uncover the discrepancies between the legal and operational responsibility for waste production.

6.3 METHODS

To explore to which extent the guidelines available in the Waste Statistics Regulation are reflected in the available data, the companies registered as waste producers are first linked to the trade registry to assign each of them to an economic sector. The computational entity linkage process follows six phases as defined by Köpcke and Rahm (2010): data preprocessing, indexing, pairwise comparisons, classification, manual review, evaluation, and refinement. A random sample of 1000 companies ((8% of the full data set) evenly distributed throughout the whole geographical study area is used to calibrate the individual parameters of the algorithm. The same sample is used for manual review and validation to evaluate how well each set of matches represents correct links between the entities in two data sets.

After the evaluation of the matching algorithm, all matches are assigned to confidence groups according to how likely the matching is to be correct. The group which has been matched with the highest confidence is then used to investigate how the lower confidence matches could or could not be improved on the basis of the Waste Statistics Regulation. Additional rules that could improve the matching results are derived from the 'Manual on Waste Statistics' (Eurostat, 2013) that guides the data collection process in Member States. The importance is not so much to obtain the highest possible matching score but to understand the reasons behind the unsuccessful matches as they reveal the differences between the official guidelines and the operational reality of data collection and waste disposal.

6.3.1 Data Sources

The first data set, further referred to as 'the LMA data set', consists of digitised waste reports filtered for all waste produced in Amsterdam Metropolitan Areas (AMA) in 2018 according to the registered postcode of a waste producer. The filtered data set consists of 208,133 reports. The reports are collected with regard to the EU Regulation (EC) No 2150/2002, amended by Regulation (EU) No. 849/2010, which mandates Member States to produce statistics relative to the generation, recovery and disposal of waste. The reports represent a chain of waste management from the original waste producer all the way to the final treatment destination.

Waste producers in the LMA data set often have two related addresses: an administrative address and a waste disposal address. Since the waste disposal address does not necessarily have to be officially associated with the waste disposing party (e.g., in the case of construction companies or other service providers), linking is performed based on the administrative address only. Finally, 8.25% of all waste reports marked as *en route* collection have been excluded from the matching as these represent the same waste stream collected from multiple companies and waste collector instead of the waste disposer registered as a waste producer. In addition to the name and address, entities from the LMA data set have a list of EWC (European Waste Classification) codes that describe which wastes they have disposed of.

If the effective waste disposal address is different from the entity's administrative address and the regulations are followed correctly, using the disposal address for linking the two data sets should point not to the entity responsible for the disposal but to an entity in which premises the waste is generated and could be considered an indirect waste producer. If the administrative address is different from a disposal address, it means that the entity effectively responsible for waste generation has provided a service to the one at whose premises the waste has been generated. It is, however, not obligatory to register the customer who has received the provided service, therefore indirect waste producers are not known and therefore not included in the waste statistics.

The second data set, further referred to as 'the KvK data set', comes from the Dutch Chamber of Commerce register (NL: *Kamer van Koophandel (KvK)*) which is the key register for all businesses and legal entities in the Netherlands. This is a highly sensitive data set, therefore only three fields could be used for linking: entity name, address and economic activity code according to the NACE Rev. 2 classification (Nomenclature statistique des Activités économiques dans la Communauté Européenne).

KvK data set provides all registered addresses of the same legal entity and multiple versions of the their names and their abbreviations. The data set used for this publication has been limited to the entities registered as active in the AMA in year 2018 and resulted in 358,406 unique combinations of names and addresses.

6.3.2 Code

The method is implemented in Python 3.7, with the help of the following scientific software packages: Numpy 1.17, Pandas 1.0, Matplotlib 3.2, Fuzzywuzzy 1.0. All data visualisations are created using Maplotlib Pyplot. A geocoder is created with GeoPy, using a Mapbox service for all data points in this experiment.

6.3.3 Data Preprocessing

The data preprocessing stage assures that data from all sources have the same format. Filtering, cleaning and harmonisation steps are necessary to identify suspicious entries, correct the obvious errors, and filter out entries that cannot be fixed. The same data preprocessing is applied to both LMA and KvK data sets.

Filtering controls if all fields of the provided addresses have a valid format, e.g., street and city names are supposed to be composed of at least 3 alphabetic characters and postcodes must follow a Dutch postcode pattern of 4 numerals and two Latin letters.

Cleaning and harmonisation deals with the problem of spelling variations that include partial or full abbreviations, different word order, hyphenation, spacing, etc. Since LMA data set is not based on any official registry, the same entity often has its name spelled differently if a report has been submitted by a different person. Spelling mistakes are also common. Subsidiary companies often have slight variations between their names that indicate different services and activities.

Geolocation (or geocoding) is the conversion of addresses into unique points with geographic coordinates. This step is necessary to compute the geographic proximity between the LMA entities and their potential equivalents in the KvK data set. Geocoding is prone to errors that happen if an address is not complete, misspelled, corresponds to multiple points or it is simply not included in the service database. To validate geocoding results and rectify the errors the Dutch postcode districts (NL: *Postcodegebied*) are used. Postcode districts are polygons that include all addresses within the same first four digits of a postcode. If a point falls within its own postcode polygon, then the location is considered valid. Otherwise, the geolocation is considered invalid and a postcode polygon centroid is assigned instead of the geolocated point. This rectification ensures that in case the geolocation has failed due to an incorrectly spelled address, an entity is located in the proximity of its counterpart in the other data set and can still be matched based on the name similarity.

6.3.4 Indexing

The goal of indexing is to reduce the quadratic complexity by effective pair candidate generation. Trying to compute the name similarity and geographic proximity between each of the LMA and each of the KvK entities would result in more than 4,5 billion pairwise comparisons. Besides an extensive computational time, such an effort would not add significant quality to the result. Increased pool of matching possibilities tends to result in less confident matches and more frequent linking due to accidental similarity. Therefore, to reduce the matching pool, the potential matches are evaluated only if they are within a certain radius from the LMA entity location.

A series of empirical tests using the data sample have been performed to choose an optimum search radius. Figure 6.1 shows how the runtime of the two most computationally intensive functions - (1) constructing searchspace by buffer intersection and (2) pairwise comparison and matching - increase in runtime with the increase of the buffer size.

Figure 6.2 shows the percentage of matches made with the increasing buffer size. It can be clearly seen that the ratio of successful matches peaks at 500m and steadily decreases with the further increase of the radius. This phenomenon is caused by the probabilistic linkage method (explained in the next section) due to which a higher number of probable matches reduces the overall matching confidence, throwing a larger number of matches to be discarded as not confident enough. It must be noted that the ratio of successful matches does not indicate the ratio

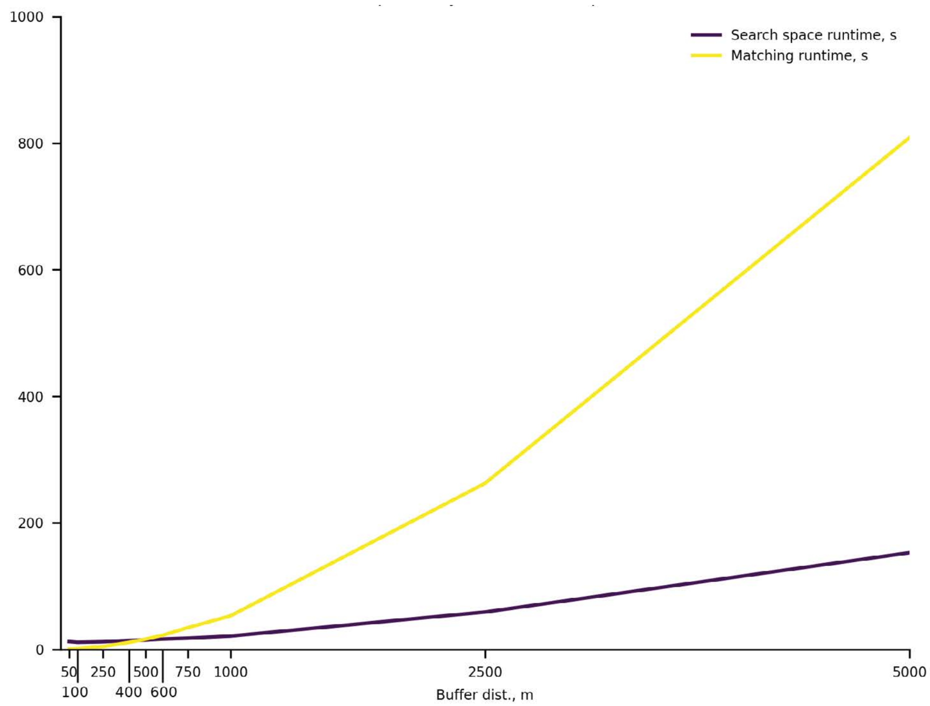


Figure 6.1. Algorithm runtime dependency on the search radius distance.

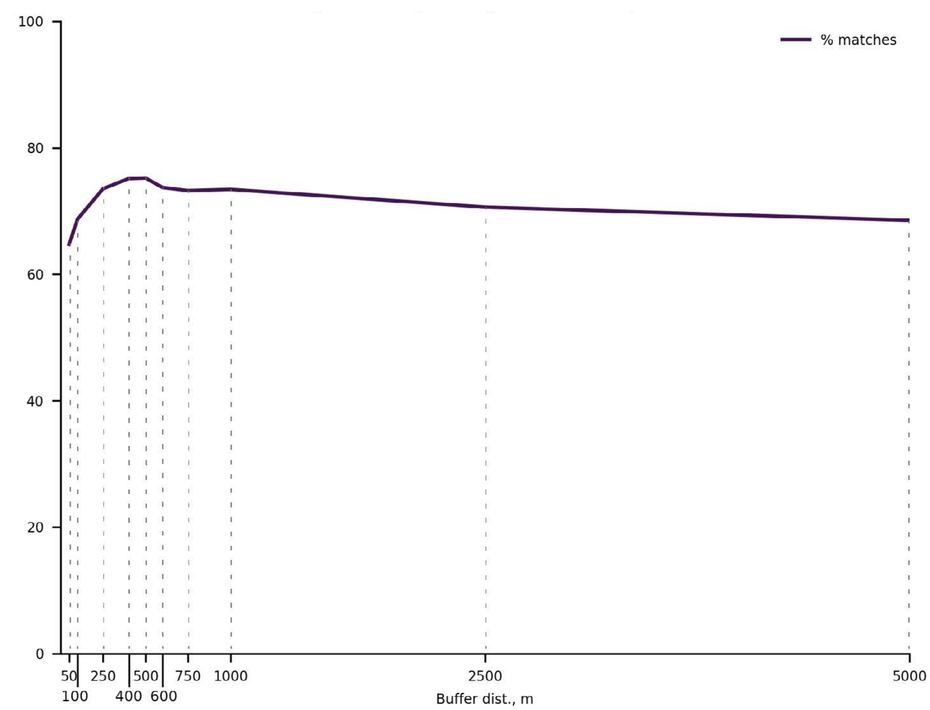


Figure 6.2. Algorithm matching success ratio dependency on the search radius distance.

Figure 6.3. 500m radius search space coverage in urban (left) and industrial/urban (right) contexts. Red dot represents an entity that needs to be matched, grey dots represent all available entities, dashed grey line represents the search radius, orange line represents postcode area boundaries.

of correct matches. However, by manually comparing the differences between matches at 500m buffer radius and 5000m buffer radius, it could be noticed that both correct and incorrect matches get discarded due to reduced confidence.

Moreover, a 500m radius provides a good balance between urban and rural areas where the distances between different entities tend to range from a few meters to a few hundred meters. Figure 6.3 provides an illustration of the 500m radius and its coverage in an urban and more industrial/rural context.

6.3.5 Pairwise Comparison

The similarity level of record pairs within a search space is determined according to two criteria: name similarity and geospatial proximity. The two criteria are not combined into a single indicator but used to complement each other while deciding the confidence of a potential match.

Name similarity is computed using the Levenshtein Distance (Levenshtein, 1966). It is one of the oldest metrics that indicates how two sequences of words resemble each other. Levenshtein distance is described as the minimum number of edits (insertions, deletions, or substitutions) required to mutate one string into the other. It is evaluated using a dynamic programming algorithm. The bigger the

Levenshtein distance between two strings, the more distinct those strings are. Equation 6.1 calculates the Levenshtein distance between two strings x and y.

$$d_{Levenshtein(x,y)}(i,j) = \begin{cases} max(i,j) & \text{if } min(i,j) = 0 \\ min \begin{cases} lev_{x,y}(i-1,j)+1 \\ lev_{x,y}(1,j-1)+1 \\ lev_{x,y}(i-1,j-1)+1_{x_i \neq y_j} \end{cases} & \text{otherwise} \end{cases} \tag{6.1}$$

where $1_{x_i \neq y_j}$ indicator refers to 0 when $x_i = y_j$ and refers to 1 otherwise. It is compared between the first i characters of x and the first j characters of y

Levenshtein Distance is used to calculate the Levenshtein Similarity Ratio. Using the ratio allows normalising the distance against the length of the string, so that the number does not fluctuate given inputs with different sizes. The ratio can be computed using Equation 6.2.

$$r_{Levenshtein(x,y)}(i,j) = (|x| + |y|) - d_{Levenshtein(x,y)}(i,j)/|x| + |y| \tag{6.2}$$

where $|x|$ and $|y|$ are the lengths of sequence x and sequence y respectively

Levenshtein Distance has been chosen against other name similarity metrics due to its ability to compare strings of different length and indicate if one string is contained by the other (especially relevant in cases where one registry includes only the trademark and the other one specifies it in more detail, e.g. *Boskalis* vs. *Boskalis Amsterdam*). It is also able to return a high similarity value in case of spelling mistakes and typos, and distinguish between anagrams.

Geographic proximity is calculated as a Euclidean distance between two points expressed in a local coordinate system based on metric units. It serves two purposes:

1. When the name similarity indicator cannot effectively distinguish between multiple probable matches, a geographically closer match is considered more probable to be the correct one;

2. In those cases where the name similarity is not sufficient to match with any of the potential counterparts in the other data set, geospatial proximity allows assigning economic activity based on the economic activities present in its immediate surroundings.

6.3.6 Classification

A probabilistic entity-linking method is developed using a waterfall approach to generate matched subsets of data, where the subsets are defined by gradually looser matching identification criteria (Cohen et al., 2018). A series of tests is applied in a specific order to evaluate whether a potential link satisfies the criteria. If an entity passes the test, it is removed from the pool and does not need to go through the following tests. Although each successive set of criteria produces a larger number of potential links, the overall confidence level of these links is lower. Before moving on to the next, looser criterion, the algorithm removes those entities that have already satisfied the previous criteria. This process continues until all entities are linked or until further loosening of the criteria results in a linkage of unacceptable quality, as illustrated in Figure 6.4.

There are five main tests (plus the remaining category) and two nested tests that split the matches into twelve subsets with decreasing confidence. If neither of the two nested tests is passed, then the match is considered insufficiently confident for the set in question and is passed to the next test. During a manual inspection of the potential matches for the 1000 sample data points, it has been noticed that the first accidental matches within the search space start occurring below the name similarity ratio of 85 and the geospatial distance of 5m. An overview of the subsets can be seen in Table 6.1. If an entity does not pass any of the tests, it is considered unmatched and is assigned to an 'Unknown Economic Activity'.

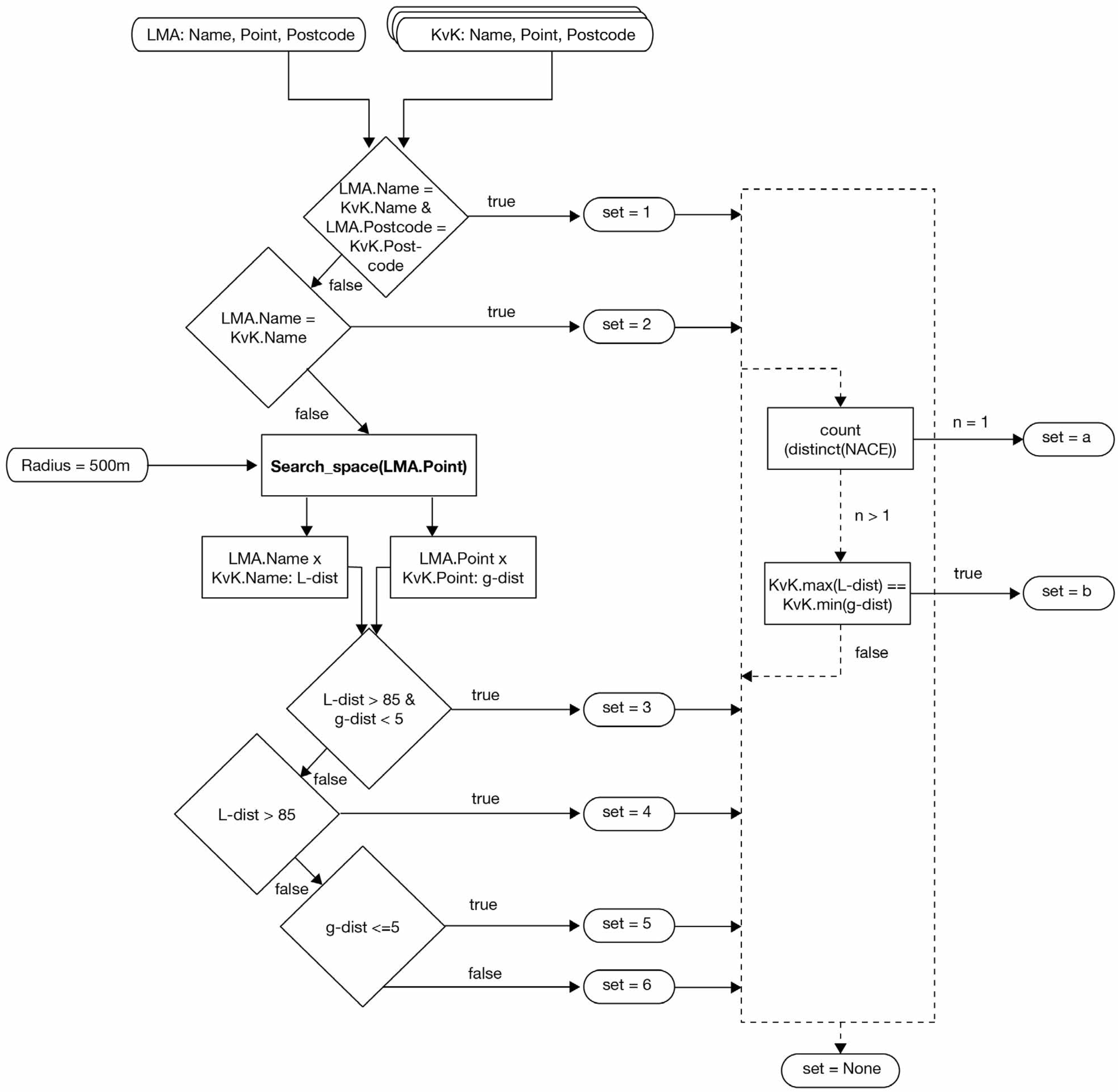


Figure 6.4. A series of tests applied as a waterfall approach in each LMA entity and its potential counterparts in the KvK data set. The algorithm results in 6 sets of matches with two subsets each, where each subsequent subset has a lower matching confidence

Set	Description	
Set 1. Same name and postcode	All LMA entities are compared to all KvK entities on the basis of the exact same name and postcode (exact string matching). This test is applied before reducing the search space.	
Set 2. Same name	Applies in those cases when an entity name is not misspelled but the address does not match any of the officially registered ones. This test is also applied before reducing the search space.	
Set 3. Similar names and locations	A search space is created for each of the LMA entities to reduce the computational runtime. Then the name similarity and geospatial proximity indicators are computed and the threshold is set to 85 fro the name similarity and 5m for the geospatial proximity.	
Set 4. Similar names	Only name similarity above 85 is considered.	
Set 5. Similar locations	Only geospatial proximity below 5m is considered.	
Set 6. Context-based probability	The remaining matches are checked for the two nested tests as described below.	
Subset	a. Unanimous NACE code	b. Most similar names and locations
	If an LMA entity matches multiple KvK entities according to the test criteria, however, all of them are registered under the same NACE code.	If the most similar name belongs to the geographically closest KvK entity.

Table 6.1. An overview of the confidence subsets and their criteria

6.3.7 Manual Review

To validate how well each set of matches represents correct links between the entities in two data sets, a manual inspection is carried out on the sample of 1000 LMA entities. The quality of the link is indicated by manually assigning one of the five tags to each match, as can be seen in Table 6.2. The inspection is performed based on the similarity between an actor's name and the linked company's name, and the correspondence between the name and the assigned economic activity. No additional search using other data sources is performed. Manual inspection not only serves to evaluate algorithm accuracy, it also provides insights behind unsuccessful matches.

Tag	Description	Example	% of the sample
2	Probably correct NACE code	*Eetcafe 't Weesperplein* and *Cafe diner 't Weesperplein*	60%
1	Likely correct NACE code	*Optisport Almere B.V.* and *Sportstudio Buiten*	3%
0	Impossible to say if it is correct or incorrect	*VvE Tuin van Houten* and *Bold Innovations B.V.*	9%
-1	Likely incorrect NACE code	*Titania Asset Advise B.V.* and *Frank a Do*	4%
-2	Probably incorrect NACE code	*VISCON GLAS* and *Ferid's Grill V.O.F.*	5%
na	Unmatched		19%

Table 6.2. Results and criteria of the manual inspection performed on the sample of 1000 entities

Figure 6.5 represents the validation results per subset, indicating the quality of the match. Manual inspection not only serves not only the evaluation of algorithm accuracy, it also provides insights behind the unsuccessful matches.

6.3.8 Evaluation

The algorithm finds a correct match in at least 68% of all cases (or at least 84% of all matched cases). The remaining 32% do not find their counterparts in the KvK data set for various reasons. On manual investigation of selected failed linkages from all subsets and interviews with LMA data providers, three main reasons for failure could be distinguished:

1. **Failed geolocation**. If the address geolocation in one of the two data sets results in a point that is not within 500m of the actual address and the entity name is not identical in both data sets, the entities will not be matched. However, upon inspection of the two data sets, it appears that only 1.3% of the points representing the same postcode lie more than 500 m apart.
2. **Heavily misspelled or an alternative name.** Besides the cases of heavily misspelled entity names, sometimes an alternative name or an old company name is used that is not similar to the one registered with the Chamber of Commerce. For example, *Hotel Campenile* can be found under the name

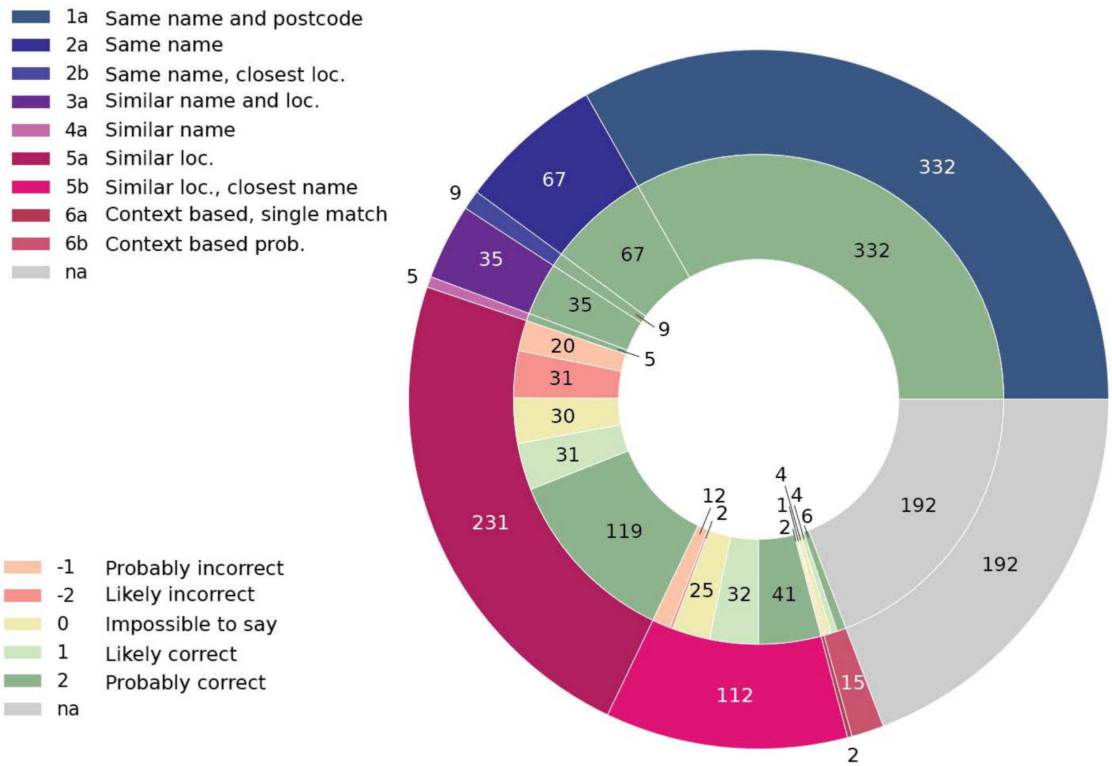


Figure 6.5. Matching quality per each subset according to manual validation. The outer circle represents confidence subsets, the inner circle represents validation results.

Hotel Gaasperpark B.V. or *Milieustraat Almere* vs. *Recyclingperron Almere Poort*. Assuming that the entity address is still correct and is correctly geolocated, this error should not account for more than 20% of the unmatched cases. This estimation is based on the number of matches that cannot be validated neither as correct nor as incorrect within the 5a and 5b subsets where the matched entities are within a 5m radius.

3. **Inconsistent address registration.** Upon manual investigation of the unmatched entities, it often occurs that the LMA data set refers to an address that, in fact, is not the address registered in the KvK data set. These are often operational rather than administrative addresses, which means that there is a great amount of confusion regarding which address is legally considered the company's administrative address. This error should account for the remaining 79% of the cases that are not matched or are incorrectly matched.

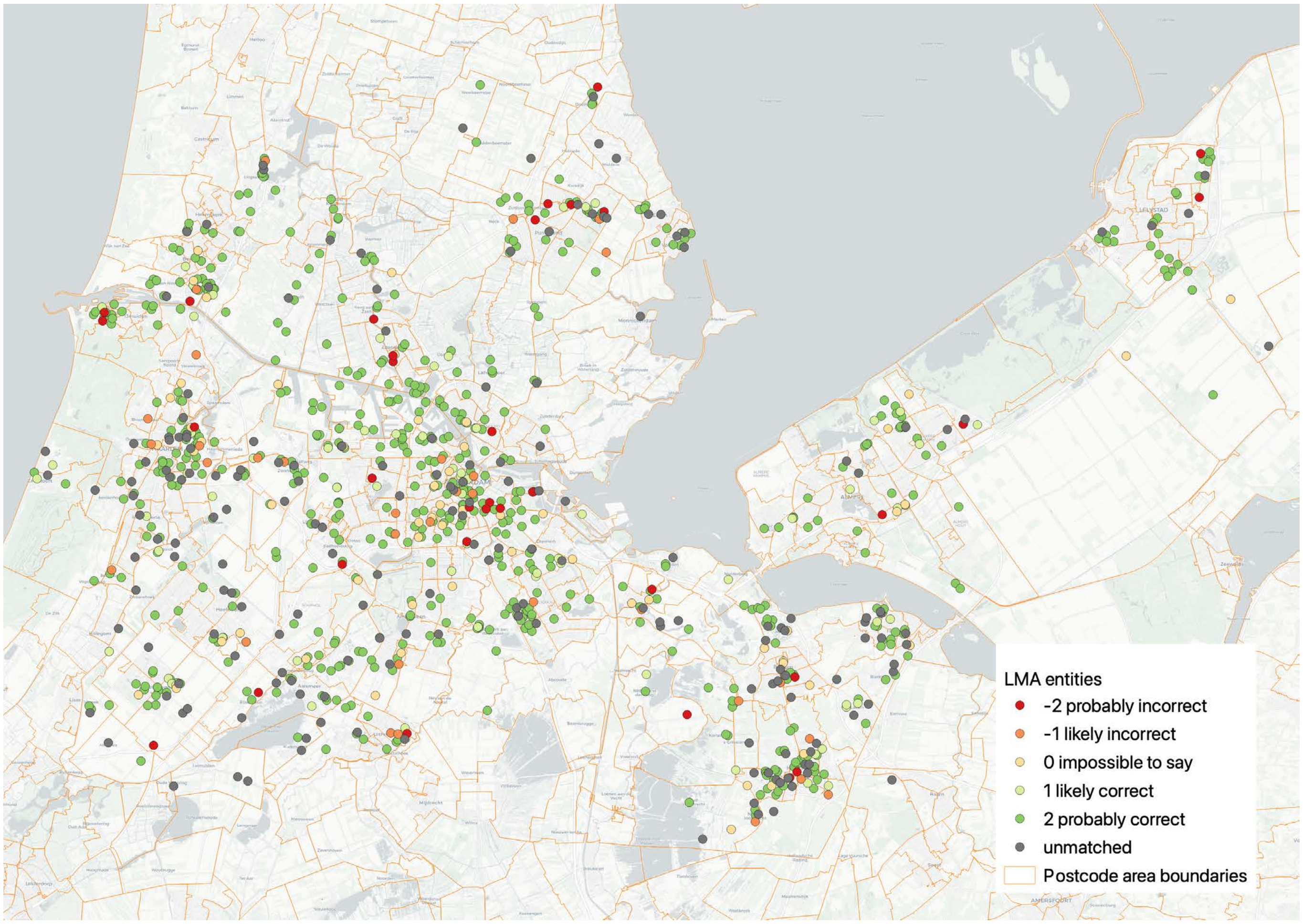


Figure 6.6. Geographical distribution of the sample of 1000 entities coloured according to the matching result.

There are no observable geographical patterns between matched, incorrectly matched, and unmatched entities, as all groups appear to be equally distributed throughout the study area, as can be seen in Figure 6.6.

6.3.9 Refinement

Given that the majority of failed matches are caused by inconsistencies of address registrations in different databases, a part of the remaining unmatched entities could still be linked to a correct economic activity by performing a name similarity check in a significantly wider geographical radius. The challenge of this approach lies in the high probability of accidental matches. If an entity's registration address cannot be trusted and used for matching, the name becomes the only information field that can be used. However, it is obvious that the name must have spelling differences with its counterpart in the KvK data set, otherwise it would have fallen into one of the first two subsets of the matching algorithm. On the other hand, in case the match has failed due to a heavily misspelled or an alternative name but the address is correct, the economic activity could be assigned by taking into account entities in the immediate context as in set 6. However, in many cases there are multiple activities happening at the same place.

Along with the entity's name and location, it is known which type of waste has been disposed of. It can be expected that certain types of waste can be produced only by certain types of economic activities. And certain economic activities (e.g., IT or financial services), according to the Waste Statistics Regulation, are not supposed to produce anything other than office waste. Therefore, the further described experiment explores whether this field could be used to limit the search space and improve matching confidence.

According to EC Regulation No. 2150/2002 on Waste Statistics:

> 'The principal activity of a statistical unit (e.g., an enterprise) is defined as the one that contributes most to its value added. <...> Therefore, in order to assign the waste generated to the correct NACE activity, the unit to be considered should be the unit that actually generates the value added and also causes the waste, rather than the unit of the customer. For instance, waste arising from the construction of a building should be assigned to the activities of the construction company itself (NACE F) rather than to the activity of the future building owner (e.g. services). As already mentioned, the waste should be attributed to the sector that generates it and gives it over to the waste management sector or takes it directly to a dump or treatment site.'

'Guidance on classification of waste according to EWC-Stat categories: Supplement to the Manual for the Implementation of Regulation (EC) No. 2150/2002 on Waste Statistics' provides guidance on the classification of waste according to EWC-Stat categories (Eurostat, 2010). The document provides all waste categories, their definitions, and the NACE rev. 2 code which refers to the most probable economic activities to produce the described waste. The correspondence table that has been used for the experiments was taken from a conversion table using 20 WStatR (Waste Statistics Regulation) items. The document provides: 1) correspondence between WStatR items and, respectively, EWC codes that contain those items, and 2) correspondence between WStatR items and, respectively, NACE codes that may produce waste containing them. This means that in some cases other economic activities could also be the source of the respective waste.

An experiment was performed to estimate whether the correspondence table between the NACE and EWC codes derived from the supplement could be used to pre-filter unlikely economic activities from the KvK data set. From the sample of 1000 entities that got linked to economic activities using the KvK data set, 681 have been manually confirmed as correct. The waste content of these 681 actors and their related economic activities have been tested for their presence in the NACE-EWC correspondence table. Since some actors dispose of more than one kind of waste, in total, there are 1186 unique EWC-NACE combinations to compare with the guidance document. The test results can be seen in Table 6.3.

Comparison has been made at three different levels:

1. NACE sections consisting of headings identified by an alphabetical code,
2. NACE divisions consisting of headings identified by a two-digit numerical code,
3. NACE classes consisting of headings identified by a four-digit numerical code.

As can be seen in Table 6.3, the guidelines cover only a quarter of the NACE-EWC combinations at the most detailed level that are available in the manually validated part of the LMA data. Even at the section level, 246 of the 681 tested entities do not belong to the NACE codes that are mentioned as possible sources of disposed waste. These results suggest that using the correspondence between the NACE-

Level	Section	2-digit NACE	4-digit NACE
Total unique combinations in the manually validated part of LMA data	653	900	1186
% combinations not mentioned in the guidelines	43.49%	60.15%	77.10%
Number of entities whose...			
all EWC codes **are not** mentioned	246	321	445
at least one EWC code is mentioned	99	98	67
all EWC codes **are** mentioned	269	195	102
...in the respective NACE section of the guidelines			

Table 6.3. Comparison of NACE-EWC combinations obtained from the manually validated part of LMA data and 'Guidance on Classification of Waste according to EWC-Stat Categories: Supplement to the Manual for the Implementation of Regulation (EC) No. 2150/2002 on Waste Statistics'

EWC codes as described by the guidelines would not improve, but rather inhibit, the current matching algorithm.

Although this experiment does not lead to an improved linking between the two data sets, it does reveal discrepancies between the waste registration data and the official guidelines, therefore the same experiment is further repeated and analysed on high-confidence matches within the full data set.

6.4 RESULTS

12,655 entities with a valid name and address were identified as primary waste producers within AMA in 2018 according to the LMA data set. These entities have been linked to the legal entities in the KvK data set using the algorithm described above.

The match distribution within the confidence subsets is very similar to that of the random sample, as can be seen in Table 6.4. A total of 5403 actors (42.7%) have been matched with high confidence, 4630 actors have been matched with low confidence (36.58%), and 2622 actors (20.72%) remain unmatched.

Subset		Confidence	Actors in sample data set		Actors in full data set	
Same name and postcode	**1a**	Highest	332	33.2%	3967	31.35%
Same name	**2a**	Highest	67	6.7%	869	6.87%
	2b	Highest	9	0.9%	72	0.57%
Similar name and location	**3a**	High	35	3.5%	354	2.8%
	3b	High	0	-	3	0.02%
Similar name	**4a**	High	5	0,5%	132	1.04%
	4b	High	0	-	6	0.05%
Similar location	**5a**	Low	231	23.1%	2756	21.78%
	5b	Low	112	11.2%	1654	13.07%
Most similar name is the closest	**6a**	Lowest	2	0.2%	24	0.19%
	6b	Lowest	15	1.5%	196	1.55%
Unmatched			192	19.2%	2622	20.72%
	Total		1000		12655	

Entities that have been matched with high confidence have been tested for their correspondence with the Waste Statistics Regulation, as explained in Subsection 6.3.9 Refinement. At the NACE section level, high-confidence matches have resulted in 1920 unique combinations of NACE sections and 6-digit EWC codes. Of them, 46,3% of the combinations do not appear in the guidelines. This means that more than half of the entities matched with high confidence have disposed of and reported waste that is not considered typical of their primary economic activity. Non-typical combinations account for 42,8% of all the waste mass reported from these entities. The complete overview can be seen in Figure 6.8.

Figure 6.8 reveals that the most common guideline noncompliances occur in the EWC Chapter 17: 'Construction and Demolition Wastes' and Chapter 20: 'Municipal Wastes'. Regarding the NACE sections, most noncompliant combinations occur within Section G: 'Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles', Section N: 'Administrative and Support Service Activities', and Section O: 'Public Administration and Defence, Compulsory Social Security.' These insights suggest that the guideline that asks for the allocation of waste generation to the company that contributes the most to the economic value at the time of waste generation is the most violated. Following this guideline, Sections N and

O, which contain mainly administrative services, should not generate anything other than insignificant amounts of office waste. Meanwhile, construction and demolition waste should be generated by the extractive industries (A, B and C), waste management activities (E) or construction and demolition services (F) only.

The high number of combinations of non-compliant NACE-EWC in EWC Sections 17 and 20 is consistent with the higher overall number of actors that dispose of this type of waste as can be seen in Figure 6.7. However, actors that remain unmatched or are matched with low confidence are proportionally slightly more common among those disposing of construction and demolition, and municipal waste than other types of waste. Otherwise, the proportional distribution between the different confidence groups and the unmatched actors stays very similar between all EWC sections.

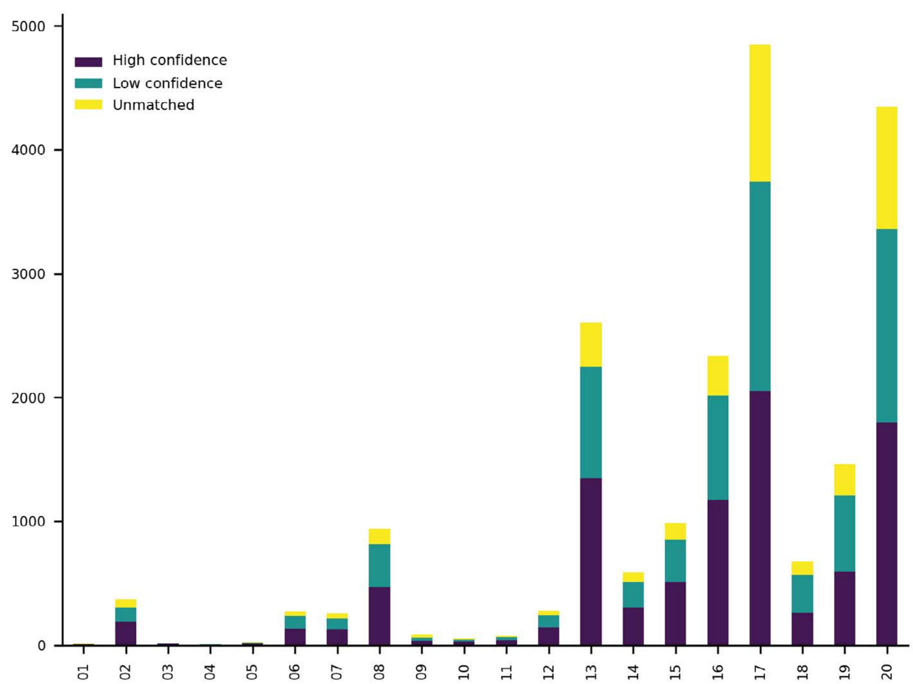


Figure 6.7. Number of entities per each EWC section (2-digit code) and their matching subsets

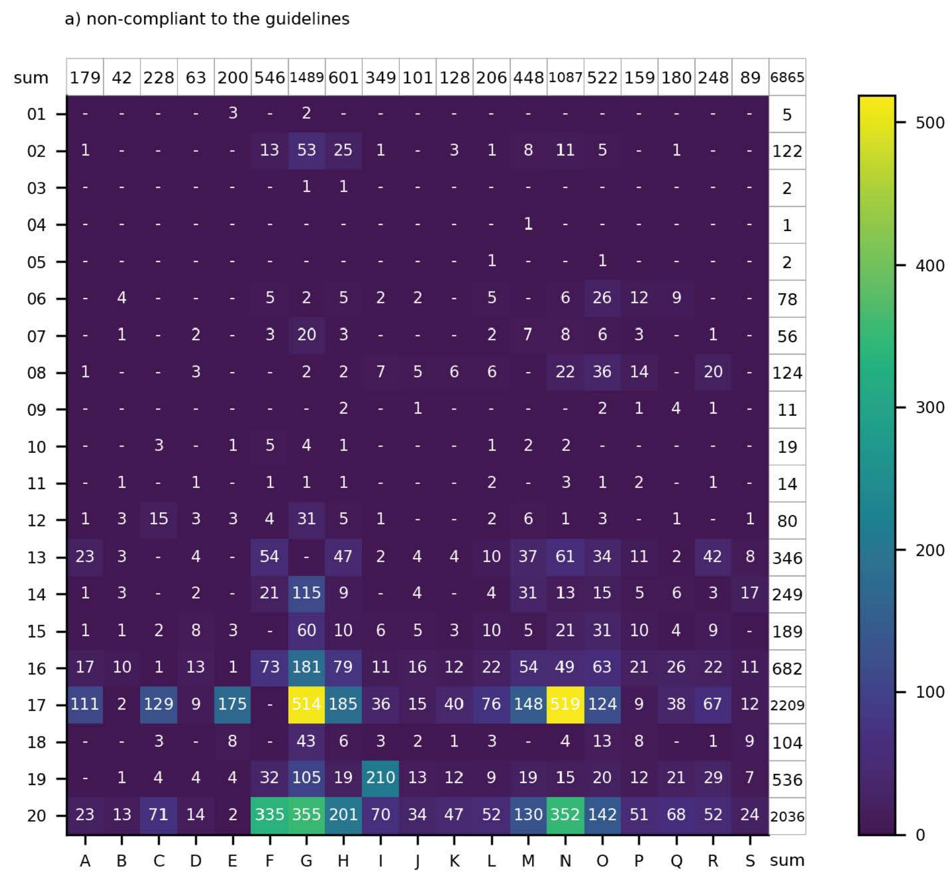
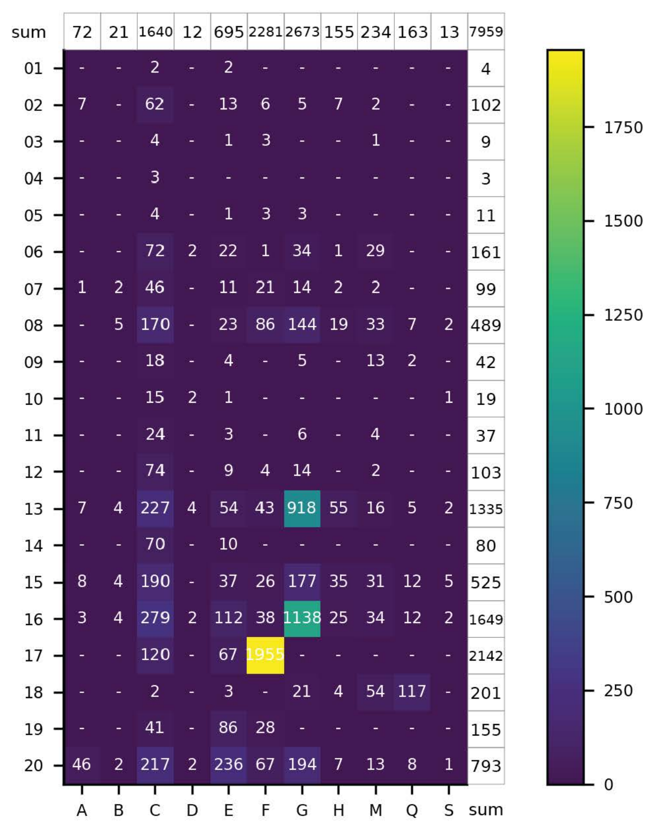


Figure 6.8. Number of entities per each combination of NACE and EWC sections that have reported waste under the EWC code, which is a) not considered typical for their NACE section; b) is considered typical for their NACE section

b) compliant to the guidelines



6.5 DISCUSSION

The algorithm presented is capable of reliably determining the primary economic activity of less than half of the registered waste producers in the Amsterdam Metropolitan Area. The suboptimal performance of the algorithm can be attributed to the quality of the data sets used. First, the waste registration data set does not use a common identifier system to recognise the same legal entities or locations among the waste producers, which allows multiple spelling variations of name and address. Second, the trade registry does not contain all the operational addresses and alternative company names used in the waste registry. Therefore, computational methods to match the two data sets have only limited capabilities to mitigate the poor data quality.

The described algorithm and experiments have demonstrated that an entity matching algorithm is limited by the lack of corresponding entities between the two data sets. However, comparisons between matched and unmatched entities in terms of reported waste types, their geographical distribution, and sample versus full data set did not expose any differences that would suggest that the unmatched actors would show different statistical patterns. Therefore, it is safe to assume that given that the algorithm performs well on approximately half of the data set, the successfully matched half could be used as a substantial sample to scale the statistics to the full waste quantity.

It must be acknowledged that if the same algorithm was applied to the same problem in a different country, its performance could be drastically different. Differences may be caused by the different registration terms in both trade and waste registries, since each country decides on those terms individually. The lack of harmonisation between the registries causes every country to adapt a different strategy to allocate its waste to the economic sectors, in this way hindering cross-comparison.

The most straightforward recommendation to improve the data quality is for the waste registry to request companies filing waste reports to provide their unique identifier used in the trade registry (in the case of the Netherlands, the KvK number). Using the unique identifiers, waste producers could be connected on the fly to their economic activities provided in the trade registry. However, this approach still leaves a few potential caveats. First, the approach would not help process historical data that existed before the implementation of the on-the-fly entity matching. Second, the question remains whether the self-assigned economic activities provided by the companies at the time of registering their business are the ones that are effectively responsible for producing certain kinds of waste.

However, if the goal of collecting detailed waste statistics on a EU level is to improve policies to ensure that the transition to a circular economy can be accelerated, the lack of reliable highly granular current or historical information may have negative consequences. On the one hand, it can hinder the visibility of emerging small-scale good practises, which need to be further cultivated to ensure their adoption in the wider economy. On the other hand, the less detailed information available, the harder it is to notice the effects of changing demand and production processes of one economic sector on waste generation in another (Salemdeeb et al., 2016). For example, it is expected that the shift from a product-based economy to a service-based one will increase resource productivity and reduce waste production. To monitor whether this is effectively the case, it would be necessary to know not only that certain wastes are generated by service providers instead of manufacturers but also which types of services they are and which economic activities they are expected to substitute for them. However, experiments have revealed that the more actors are considered, the more unique combinations of NACE and EWC codes can be found. Therefore, using a representative sample would only help to monitor major changes after they have already occurred and not in their state of emergence.

The second risk of a statistical blind spot that was exposed during the experiments is related to the question of which entity must be considered effectively as a responsible waste producer. While the Waste Statistics regulation clearly states that it must be the 'unit that actually generates the value added and that also causes the waste rather than the unit of the customer', the waste registry shows that this rule is often disregarded, and the registered waste producer is that entity which eventually pays the waste management costs. For example, construction and demolition waste is often reported by companies whose core business is not related to construction, food-related waste is reported by companies that provide catering for their own employees only, and various wastes are reported by companies whose subsidiaries provide financial administration. Instead of pointing out multiple violations of the regulation, these insights question the regulation itself.

Furthermore, the requirement to attribute waste to the unit that generates the most financial value added places the burden of waste production on those companies whose business model is directly related to the amount of waste produced, meaning that more produced waste should directly correlate with increased revenues. Using restrictive policies to stimulate those companies to reduce their waste production might cause an undesired backlash. To enable the strategy in which companies are encouraged to change their business models in a way that used resources are not discarded but kept in the economy, consumers of their products or services need to be stimulated to choose a more sustainable alternative. In that case, the information about the customer is as important as the information about the provider.

Another important consideration is the ownership of waste. In the economy where waste is considered a burden, the company that causes its production tends to assume responsibility. However, in a circular economy where redundant materials are considered an asset instead of waste and, therefore, may have economic value, it is more likely that the ownership will stay with the company that has paid for the materials before they have become redundant. In addition, sectors with long supply chains tend to generate more indirect waste that is distributed over a number of different supporting economic activities.

Finally, it should be noted that there is no official correspondence table that relates the NACE and EWC codes, meaning that there is no guidance on what types of waste should be expected from which type of companies. Having WStatR items as a significantly less detailed intermediary layer between the two detailed classification systems causes unlikely combinations to be valid (e.g. Glass waste connects EWC code '15 01 07 glass packaging' with NACE code '4310 Demolition and site preparation'). At the same time, it excludes a large number of possible combinations for the sake of clarity. When data across the EU are collected using sample surveys and combinations of registries, a high-quality correspondence between NACE and EWC codes would not only help to control the quality of the statistics, but also improve data consistency and consequently knowledge transfer regarding the circular economy transition.

6.6 CONCLUSIONS AND RECOMMENDATIONS

A data set from the Dutch national waste registry for 2018 limited to the Amsterdam Metropolitan Area has been used to explore which economic activities effectively produce which types of waste and if these activities can be held responsible for waste production. The Dutch trade registry has been used as a reference data set that connects company names and addresses to their primary economic activities according to the NACE codes. The conducted experiments have demonstrated that using geospatial proximity in combination with name similarity is able to speed up the linking process in comparison to only using textual information on the entity's name and address. In addition, considering geospatial proximity next to the traditional approach of name similarity for legal entity matching can limit the search space for each individual entity and, therefore, solve multiple data quality issues.

Manual validation of a random sample of 1000 waste producers has shown that the algorithm can correctly assign primary economic activity to approximately 43% of all waste producers. An additional 37% of the actors are assigned an economic activity with low confidence, while the remaining 20% cannot be assigned at all. The reasons for the suboptimal assignment success rate stem mostly from the quality of the underlying data sets and their limitations. The waste registry data set contains multiple entities with misspelled names and addresses and addresses that do not point to the actual registration addresses in the KvK trade registry. At the same time, the KvK data set provides outdated or incomplete data points where not all relevant addresses are present.

The attempt to refine the algorithm on the basis of the type of waste that an entity disposes of has been unsuccessful. Comparing the available guidance and conversion tables to the NACE-EWC combinations obtained from the high-confidence linking subsets has revealed that even at the least detailed level of economic activity classification, roughly half of all actors do not comply with the regulation guidelines. The lack of compliance can be explained by the unrealistic expectations of the guidelines set by the lack of a high-quality correspondence table and a non-operational definition of the waste producer.

No statistical differences could be observed between the matched and unmatched parts of the entities; therefore, the waste production statistics obtained from the matched part could be scaled to the full data set to show which economic sectors have produced which amounts and types of waste. However, this method is not able to provide a more detailed representation of an economic activity instead of the sector level.

Based on the described experiment, the following recommendations can be made regarding the Waste Statistics Regulation and other related research. First, a guidance document that provides high-level-of-detail correspondence between EWC and NACE codes would provide a control mechanism for the consistency of the reported statistics, especially given that every member state applies different data collection and reporting methods. The definition of a waste producer should be chosen in light of which statistics are necessary to support the transition towards a circular economy and not which entity needs to be charged for the waste management costs as typical to the linear economy. Furthermore, waste statistics could collect not only data related to the entity that disposes of waste but also the economic activities that have preceded the disposal.

Finally, Waste Statistics Regulation suggests using the National Trade Registry as a reference for the economic activities of the waste producers. However, this experiment has demonstrated that a Trade Registry in the Netherlands does not sufficiently correspond to the operational reality in terms of company data. Moreover, the primary economic activities assigned in the Trade Registry may not be those that actually cause waste generation. Future research should include other Member States and their waste data collection methods to ensure that the Waste Statistics Regulation is able to support the required variety of geographical contexts and compile supranational data sets necessary to support a circular economy transition.

REFLECTION ON THE FINDINGS

The experiment described in this chapter has shown that it is possible to analyse patterns of waste production and economic activities using the LMA registry. It is also possible to link the LMA Registry to the KvK Registry using an algorithmic process, although linking is not possible for a significant sample of companies. At the same time, the experiment has revealed that economic sectors deemed financially responsible for waste production are often not those that carry out processes which result in waste.

This revelation that in the operational reality process and activity to a large extent are not carried by the same company requires adaptation of the CE ontology. Previously, it has been understood that an Actor class belongs to an Economy Activity class and at the same time carries out a task that is defined by a Process class and that causes waste production. Activities are aggregated into larger groups of Economic Sectors. An Activity and a Process might be the same (e.g., a company in the Construction sector might carry out Construction Process or Demolition Process) or closely related (e.g., a company in the Hospitality sector might carry out Food Preparation and Storage Process).

However, the experiment has revealed that in most cases there are (at least) two actors involved in the waste disposal process. An actor that pays for and, therefore, carries the responsibility of waste disposal often does not carry out any processes related to waste production. At the same time, an actor who performs the responsible process does not report waste and therefore does not appear in waste statistics. According to the CE ontology, such an actor is not participating in a flow, but only providing a service. To make this distinction clear in the CEM, the following adjustments are made to the CE ontology.

Activity - a property of an actor that describes the reason an actor is ~~carrying out a certain process~~ *participating in a flow*.

Changed definition

New class **WasteProductionProcess (is-a Process)** - defines a Process through which certain materials change their status into Waste. A list of processes can be obtained from the LoW chapters.

New class **WasteRegistrationService (is-a Service)** - defines a Service that takes the responsibility of waste production and pays for it.

Waste Production Process and Waste Registration Service can be carried out by the same or by different actors.

These changes and insights are very important for policy making, as it must be taken into account which groups of companies will be directly and which indirectly affected by the policies.

DATA AND SOFTWARE AVAILABILITY

The data sets used for this publication were obtained through two Horizon2020 projects: REPAiR and CINDERELA. Data supporting the findings of this study are available from the Waste Registry Division of the Dutch Ministry of Infrastructure and Public Works (NL: *Landelijk Meldpunt Afvalstoffen (LMA)* in the Netherlands. Restrictions apply to the availability of these data, which were used under licence for this study. The data are not available from the authors and can only be accessed directly from the Ministry. All code developed for this experiment is open source as part of the GitHub repository here: `https://github.com/rusne/lma-data-pipeline/tree/master/nace-ewc`

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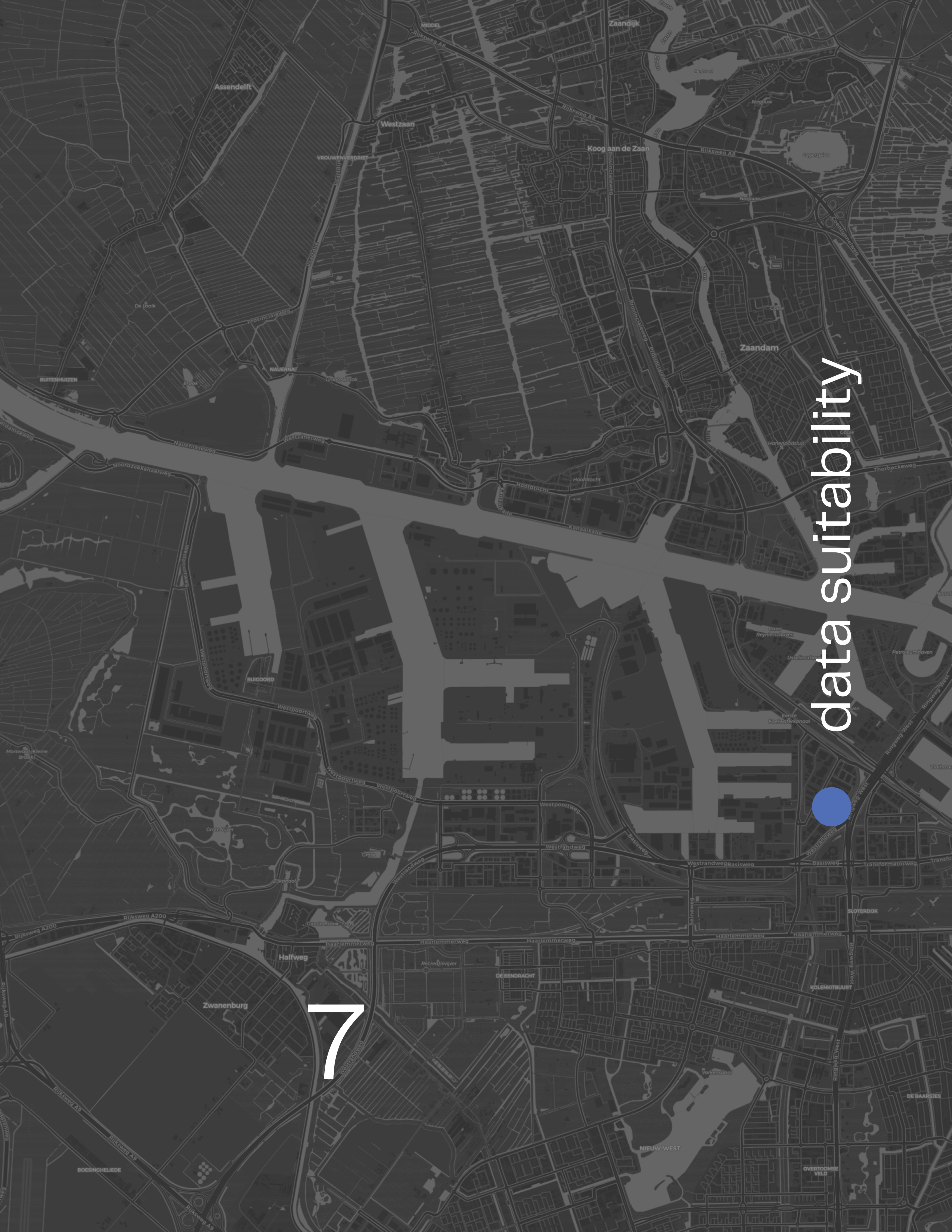
7

data suitability



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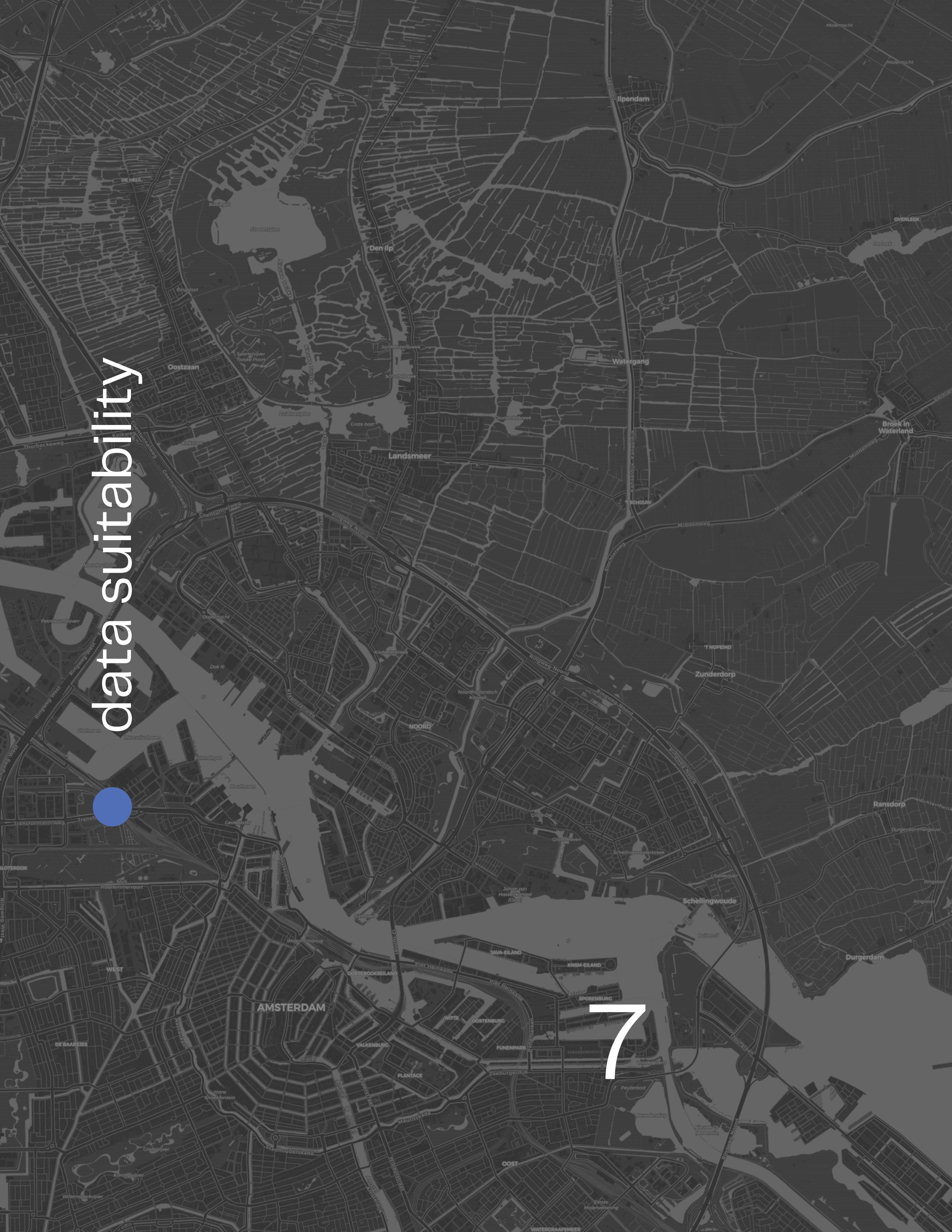
data suitability



EUROPEAN WASTE STATISTICS DATA FOR A CIRCULAR ECONOMY MONITOR

Research questions:

- A How can the data from the Dutch National Waste Registry help assess the impacts of decisions in the pursuit of a circular economy in the Amsterdam Metropolitan Area?
- B Which data limitations hinder monitoring and transition towards a circular economy?
- C How can the European Waste Statistics Regulation be improved to better support the transition?

Based on:

Sileryte, R., Sabbe, A., Bouzas, V., Meister, K., Wandl, A., & van Timmeren, A. (2021)

The Responsibility of Waste Production: comparison of European Waste Statistics Regulation and Dutch National Waste Registry

Published in Journal of Cleaner Production, Vol. 358, 131767

ISSN 0959-6526

DOI 10.1016/j.jclepro.2022.131767

PREAMBLE

The previous chapter has formulated a hypothesis for testing with respect to the classification of waste producers according to their economic activities. The hypothesis had three underlying assumptions that were not tested in the previous chapter. One of the assumptions stated that "the assessment of which companies should first be targeted can be performed based on waste data, for example, by assessing its environmental impact from treatment and transport, the potential for circularity of waste materials, etc.'. This assumption is strongly related to the research question "A How can the data from the Dutch National Waste Registry help assess the impacts of decisions in the pursuit of a circular economy in the Amsterdam Metropolitan Area?" and, therefore, is tested in this chapter.

The assumption is tested on the basis of four queries that are considered important by the decision-makers at the Municipality of Amsterdam. The four queries are also a result of the interviews as described in Chapter 5 in relation to the development of the User-based Ontology. Three of the queries relate to the context importance side of the significance assessment and one is related to the impact characteristics side (Table 7.1). The first two queries are meta-level assessment for determining the decision space and, therefore, appropriate values and extent in the different dimensions. For example, the question about the spatial extent of the waste flows is a meta-level question for the further preparation of assessments. If the waste flows do not extend beyond metropolitan boundaries, then it is not meaningful to include international considerations in the assessment. However, if a significant amount of waste flows crosses national boundaries, then it becomes important to discuss whether different foreign destinations should be regarded differently. At the same time, the question about the economic sectors strongly relates to choosing the dimension values. If the data do not allow for assessment of the process dimension using the taxonomy of the economic activities, then it is not meaningful to discuss the importance using this taxonomy.

The characteristics of waste statistics are discussed, relating them to five dimensions discussed in Section 5.6 There is a considerate overlap between this and the previous chapter, as they have been simultaneously published in two separate journals.

Broader CEM goal	Example query	Role in significance assessment
Determining the CE decision-making space: geographical scope and scale	What is the spatial extent of the waste flows that originate within the municipality of Amsterdam?	Determining appropriate spatial dimension values and extent for the assessment of context importance
Determining the CE decision-making space: stakeholders	Which economic sectors need to be included in the circular economy strategy development and decision-making?	Determining appropriate process dimension values and extent for the assessment of context importance
Evaluating the feasibility for local CE strategies	Which secondary materials are present in the area and have the potential to be reused?	Assessing context importance values for the object dimension
Assessing the social and ecological impact	What is the current carbon emission impact of waste transportation?	Assessing impact characteristics

Table 7.1. CEM goals, queries and their roles in significance assessment

7.1 INTRODUCTION

Being a supranational document, the EU Circular Economy Action Plan (CEAP) has rippling effects on national, regional and local policies throughout Europe. Several cities and urban regions have already announced their own circularity ambitions and strategies to enhance circularity on a local level (Petit-Boix and Leipold, 2018), while others will be mandated by the Commission to prepare plans for “making the best use of EU funds” (European Commission, 2020). Since the organisation of material flows in all cities and regions depends on local conditions (Tapia et al., 2018), “the best use” will have to be determined by measuring and comparing the impact significance in the local context (Sileryte et al., 2018).

Monitoring frameworks are a crucial component of the CE strategies of many European cities. Their main purpose is to assess how the city is performing toward the achievement of set targets and to steer the decision-making based on the measurements (OECD, 2020). The City of Amsterdam in The Netherlands has created a monitoring framework as part of its Circular Strategy 2020-2025 and is currently on the way to implement a digital Circular Economy Monitor (CEM) (Gemeente Amsterdam, 2020). The CEM tracks progress over time towards the set goals, highlights which areas need improvement, and estimates target feasibility.

The Amsterdam CEM is expected to use a wide variety of public and private data sets integrated into a single framework. One of the largest and most detailed utilised data sets represents industrial waste production, disposal and treatment flows. Collection of this data is mandated by the EC Regulation No 2150/2002 on Waste Statistics, which enables Eurostat to collect biannual statistics on waste generation and treatment per economic activity, treatment method, and population served. Although waste data collection is initially meant for supranational monitoring and legislative purposes, the same data collection infrastructure is now being used for local decision-making purposes. Furthermore, infrastructure has been established before including CE strategies in policy making. In light of the Circular Economy transition, this paper attempts to use the existing waste reports to answer Amsterdam CEM queries and, in this way, explore how the existing system of waste registry in the Netherlands is able to support city-scale decision-making.

After investigating the raw data, relevant data mapping processes are proposed based on the CEM goals. The mapping results are visualised to explore the strengths and limitations of the available data. Finally, an extensive discussion is provided on the possible improvements in the data collection system on local and national scales. Given the data collection is mandated on European scale, the recommendations can be taken into account for any European city CEM and European-wide guidelines. The lessons are also relevant for the non-European countries which are setting up new environmental data collection and monitoring infrastructures as they have an opportunity to leapfrog the discussed flaws.

7.2 KEY OBJECTIVES OF CIRCULAR ECONOMY MONITORING

The OECD Report on the Circular Economy in cities and regions (OECD, 2020) distinguishes four key objectives in monitoring CE: triggering actions; making the case for the circular economy; monitoring performance and evaluating results; and raising awareness. The same objectives, although termed differently, are set forward in the Amsterdam CEM: determining the CE decision-making space; evaluating the feasibility of local CE strategies; assessing the social and ecological impact; and communicating the results to the public (Gemeente Amsterdam, 2020). The focus of this research lies on the first three goals and objectives, leaving awareness and public communication beyond the current scope. The following three subsections explore how data has been used in other related research to achieve the mentioned objectives, while the last subsection summarises the most important data requirements. Based on the provided summary, this paper studies how the most granular available waste flow data collected for Eurostat reporting purposes corresponds to the requirements set forward in the reviewed studies.

7.2.1 Determining the CE decision-making space

Triggering actions based on the monitoring data relate to the meta-choices of the decision-making process (Ferretti and Montibeller, 2016), such as the assignment of decision boundaries and scales, the identification of relevant stakeholders and the formulation of concrete objectives. The optimal spatial scale and decision boundaries of CE strategies depend on a number of variables such as the current extent of material flows (Furlan et al., 2020), material processing capacity (Graedel et al., 2019), material market value and transportation costs (Rahman and Kim, 2020) and to which extent the indirect impacts are considered (Obersteg et al., 2019).

While Obersteg et al. (2019) and Wandl et al. (2019) emphasize that in comparison to cities, urban regions are a more sustainable spatial scale to act for the actualisation of CE actions, Graedel et al. (2019) demonstrated that a circular economy is difficult to impossible to achieve at the scale of a single country. Furthermore, Zeller et al. (2019) have noticed that there is no optimal scale that fits all resource types. Waste with high market value, specialised industrial processing, and relatively low transportation cost, such as metal or glass, will be recovered at a large scale (Rahman and Kim, 2020). Waste with low market value, high accumulation density and costly transportation, such as organic or bulky waste, is more suited for closing material loops locally.

At the same time, Morseletto (2020) has noticed that all end-of-life products and materials cannot fall under the same targets and policies. For example, organic waste clearly cannot be 'refurbished' or 'repaired', scrap from the production process cannot be “reused” and renewable materials should not be 'refused' if they are substituted by critical raw materials. This demands the distinction of targets and, therefore, metrics, at least by material groups and economic sectors. The need for more granular data regarding the waste content has also been acknowledged by (Alexander and O'Hare, 2020) who notice that blind spots are created by privileging one kind of measurement over the other, and therefore 'a more open acknowledgement of different kinds of material characteristics and different methods of evaluation that attend to qualities might help sidestep certain wasting processes.'

7.2.2 Evaluating the feasibility of local CE strategies

Making the case for the circular economy requires understanding of the costs and benefits of scoping which CE activities may be feasible in terms of sufficient quantity and quality of a given material to allow for a given technology of reuse, recycling or transformation. A typical example of secondary resource supply and demand matching are recommender systems for industrial symbiotic networks (Gatzioura et al., 2019). They recommend the best suitable alternative destination for industrial waste instead of a conventional waste disposal option based on such information fields as waste codes (van Capelleveen, 2020), user assigned keywords and descriptions, waste/material quantities (Yeo et al., 2019), generation frequency, and site location (Maqbool et al., 2019).

The same data characteristics are relevant in regional assessments when the total amount of potentially available secondary resources is compared with the current primary resource demands. To evaluate the feasibility of circular strategies, high spatial (Voskamp et al., 2016) and high temporal (Akram et al., 2019) resolutions of material flow data are necessary. Understanding the spatial and temporal dynamics that can be influenced by external government incentives also serves the design of circular supply chains Yu et al. (2021). Finally, increasing the resolution of input data creates a more realistic picture of recycling needs and cost efficiency; therefore, it is important to have high-quality data on resources, in terms of quantity, quality, geolocation, and time of resources becoming available, at different scales (Akram et al., 2019).

The geopolitical scale is also an important aspect while considering closing material loops. While Graedel et al. (2019) argue that no country anywhere has a complete collection of the technologies that would be needed to achieve circularity for all the required materials, Schaubroeck (2020) notices that if a loop is closed outside of Europe, 'it can be concluded that there is no circular economy within Europe for that material, yet on a global level, it is the case.' Therefore, the availability of technologies, material criticality and socio-economic conditions are relevant not only in the local context of decision-making but also beyond (Schaubroeck, 2020).

7.2.3 Assessing the impacts

The third goal of a CEM comes from an obligation to study the impacts caused by circular resource use (Harris et al., 2020). On the one hand, circular resource use is expected to replace primary resource use and extraction and, in this way, reduce the associated environmental impacts. On the other hand, the specialised technologies necessary to upscale resources are not always available locally (Rahman and Kim, 2020) and circular practises may lead to unwanted rebound effects (Schaubroeck, 2020). Therefore, the environmental impacts of transport and energy must be assessed to evaluate the actual environmental impact of circular material use (Graedel et al., 2019), and geopolitical, socioeconomic, and trade-off aspects must be covered to determine whether circularity leads to better sustainability (Schaubroeck, 2020). Furthermore, CE itself affects the spatial structure of the social (employment, occupational health, accessibility, etc.) and material (infrastructure, built environment, etc.) contexts in which it is implemented (Jedelhauser and Binder, 2018).

Pincetl and Newell (2017) argue for the use of big data that are also granular to place and spatially explicit on the production and consumption patterns of urban landscapes, so that they reveal processes by connecting actors, activities, and impacts throughout time and space and reveal their resulting political, industrial, and ecological implications. Their research has found that big data that encompass the institutional and ecological context of urban activities provides a framework for exploring questions of equity and policy development and helping to enable reform by identifying patterns and drivers of use.

CE impact assessment falls within the field of socio-economic metabolism (SEM) studies (Haberl et al., 2019). It is most often performed by using a combination of Material Flow Assessment (MFA), Life Cycle Assessment (LCA) and Input-Output Analysis (IOA) methods (Corona et al., 2019). Cano Londoño and Cabezas (2021) have suggested additionally including Exergy Analysis (ExA) and Emergy Accounting (EmA) methods. All of these methods are data-intensive and require integration and semantic correspondence between a number of interdisciplinary data sets (Pauliuk et al., 2016). Although model and data harmonisation between different SEM fields lately has been advanced (Krausmann et al., 2018), there is still no single nomenclature or formal ontology of the used terms and concepts (Sileryte et al., 2021a).

To improve data integration and reduce uncertainty, Pauliuk et al. (2019) have suggested a general data model for SEM studies that requires all data sets to be described in five dimensions: 1) time dimension, 2) location dimension, 3) process dimension, 4) object dimension (substances, materials, goods, products or commodities) and 5) layer dimension (unit). In addition to publishing values and their metadata, they suggested that data providers store correspondences between different classifications.

7.2.4 Data requirements for the Circular Economy Monitoring

Although the data requirements are labelled differently in different studies, there are common denominators that relate to all monitoring purposes:

1. Studying **flows, relations, and transformations** rather than static numbers is the most commonly mentioned requirement necessary for all monitoring purposes. Studying geographical flows is necessary for the determination of the decision-making scale and circularity metrics. Relations between economic sectors and activities allow understanding how the decision effects trickle down to the material flow networks, and how innovation and

cooperation can be stimulated. Material transformation processes mostly relate to the environmental and social impacts of the material flows. They also describe material quality and capacity to substitute virgin resources.

2. Material quantity in both mass and volume and material market value are the most important **measurement units** that relate to the feasibility of the CE strategies and the eventual environmental impacts.

3. As detailed information as possible on the **material content** is a key aspect that is necessary to determine the best applicable treatment or up-cycling process, connect material supply with demand and calculate impact on the primary resource depletion.

4. High level-of-detail **temporal and geographical information** about the material locations and movements is necessary to determine the decision-making boundaries and relevant stakeholders, transportation and processing costs, material accumulation density and storage capacities. Information on the flow frequency allows monitoring changes over time and therefore evaluating the progress. At the same time it is important for setting targets and assessing their feasibility.

5. Finally, the integration of multiple data sets and assessing the quality of monitoring itself requires the **availability of metadata** that describes the data collection process, units and used nomenclature.

Such requirements are desirable for the data to support city-scale decision-making. Although CEAP stresses the importance of monitoring and data availability to support the decision-making on all governance levels, very few researchers discuss whether the data sets enabled by Eurostat allow for the required monitoring. The system of Economy-Wide Material Flow Accounts (EW-MFA) (Eurostat, 2018), which have been published by most European countries, have improved the data availability, but the data is only available aggregated at country scale (Zeller et al., 2019). To date, there are very few published examples of high granularity waste flow data being used in support of city-scale CE decision-making. Geldermans et al. (2018) have been using the Dutch waste registry for spatial, social and material flow analysis in Peri-Urban Living Lab (PULL) workshops. Geldermans (2020) has further mapped specific economic activities relating to material flows and stocks from waste production in cities' subsystems, as well as the involved actors and their interrelations regarding the circular indoor partitioning. Furlan et al. (2020) has used the same data set to map and study waste flows as part of the urban metabolism in the Amsterdam Metropolitan Area. The three studies conclude that the data set is useful, especially due to its explicit spatial dimension, however, do not further discuss its limitations and opportunities.

7.3 METHODS

The primary purpose of industrial waste data collection is not supporting CEM purposes but providing insights into waste management activities. Therefore it is expected that to answer the questions of the monitor's users, the data needs to undergo the process of mapping (Sileryte et al., 2021a). Mapping refers to a mathematical correspondence that assigns exactly one element of one set to each element of the same or another set (Merriam-Webster, 2022). Basically, the need for data mapping arises when the question at hand has to be answered using the terms or values which are not used in the original data set.

The process of mapping always requires three fundamental elements: an object (or multiple objects) to be mapped (domain), a set towards which the object is mapped (co-domain), and a mapping function which describes the relationship between each object and the sets. The quality of the mapping depends directly on the quality of those elements. For this research, the values in the industrial waste data set are the objects to be mapped. The sets towards which the mapping is performed and the functions used for mapping depend on the query at hand.

Four general queries have been formulated together with the CEM development team at the City of Amsterdam that could be answered using industrial waste reports. The queries relate to the different purposes of monitoring circularity at the city level, as defined in the Amsterdam Circular Economy Strategy (Gemeente Amsterdam, 2020). The four queries (Table 7.2) should be viewed as typical examples rather than an exhaustive list. Four data mapping experiments have been chosen as the most relevant to answer the formulated queries.

The experiments are executed in the four following steps. First, the waste reports are acquired in their raw state and relevant data sets are selected as necessary for the mapping functions. Next, the raw data is cleaned, filtered and harmonised to avoid corrupted data points and fix inconsistencies. Afterwards, the selected mapping functions are applied. All information is combined in a single comprehensive table that can be further used to do statistical analysis and produce data visualisations. The observations and the limitations encountered during the mapping process are used for an extensive discussion about the current potentials and limitations of the current waste reporting system in the Netherlands.

7.3.1 Data Acquisition

Dutch National Waste Registry

Industrial waste statistics in the Netherlands are currently carried out under the framework of the Waste Statistics Regulation (Eurostat, 2013) and are used in the annual monitoring of the National Waste Management Plan (NL: *Landelijk afvalbeheerplan (LAP)*). The Waste Management Division (NL: *Landelijk Meldpunt Afvalstoffen (LMA)*) within the Dutch Ministry of Infrastructure and Public Works (NL: *Rijkswaterstaat*) is responsible for the reporting of industrial waste. Every waste management company in the Netherlands is obliged to file a waste report after receiving a significant amount of waste (i.e., more than $50m^3$) that is legally processed as waste and not as secondary raw material. The reports represent a chain of waste management companies from the original waste producer to the final treatment destination. LMA estimates that around 60% of all waste produced or treated in the Netherlands is reported to them. Reports are not

CEM goal I	Determining the CE decision-making space: geographical scope and scale
Query I	What is the spatial extent of the waste flows that originate within the municipality of Amsterdam?
Mapping domain	Company addresses
Mapping function	Geolocation
Mapping co-domain	Geographical coordinates
CEM goal II	Determining the CE decision-making space: stakeholders
Query II	Which economic sectors need to be included in the circular economy strategy development and decision-making?
Mapping domain	Waste producer names and addresses
Mapping function	Entity linking using the Chamber of Commerce (KvK) business registry
Mapping co-domain	Economic sectors according to NACE (*Nomenclature statistique des activités économiques dans la Communauté européenne*)
CEM goal III	Evaluating the feasibility for local CE strategies
Query III	Which secondary materials are present in the area and have the potential to be reused?
Mapping domain	LoW codes
Mapping function	Manual semantic annotation
Mapping co-domain	Classes that describe waste reuse potential
CEM goal IV	Assessing the social and ecological impact
Query III	What is the current carbon emission impact of waste transportation?
Mapping domain	Waste production and treatment locations, number of transport trips and weight per trip
Mapping function	Shortest distance estimation and probable vehicle assignment based on transported weight
Mapping co-domain	Carbon emissions from transport, CO_2 equivalent

Table 7.2. Overview of the four experiments that aim to answer CEM queries by mapping the waste registry data set into a relevant set of values.

publicly accessible as they contain company-sensitive information.

The LMA data set has been filtered for all waste produced and / or treated in the Amsterdam Metropolitan Area (AMA) in 2018 and consists of two subsets:

Receipt Notifications (NL: *Ontvangst Meldingen*) are reports of primary and secondary (waste from waste treatment facilities) waste submitted by waste processors that receive industrial waste and are obliged to report waste under the Dutch law.

Issue Notifications (NL: *Afgifte Meldingen*) are reports of secondary waste coming from waste treatment facilities. These reports need to be filed when: a) secondary waste is upcycled and sold as a product; b) secondary waste is further processed by a company that is not obliged to report to the LMA; this especially applies to companies outside of the Netherlands. Secondary waste is reported using LoW (European List of Waste) codes or GN (General Nomenclature) codes, depending on the applicable legislation.

All data that has been used for this case study has been provided by the LMA under the framework of the Baseline for the Amsterdam Circular Economy Monitor project in collaboration with the Amsterdam City Chief Technology Office (CTO).

Chamber of Commerce Registry

The LMA data set does not contain any additional information on the companies that produce waste except for their name and address. This poses a limitation to determine the actual waste origin and especially the economic activity that is responsible for the waste generation. To provide the missing information, LMA data set is linked with the data from the Chamber of Commerce (NL: *Kamer van Koophandel* (KvK)) as suggested by the Eurostat guidelines (Eurostat, 2013). It is a trade register which holds the registry of all companies and their addresses in the Netherlands. The KvK data set has been limited to the extent of the Amsterdam Metropolitan Area in 2018.

Road Network

A simplified road network is used to assess carbon emissions caused by waste transportation. The original data for the Dutch road network is provided by OpenStreetMap (OSM) and GEOFABRIK. From all available OSM tags related to road networks, only the following have been extracted: motorway, trunk, primary, and secondary. In this subset, a custom simplification algorithm has been applied that 1) merges contiguous segments into linestrings, 2) collapses junctions into single points through clustering, and 3) simplifies line segments based on the Douglas-Peucker algorithm.

7.3.2 Data Processing

The waste reports do not undergo any quality or validity checks before or after being submitted. As long as all required fields are filled out, a report is allowed for submission. Therefore, errors of various natures are common. Although it is not possible to check how well the reports represent reality, a number of sanity checks can be applied in an automated process to remove or rectify faulty entries and harmonise values that are likely to represent the same entities.

Filtering removes blunders that would confuse further processes and affect the analysis results. Blunders are considered those entries that have invalid postcodes, company names without alphabetical characters, or waste amounts less than 1kg or more than 45t per transport event. These thresholds are selected in consultation with LMA representatives. Cleaning removes all non-alphanumeric characters and repeating white-spaces from the free-form text fields and compares data fields to identify such cases as company name entered instead of the street name and similar ones. Harmonisation unifies the capitalisation and formatting of such fields as postcodes and addresses. Additionally, it attempts to harmonise company names by removing the acronyms related to the company legal structure (i.e., BV, VOF, NV, SV, CV) and articles containing apostrophes ('t and 's) common in Dutch language.

7.3.3 Data Mapping

Geospatial Mapping

The necessity to know the geospatial location where waste is produced, transported and treated is mentioned in relation to all CEM goals. Geospatial representation of waste flows is able to answer the queries related to scale, understanding the decision-making context, and finally, it helps answering the question whether secondary material supply meets the demand within certain geographical boundaries.

The LMA data provides information on the waste disposal and treatment locations by using building or site addresses. Geolocation allows the conversion of addresses into unique points with geographic coordinates in a chosen coordinate reference system using a service database with all available addresses. The Mapbox Geocoding API has been chosen for the mapping of all waste disposal and waste treatment locations available in the LMA data set.

Geocoding is prone to errors that occur if an address is not complete, misspelled, corresponds to multiple points, or it is simply not included in the service database. To validate the geocoding results and correct errors, additional spatial data were incorporated into the analysis; that is, the Dutch postcode districts (NL: *Postcodegebied*). Postcode districts are polygons that include all addresses within the first four digits of a postcode. If a point falls within its own postcode polygon, then the location is considered valid. Otherwise, the geolocation is considered invalid and a postcode polygon centroid is assigned instead of the geolocated point.

Mapping Waste Producers to their Economic Activities

The EC Regulation No 2150/2002 on Waste Statistics enables Eurostat to collect statistics from member states on 1) waste generation per economic sector and household consumption; 2) waste treatment by waste category and type of treatment and 3) number and capacity of recovery and disposal facilities (per NUTS 2 region) and population served. However, waste treatment statistics are collected directly from the waste treatment facilities and therefore disconnected from the waste producers. Companies in the LMA data set are reported only by their name and address but neither their economic sector nor unique identifiers are available to establish a link with other business registries.

Knowing which economic activities produce which kinds of waste is necessary to answer which economic sectors need to be specifically addressed due to their waste production. It also describes the characteristics of waste content (e.g. by distinguishing between post-consumer or production and distribution waste). From an impact assessment perspective, the economic sector should be able to describe the process that has been applied to the material, product, or substance before it has turned into waste.

The mapping method that has been used to connect waste producers to their economic activities is based on entity linkage between the LMA and KvK data sets using name similarity according to the Levenshtein distance and geospatial proximity as described in Sileryte et al. (2021b).

Semantic Mapping of Waste Content

The content of the reported primary waste stream is described using two information fields: a free text field and a LoW (European List of Waste) code. The LoW code provides a standardised description of different types and sources of waste. The codes are used to decide on the most appropriate treatment process; identify the rules that apply to movement, storage, and treatment; and provide guidance on waste hazardousness. Although not intended for this purpose, LoW codes are often used for the identification of new symbiotic relations (Capelleveen et al., 2021). Two key limitations of this kind of LoW usage are mentioned in the literature: 1) the lack of information on the actual material content; and 2) possible overlaps between the codes.

The free text field does not have any additional guidelines; the reporting person is only asked to provide a description of the waste stream in their own words. Filling in the free text field is not mandatory. Approximately 40% of the entries in this field are identical or almost identical to the LoW code description.

There exists no correspondence between the LoW codes and the potential resources contained in them, neither in terms of which goods would eventually become which type of waste nor in terms of which wastes could be up-cycled to produce which goods. Therefore, no automated mapping function could be applied to answer the query of which secondary materials are present in the area and therefore have the potential to be reused. To provide an example of the mapping, LoW codes have been manually assigned semantic tags as in Table 7.3.

For the sake of this experiment, the 200 largest waste streams have been semantically annotated, of which 100 hazardous and 100 non-hazardous streams. The annotated waste streams make up 91% of all waste mass that has been produced or treated in AMA in 2018.

Mapping Waste Transport Needs to Carbon Emissions

Studying waste transportation routes serves two purposes. First, it allows estimating the costs associated with waste transport and collection and therefore the financial feasibility of the strategies. Second, it relates to the energy needs for moving materials and thus the associated emissions which cause negative environmental impacts. To answer the query about the current carbon emission impact of waste transportation, this paper attempts to provide the mapping of waste flows to the anticipated amount of carbon emissions directly caused by waste transportation by heavy duty vehicles.

The basis for the calculation is the emission factors per vehicle group published by Klein et al. (2020). The STREAM report (Study on Transport Emissions for All Modes) provides emissions on various air pollutants (carbon dioxide, nitrogen oxides, etc.) for different modes of transport and vehicle groups of specified payloads. To assign waste flows to the most probable vehicle groups, payload sets are created with ranges from the minimum to the maximum capacity of a vehicle group. The maximum amount is assumed to be equal to the maximum payload of the given group, and the minimum payload is assumed to be the maximum payload of the closest group of a smaller payload. The most probable vehicle is selected on the basis of the waste amount reported per single transport trip.

Tag	Description
Clean / Contaminated	Contamination indicates whether the waste content requires an additional cleaning process to be applied before the valuable material can be reused for a different purpose. If no contamination is mentioned in the LoW description, the stream is assumed to be clean.
Pure / Mixed / Unknown	Material purity indicates that the waste stream contains only one type of material (e.g. concrete, plastics, paper, food waste), also called a mono stream. Purity indicates that the waste stream does not need to undergo a separation process before it can be reused for a different purpose. If the description does not indicate anything about the material content, it is tagged as "unknown". Contaminated waste streams are by definition also mixed.
Biotic / Abiotic / Unknown	Biotic substances (e.g. wood, agricultural crops, animal products) are renewable on a short term while abiotic substances (e.g. minerals, metals and fossil fuels) are not renewable on a short term. If the description does not indicate anything about the material content or the material content is expected to contain a mixture of biotic and abiotic materials, it is tagged as "unknown".
Organic / Inorganic / Unknown	Organic substances are separated from the inorganic ones from a chemical point of view. The distinction between organic and biotic materials is necessary as some abiotic materials are organic in chemical structure, e.g. petroleum and other fossil materials. They are not renewable in the short term, although their chemical structure is more similar to the renewable biotic resources than to minerals and metals. If the description does not indicate anything about the material content or the material content is expected to contain a mixture of organic and inorganic materials, it is tagged as "unknown".
Material	This a free form semantic tag that describes which materials are expected in a given waste stream.

Table 7.3. The semantic annotation system applied to the LoW codes to identify the potential for material reuse in the waste registry. All tags are indicative only as the actual reusability potential would require a more thorough investigation of the particular contents within these waste streams and their alternative use.

The computation of the CO_2 emissions results from the product of the following variables: 1) the estimated emissions of CO_2, CH_4 and N_2O (summed as CO_2-eq.) per tonne kilometre for an assigned vehicle group; 2) the distance in kilometres between the flow origin and destination following the shortest path; and 3) the waste amount per trip in tonnes. The shortest distance path is estimated using the Dijkstra shortest path algorithm and a simplified Dutch road network.

7.4 RESULTS

The described data mapping methods have been applied to 215 057 receipt notifications and 10 295 issue notifications from the year 2018 where either the company disposing waste, the waste pickup location or the waste treatment location has been registered under a postcode that belongs to the Amsterdam Metropolitan Area.

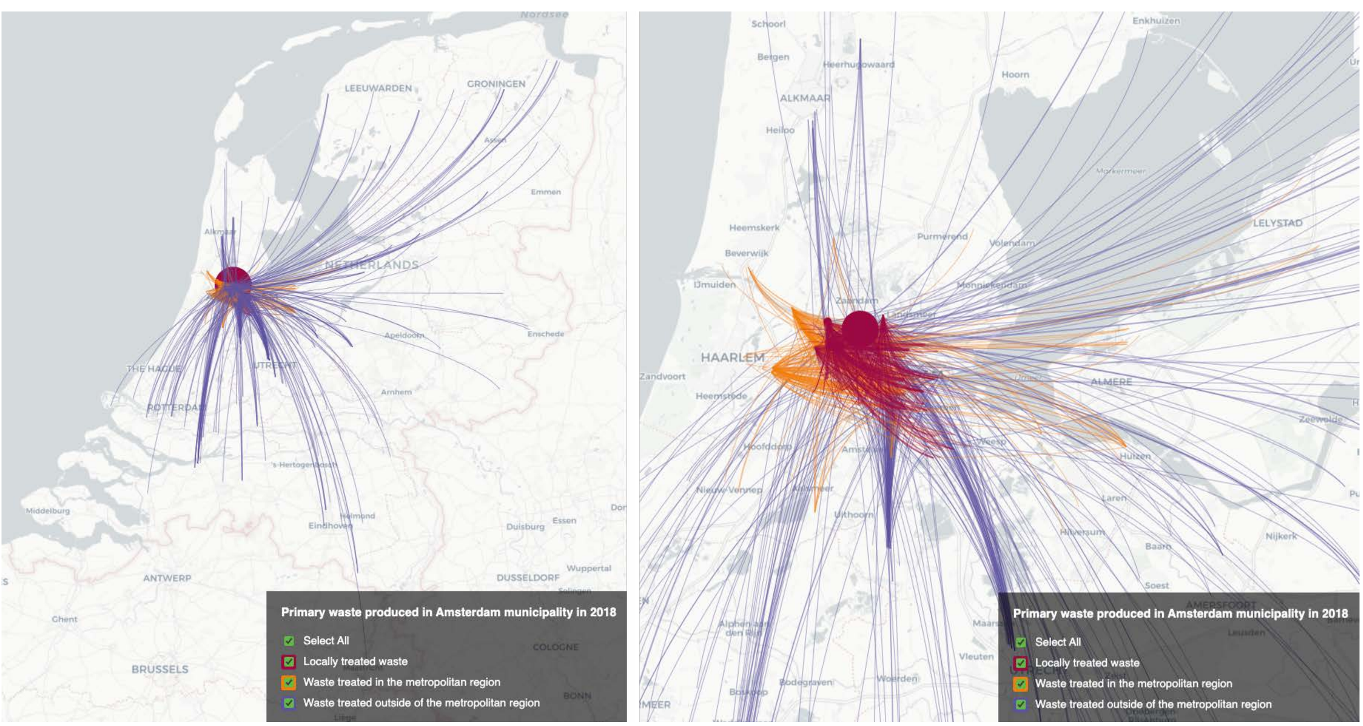
1730 (0,8%) of all receipt notifications and 532 (5,2%) of all issue notifications have been discarded, mostly on the basis of missing waste disposal or treatment locations (0,38% and 3,5% respectively) and unrealistic reported amounts (too small to be reported or too large to be transported according to the reported number of transport trips) (0,4% and 1,6% respectively). The higher number of waste treatment locations missing within the issue notifications can be explained by a relatively large portion of secondary waste being exported abroad (8,9% of all issue notifications). Foreign addresses tend to be reported incompletely more often than local addresses.

The total amount of waste reported by the valid receipt notifications is 9419 Mt of which 87,3% is primary waste and 12,7% is secondary waste. The total amount of waste reported by the valid issue notifications amounts to 3466 Mt. It is not known to which extent those amounts are overlapping.

Query 1. What is the spatial extent of waste flows that originate within the municipality of Amsterdam?

Geospatial mapping has resulted in a successful assignment of coordinate pairs to 98,7% of all addresses. Visualising the flows on a map allows for a very high level of detail, allowing us to zoom in and trace flows on as granular as a building scale. To answer the first query, Figure 7.1 depicts all waste flows reported by receipt notifications that originate in the municipality of Amsterdam and distinguishes them according to local treatment, treatment in the AMA and treatment elsewhere in the Netherlands. It can be seen that 57% (2 135 Mt) of waste is treated locally, 17% (661 Mt) is transported from the municipality to the region, and the remaining 25% (945 Mt) are treated elsewhere in the Netherlands.

Figure 7.1. Waste flows that have originated in the municipality of Amsterdam in 2018. Line thickness corresponds to the total mass of waste transported between the two points; the darker side of the line presents the waste transport destination and the lighter side the waste transport origin. For readability purposes, only flows larger than 1Mt are rendered on the map.

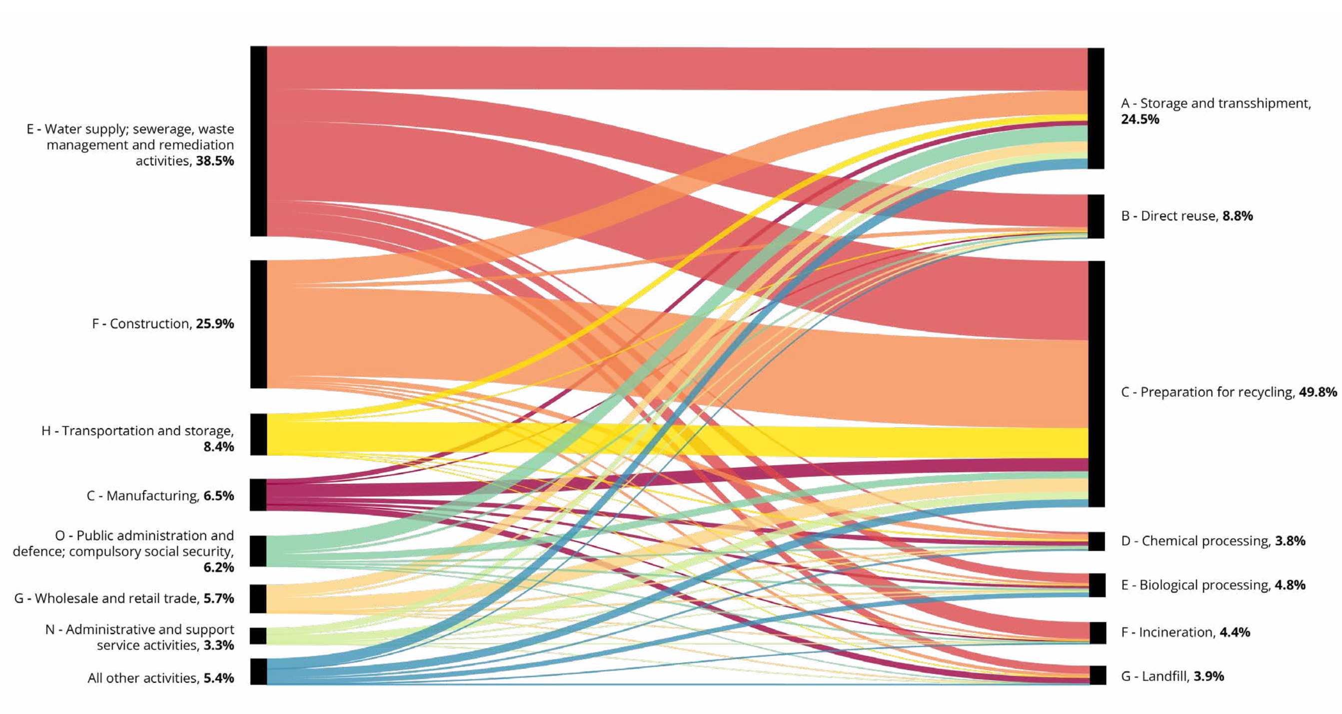


Query 2. Which economic sectors need to be included in circular economy strategy development and decision-making?

Assigning economic sectors to the waste disposing entities has been successful for a significant fraction (79.28%) of all companies in the AMA of which 42.7% have been matched with high confidence, and 36.58% with low confidence. 20.72% of all companies remain unmatched. The unsuccessful matches stem for a small part from failed geolocations (1.3%), partly from heavily misspelled company names (20%) and mostly from inconsistent company address registrations in the Chamber of Commerce data set (79%).

However, as discussed in Sileryte et al. (2021b), the unmatched entities do not show statistical patterns different from the matched ones, neither in terms of the types of waste reported nor their geographical distribution. Therefore, it is safe to assume that the successfully matched part could be used as a substantial sample for statistical analysis. Figure 7.2 visualises the proportions of waste produced by the different economic sectors in the AMA and the applied processing methods.

Figure 7.2. Waste distribution between economic sectors according to the NACE classification and the applied waste processing method. The distribution is based only on the high confidence matches.

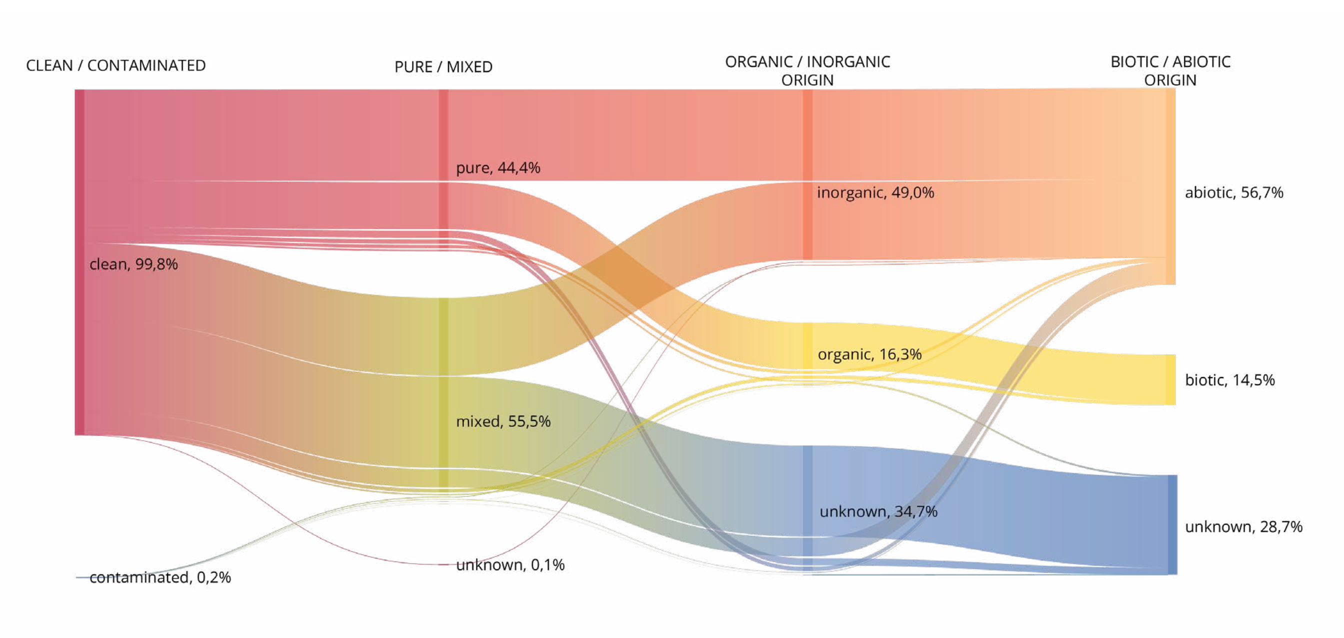


Query 3. Which secondary materials are present in the area and have the potential to be reused?

Semantic annotation has been applied to 200 of the most common LoW codes (91% of all primary waste flows) in the AMA. Mapping has resulted in a range of 148 materials with four additional properties, specifically biotic, organic, purity, and cleanliness. The material list is neither collectively exhaustive nor mutually exclusive and serves as a guide for whether the given material or product is likely to be the major compound of an indicated waste stream. Materials from construction and demolition activities, such as concrete, bricks, stones, and soil, are among the largest waste streams. 20 of 200 LoW codes could not be assigned any material as their description indicates which materials the code is not supposed to contain (e.g. '19 12 12: Other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11') or a mixture of multiple unidentified materials (e.g. '20 03 06: Waste from sewage cleaning').

Biotic or organic origin could not be assigned to additional 47 codes mostly on the basis of material mixture of diverse origin (e.g. '07 04 13: Solid wastes containing hazardous substances from manufacture, formulation, supply, and use of organic plant protection products'). Purity and cleanliness could be assigned in all but

Figure 7.3. Parallel sets of the waste distribution according to the assigned semantic tags.



one case since mixed or contaminated waste indicates the lack thereof.

Figure 7.3 shows how waste produced or treated in the AMA distributes between the assigned classes. The group containing clean pure abiotic inorganic resources is considered to have the highest potential for reuse and constitutes 20.3% (2 258 Mt) of all classified waste streams. Approximately 28% of all waste is reported without providing any information about its content.

Query 4. What is the current carbon emission impact of waste transportation?

The mapping of waste transportation has been applied only to flows within the Netherlands, excluding any of the cross-border flows due to the geographical limitations of the transport network. The amount of waste excluded from the estimate is less than 1% of the total.

The average length of a waste disposal trip is 60km, which on average causes 52 kg of CO_2 emissions. The total amount of CO_2-eq. emissions due to waste transportation that starts or ends at the AMA is 167 074 t. It can be seen in Figure 7.4 that side roads tend to have relatively higher emissions per unit of weight transported than main roads. This observation can be explained by the number of transport trips used to transport smaller amounts of waste.

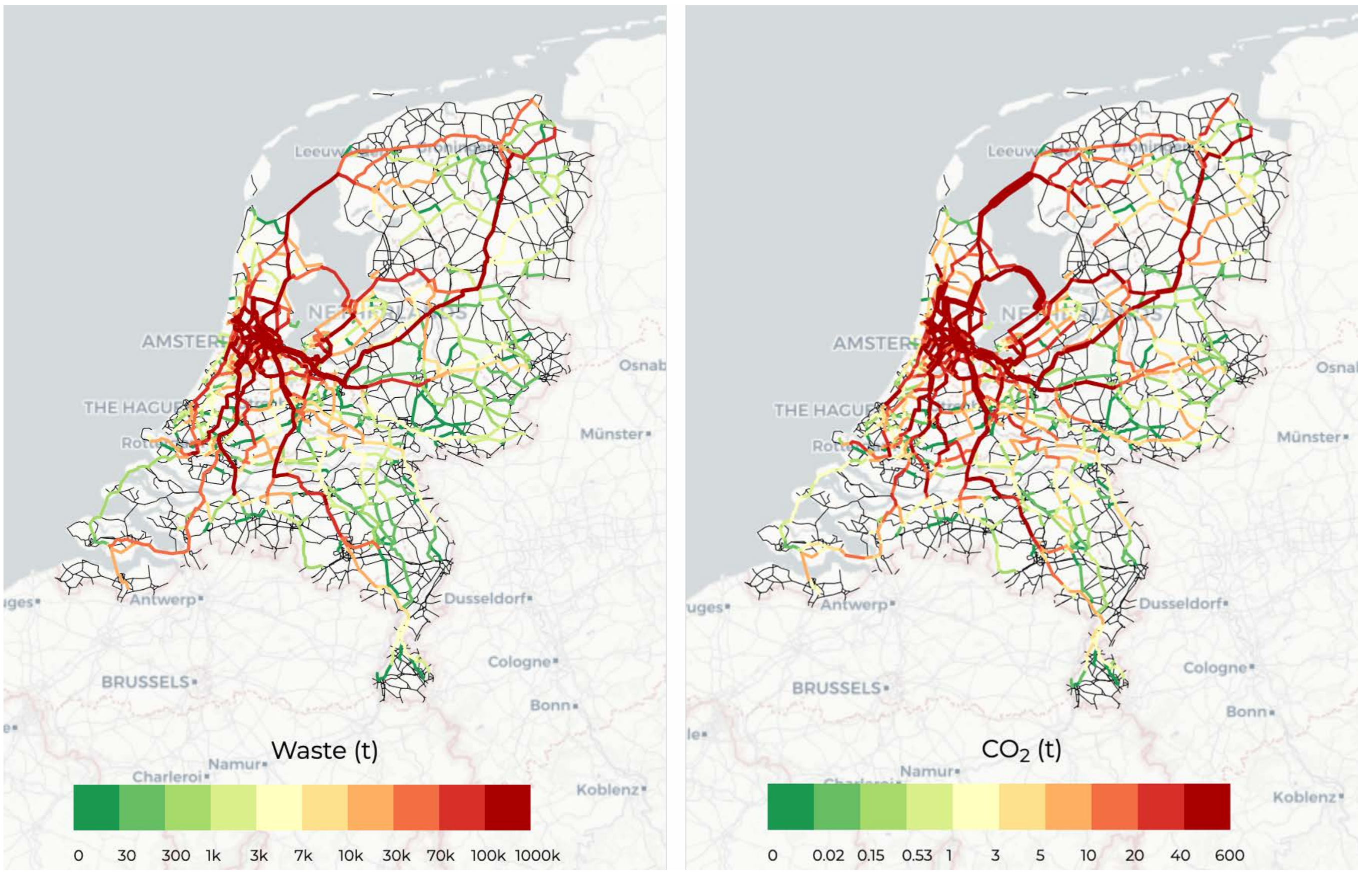


Figure 7.4. Road network map of the Netherlands coloured according to the amount of waste transported in 2018 (left) and the greenhouse gas emissions CO_2 eq. caused by transportation (right).

7.5 DISCUSSION AND RECOMMENDATIONS

The lessons learnt during the mapping process are further discussed according to the five requirements set forth in the theoretical framework and provide recommendations for data improvement. At this point, it is not known to which extent these lessons are applicable for the waste registries in other EU countries and if it is possible to integrate the reporting systems into a Europe-wide CEM as outlined in the CEAP. Therefore, a similar investigation is necessary in the other member countries within the European Union to which the same reporting obligations apply. However, the findings and recommendations discussed can be used as guidance for improving the European Waste Statistics Regulation.

Regarding the applicability of the findings to the non-EU countries, the biggest limitation for replicating the described experiments lies in limited data availability. Therefore, developing CEMs first requires setting up data collection infrastructures. The discussed changes and improvements can be used as guidelines to design infrastructures that are not only meant for environmental control but also supporting the CE transitions.

7.5.1 Flows, Relations and Transformations

The waste data allows tracing waste flows from their producers to the first waste management facility that receives it. Therefore, it is possible to determine the necessary geographical scale for the decision-making. E.g., the geographical extent of food waste flows is smaller than that of construction and demolition waste. It is also possible to distinguish between waste produced in the region versus the waste treated in the region. Relations between economic activities, materials and waste processing methods are in theory possible to trace, however, in practice this information proves to be unreliable or insufficiently granular.

The main limitation of studying waste flows is the lack of continuity in the data.

Although there are secondary waste data, it is incomplete as not all secondary wastes are required to be registered. Moreover, currently, it is not possible to trace which primary waste has been turned into which secondary waste. Even when the indicated waste processing method suggests that the waste stream has not been disposed of (e.g. 'Reuse as building material', 'Shredding', 'Separation'), it is not clear which part has been effectively brought back into the economy and for which purpose and use. This prevents an effective estimate of the current material circularity that passes through the waste system.

Furthermore, it is not known which process the waste has effectively originated from. As discussed in Sileryte et al. (2021b), entities that report waste are often those that pay for waste disposal rather than those that actually contributed to the waste production (e.g., administrative holdings instead of manufacturers themselves). When the actual process that causes waste production is not known or is statistically underestimated due to shifted responsibility, it is not known which policies are necessary to tackle the actual sources of waste production.

The flaws of assigning the right economic sector to the waste disposing actors also have direct influence on determining material content of a waste flow. Although some content characteristics are available in the LoW-based waste description, combining this information with the economic activity that has produced waste may provide additional insights into material quality and potential for reuse. This is especially relevant in cases when LoW code description is based on describing which materials the waste stream does not include (e.g. "02 06 99 wastes not otherwise specified") instead of describing the actual content or source.

The mapping of waste flows to the energy needs for their transport has led to an example estimation of environmental impacts. Although waste reporting should not be burdened with additional reporting of related emissions and other impacts, the reporting system should allow the integration of this information from other sources. For example, waste processing methods could be reported using the same taxonomies that are used to estimate the environmental impact of these processes. Regarding the impact related to transport, registration of the transporting vehicle would allow the coupling of this information with actual emission rates.

7.5.2 Measurement Units

Currently, the waste registry system allows one to trace the total mass of waste disposed of by one company within a month. This allows tracing the changes of waste generation patterns over time and space and roughly estimating the environmental impacts, as impact databases typically relate to material mass rather than other units.

In case of waste streams that contain mixtures of materials, it is not possible to estimate the actual proportions of the different materials and, consequently, the material quality and value that can be recovered from waste. Therefore, more granular information on the waste content, including the estimated proportions of different materials or products and better indication of the material quality and origin, would allow further estimations on the actual market value and, as a result, the feasibility of CE strategies.

7.5.3 Material Content

LoW codes provide standardised information on the waste content and, therefore, play a major role in determining the best applicable waste handling, treatment or up-cycling process for the given type of waste. However, LoW codes have been designed for the linear economy, where the main problem of waste management is avoiding or minimising the negative impacts caused by collection, transport, or disposal. With the shift towards the circular economy, the main problem of the linear economy is likewise shifting towards material scarcity. Therefore, the registration of waste streams should provide information on the content of the material from the perspective of waste prevention, possible reuse, or up-cycling.

Better insights into the waste content can be achieved by either updating the LoW taxonomy or introducing a new taxonomy which describes the waste content in relation to its potential for the circular economy. Initiatives of such taxonomies or ontologies already exist in the literature as material passports (Gligoric et al., 2019), supply chain tracking systems (Mboli et al., 2020) or tag recommenders (Gatzioura et al., 2019). Ideally, such an improved taxonomy would allow correspondence between the established taxonomies for waste as well as product registration to allow full supply and demand modelling and design of the circular instead of linear supply chains.

Finally, the material content is strongly determined by the economic activity that caused the production of waste. Therefore, a more detailed registration of the waste producing entity and the economic activities that preceded the waste generation would allow a better estimation of the material characteristics after they have entered the waste stream. This, in turn, requires an update of the guidelines on which entities should be considered responsible for the production of waste.

7.5.4 Spatio-temporal Information

The waste reports allow for an efficient geolocation of activities. Through the high level of detail, the spatial information also allows estimating the transportation distances and using them as proxies for transportation costs and transport-related emissions. Temporal information is presented in timestamps that refer to the relevant year and month of disposal of the flow. It allows tracking annual as well as seasonal changes of waste production frequency and occurrence within a certain period.

The most noticeable limitation that can be observed in Figure 7.1 is the presence of the national borders. Only a very insignificant number of waste reports (<1%) register waste imports or exports. In the Netherlands, this limitation is caused by a different institution being responsible to collect waste movements across national boundaries. Therefore, it is important to note that integrating both sources of waste reports would provide a more complete picture of the actual waste system, its scale and the necessary decision-making boundaries and relevant stakeholders.

Currently, timestamps are available only for the month in which the waste has been transported from its producer to the processor. It does not provide information about when the waste has effectively been produced and the time needed for its storage and accumulation neither at the producer nor at the processor side. Including this information would be relevant for the estimation of space needed to change the waste system and reroute the materials that currently become waste. Additionally, recording the duration before the materials have become waste and how long it takes to bring them back into the economy would allow for a better modelling of stocks that will become available in the future.

7.5.5 Availability of Metadata

Limited metadata is available for waste data. The main standard nomenclature used to describe waste content is LoW codes. Entity addresses also follow a standard format of a Dutch address and postcode, due to which the spatial mapping is highly successful. Finally, the reporting unit is always a kilogramme and is consistent throughout all reports.

The mapping of waste producers to their economic activities has revealed that the lack of standardised entity registration and identification creates difficulties for an effective matching of different databases. The semantic mapping of waste content could have used the additional description field, however, it is entered in a free-text form and therefore would require natural language processing which is an expensive procedure given the size of the data set.

Impact assessment requires coupling local material flow data with Life Cycle Inventory databases that characterise different processes. Coupling requires the mapping of values available in one data set to the ones available in the other according to different regional, temporal and semantic characteristics (Pauliuk et al., 2019). If a data integration scheme is not available and coupling can be performed in a variety of ways, the overall uncertainty of the impact assessment increases drastically (Pauer et al., 2020). Therefore, to assess the environmental impacts of waste processing methods, a standard classification of processes would allow data coupling with impact databases.

The most important lack of metadata relates to data quality and completeness. At this point, data providers are not able to estimate how much of all waste is effectively reported and how well the reports represent reality. Since reporting entities are required to do so for administrative reasons, submission of high-quality reports is only motivated by occasional government controls. Given that the transition toward a circular economy is expected to bring financial benefits to businesses, including them in the strategic discussions and tailored policies according to the Circular Economy Monitor, it would provide additional motivation for high quality of waste reporting.

7.6 CONCLUSIONS

In light of the transition to circular economy, this paper has analysed all waste reports submitted in 2018 to the Waste Management Division of the Dutch Ministry of Infrastructure and Public Works related to the Amsterdam Metropolitan Area. The reported data are of high quality, as only 1% of the reports could be marked as containing errors. However, it is not known how well the reports represent the actual amounts of waste and their content. Moreover, certain groups of waste are not required to be reported (e.g., mono streams of paper, textiles, metals, glass, etc.), while international waste flows use a different reporting system. Finally, only waste that is legally termed "waste" is registered, therefore by-products and secondary resources or informal waste management flows are invisible to official waste statistics.

The analysis process has revealed that the existing system of waste registry in the Netherlands is able to support city-scale CEM by providing relevant insights into industrial waste. First, the waste reports are able to provide a high geographical level of detail regarding waste production and treatment locations and transport flows between them. Therefore, the geographical mapping of waste reports allows visualising the scales of different waste scopes and assessing transport-related environmental impacts. The changes of the total mass of disposed waste can be traced over time, space and in relation to specific companies and waste treatment methods. While it does not allow measuring the circular use of resources, it allows monitoring the remaining linear part of the economy. Finally, the available free text field descriptions and LoW codes, which are used to describe waste, allow estimating the material content for roughly 70% of the total reported waste flow mass.

At the same time, the mapping process has revealed a number of limitations present in the waste data collection and a number of research gaps related to circular economy data analysis. First, the waste registry currently has low interoperability with other registries and data sets whose use would benefit the CEM, e.g., Chamber of Commerce registry or impact databases. A large research gap could be identified regarding the waste flow material content. To date, there is no formal ontology that connects different products and by-products with their constituent materials and consequently their potential in the circular economy. The LoW codes used in the waste registry are suitable to assign the most appropriate waste treatment method, however, have limited utility in assigning circular economy strategies and assessing their feasibility. Therefore, future work on the CEM should include developing such a material ontology and including its use in the waste registry.

The assumption that "assessment on which companies should be targeted first can be done on the basis of the waste data", is true under certain conditions as discussed in the publication. The conditions strongly relate to the five dimensions of the significance assessment. As discussed in the reflection sections of Chapters 4 and 5, there are three meta-level considerations that determine if significance assessment can be carried out in a qualitative manner. The first one relates to the extent that dimension values should be able to cover, e.g., geographic extent can be related to administrative boundaries (local, national, continental, etc.), distance from a point or territory, a set of municipalities, and other ways to describe geographical coverage. The second consideration relates to the granularity in which information is available, e.g. the temporal dimension can be divided in years, months, days, or other scales of units. Finally, dimension values are labels that are used to classify the values. They relate to the kind of taxonomy used to explore the dimension. For example, the object dimension can be described using material, substance, product, or other taxonomies.

Table 7.4 summarises how the Dutch National Waste Registry corresponds to the three considerations in all five dimensions.

Furthermore, it can be observed that the monitoring goals formulated in Section 7.2 Key objectives of Circular Economy Monitoring fit into the Significance Assessment framework described in Chapter 4 Assessing Decision Impacts in Pursuit of a Circular Economy and further extended throughout the dissertation.

The first goal, "triggering actions" (OECD, 2020) or "determining the CE decision-making space" (Gemeente Amsterdam, 2020) requires data exploration and uses data to inspire and scope actions and strategies that can be later assessed in greater detail. Deciding upon the relevant spatial scale of decision-making (i.e. coverage of geographical dimensions), material scope (i.e. coverage and dimension values), goals and targets (i.e. importance), and level of detail (i.e. taxonomies) are all

	Coverage	Granularity	Dimension values
Time	Since 2013, updated every 6 weeks	A month	Time of waste transport from producer to treatment
Location	Full national coverage, limited international flow registration	Address	Locations of waste production and first treatment
Process	- Companies that produce hazardous waste or more than 50m3 of any waste except mono streams of paper, textile, metal, clean plastics, glass, tyres, wires and waste is reported back to the product producers. - All legal waste treatment methods including temporary storage and transshipment.	- Waste producing and treating company names. - Waste treatment taxonomy provided in the LMA registration system AMICE	- Company that registers as waste producer - Company that registers as first waste treatment location - First waste treatment method including storage and transshipment - Industrial process from which waste originates
Object	All waste from companies according the EU definition of waste except for mono streams of paper, textile, metal, clean plastics, glass, tyres, wires and waste is reported back to the product producers	- List of Waste taxonomy - Free text field that does not correspond to any structured taxonomy	- Waste taxonomy - Hazardousness - Free text field descriptions
Layer (unit)	>1kg, <45t per transport trip	- kg - number of treatment trips	- Mass - Transport trips

Table 7.4. The characteristics of the Dutch National Waste Registry (Waste Statistics) according to the three meta-level considerations in five dimensions that are relevant to the CEM development.

meta-level choices necessary for the significance assessment.

The second goal, “making the case for the circular economy” (OECD, 2020) or “evaluating the feasibility of local CE strategies” (Gemeente Amsterdam, 2020) relates to the assessment of context importance. Assessing material recycling and reuse capacities, projected material scarcity, business potentials, transport needs, time and duration of effective product use, reuse and disposal, current employment rates, etc. are all considerations of judgment which make part of significance assessment.

The third goal, “monitoring performance and evaluating results” (OECD, 2020) or “assessing social and ecological impact” (Gemeente Amsterdam, 2020), strongly relates to both impact assessment and assessing decision impacts. The OECD definition of the goal is related to the continuous monitoring of social and ecological changes while the Amsterdam Municipality definition is related to the a-priori assessment of the impacts. In both cases impact characteristics do not yet inform the decision-making unless they are coupled with judgment and significance assessment.

The final goal, “raising awareness” (OECD, 2020) or “communicating the results to the public” (Gemeente Amsterdam, 2020), is considered outside the scope of this research and should be addressed in the future.

DATA AND SOFTWARE AVAILABILITY

data sets used for this publication have been obtained under two Horizon2020 projects: REPAiR and CINDERELA (New Circular Economy Business Model for More Sustainable Urban Construction). The data that support the findings of this study are available from the Waste Registry Division of the Dutch Ministry of Infrastructure and Public Works (NL: *Landelijk Meldpunt Afvalstoffen (LMA)* in the Netherlands. Restrictions apply to the availability of these data, which were used under license for this study. Data are not available from the authors and can only be accessed directly from the Ministry.

The research data are considered sensitive and, therefore, prohibited from being shared publicly by the Dutch Ministry of Infrastructure and Public Works. Data behind each of the four images in the Results section is available in an aggregated format and is published along with this article. The computational workflow in this publication is executed via a series of script files published under GNU General Public Licence v2 at https://github.com/rusne/lma-data-pipeline.

Data files used to create the images in this chapter are available in supporting information of the published article and on OSF repository via the following link: `https://osf.io/p7cft/`

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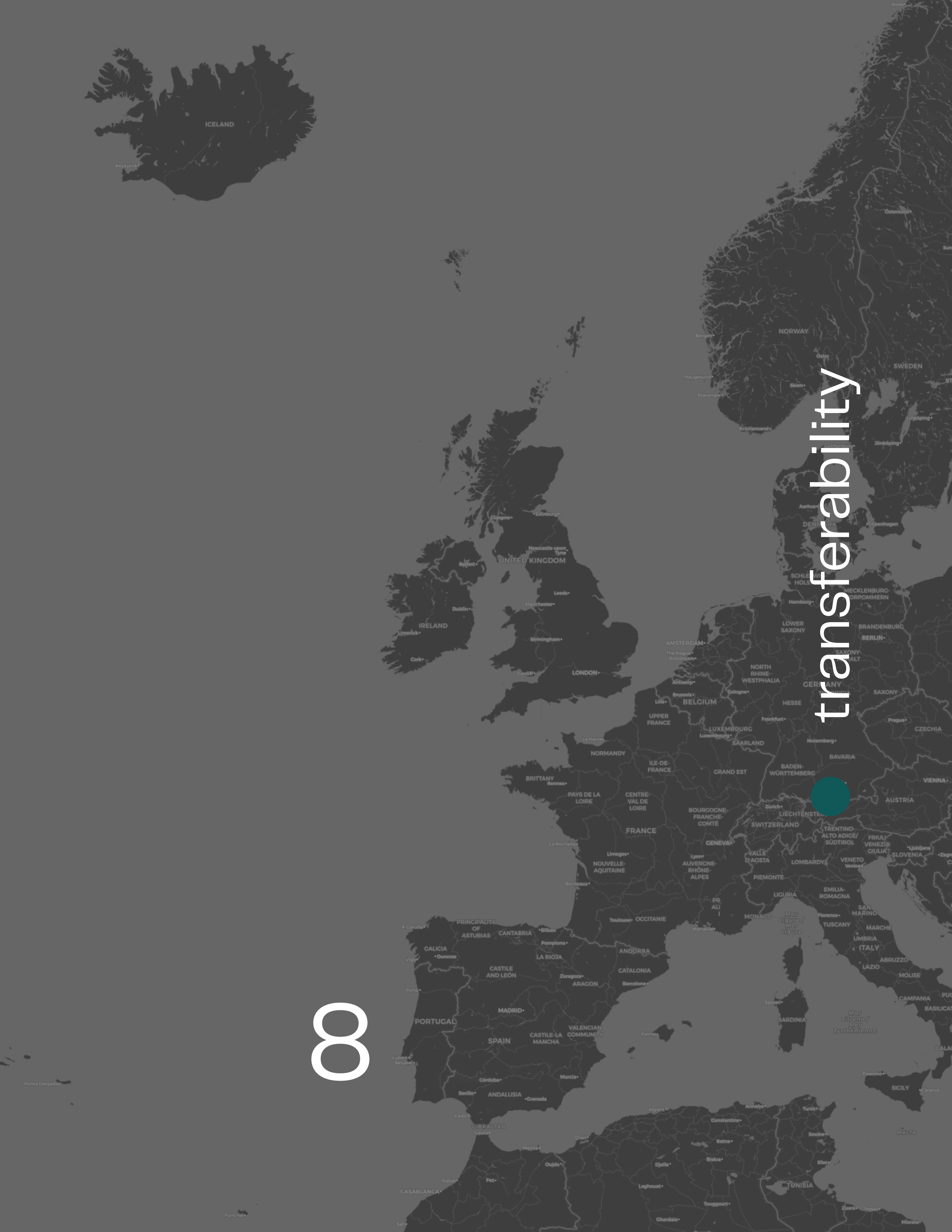
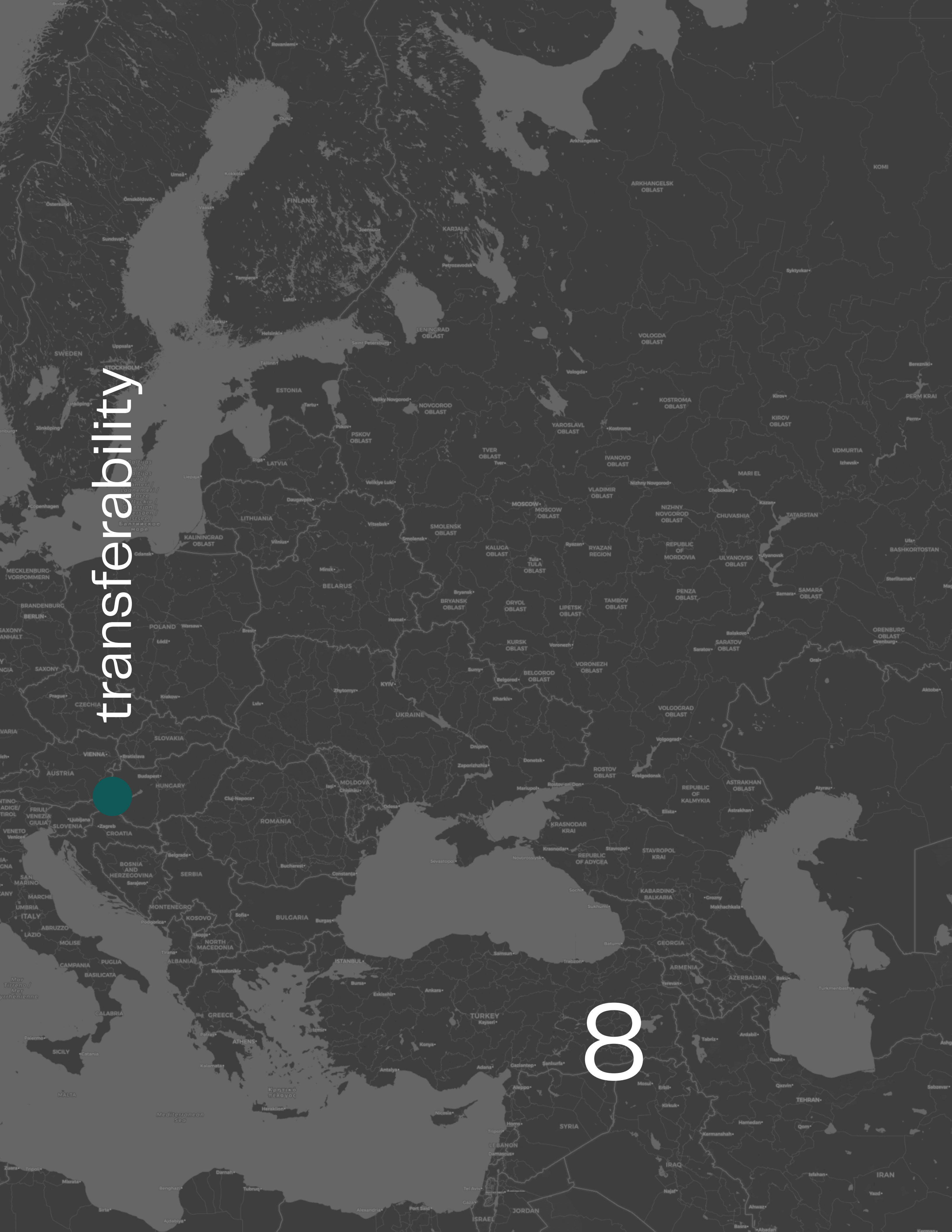
8

transferability





8 transferability

RESEARCH TRANSFERABILITY TO THE OTHER EUROPEAN REGIONS

The EC Regulation No. 2150/2002 on Waste Statistics enables Eurostat to collect statistics from all member states on waste generation, treatment, and capacity of recovery and disposal facilities. The statistics collected are aggregated by economic activity, treatment method groups, and NUTS2 regions. Therefore, Eurostat itself does not own the most detailed data for each member state. Each member state chooses its own data collection method to serve the Waste Statistics regulation; therefore, there is no centralised location where all waste-related data for the European Union are stored or through which it can be accessed.

Given that detailed waste statistics must be accessed directly from each member state, the question arises to what extent the findings, namely, the opportunities and limitations caused by the temporal, spatial and semantic boundaries, granularity, and dimension values, are applicable in other European contexts.

8.1 METHODS AND DATA

Being associated with the H2020 projects REPAiR and CINDERELA (as explained in Chapter 3 Section 3.2) allowed collaborations with researchers working in other European regions who have been asked to carry out similar experiments as described in Chapter 7. European Waste Statistics data for a Circular Economy Monitor. Waste statistics data from other regions were used during the project in the Geodesign Decision Support Environment, in the Status Quo module. The module is designed as one of the collaboration steps during a Peri-Urban Living Lab and visualises current process models of material flows in a chosen region. The process models are later used to design eco-innovative solutions which are supposed to change the flows and in this way deliver a more circular economy.

Each region within the REPAiR project had a specific focus on a certain type of waste depending on their previous analysis and stakeholder interviews, e.g., municipal waste, construction waste, plastic packaging waste, etc. All regions of the CINDERELA project have focused solely on construction and demolition waste.

Each partner region has been asked to:

1. Find an institution in your region that is able to provide relevant waste flow data in terms of geographic extent and their chosen waste type;
2. obtain the data in the available format;
3. process the data to fit the data structure of the GDSE described in the Data Upload Manual;
4. upload the data into a shared project database according to the given instructions;
5. use the data analysis and visualisation tools available in the GDSE to prepare the PULL workshops.

The results of waste data collection, processing and analysis in REPAiR regions are described in REPAiR project deliverables D 3.3 'Process model for the two pilot cases – Amsterdam, the Netherlands and Naples, Italy', D 3.4 'Process model of Ghent', D 3.5 'Process model Lodz', D 3.6 'Process Model Hamburg', D 3.7 'Process model Pecs'. The results of CINDERELA regions are described in a CINDERELA project deliverable D 3.1 'Flow maps and data based for selected urban areas'.

As a result, each region has used a different approach to find and access waste flow data. The data sets used have been collected for different purposes and by different institutions. Some regions have obtained data from local governments, while others have approached waste processing plants directly. Moreover, each region focused on a different type of waste (e.g. some focused solely on municipal waste while others considered only industrial waste). Finally, even though common training and assistance for data processing have been provided, the data obtained have been processed using different methods by people with highly varying data analysis skills.

Due to the above-mentioned reasons, the data from different regions are not strictly comparable. Therefore, it is not possible to provide the same detailed analysis of the suitability of the data for the monitoring of circular economy in the different European regions. Nevertheless, the obtained data can still be visualised in different dimensions, which reveals that some of the observations made based on the Amsterdam data are also applicable to the other regions.

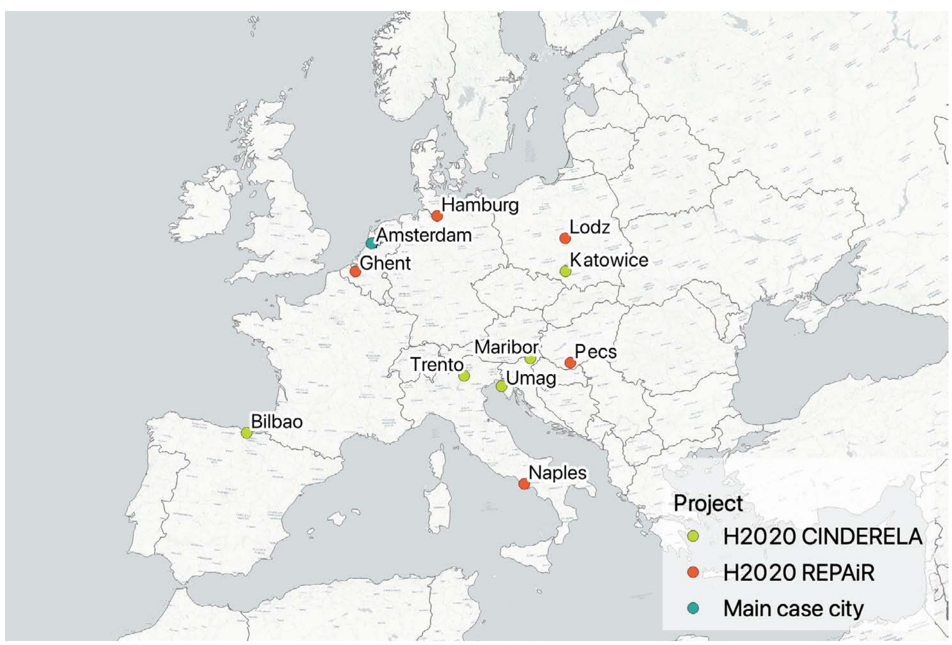


Figure 8.1. All case cities whose data has been obtained through H2020 REPAiR and CINDERELA projects to validate transferability of the research findings

8.2 WASTE STATISTICS IN OTHER EUROPEAN REGIONS

A common framework has been used to compare waste-related data sets obtained from the other regions. The framework follows the research findings described in Chapter 5, which suggest that waste data requires sufficient coverage, granularity, and values in five main dimensions: time, space, process, object, and unit. Therefore, a table and flow map illustration are provided to describe the findings across those five dimensions in each region.

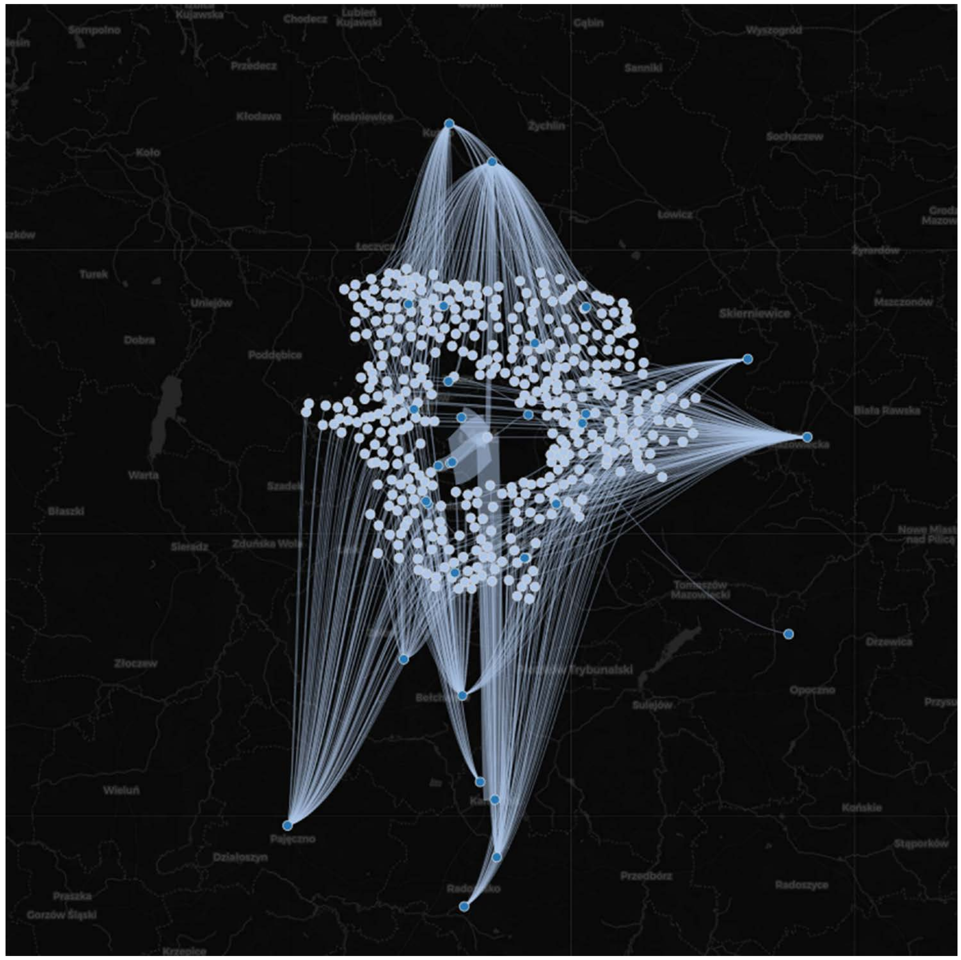
Due to data sensitivity issues, all maps are provided without legends and scale reference and serve only as a rough illustration of the available data rather than a flow map visualisation.

8.2.1 Naples, Italy

Waste type focus	Organic waste, Construction and demolition waste
Data provider	ARPAC (Agenzia Regionale per la Protezione Ambientale in Campania)
Time	Aggregated per year
Space	Waste produced in Campania Region, company address level of detail
Process	Company names that are related to NACE classification for production and treatment
Object	LoW codes, 6 digits
Unit	Waste mass

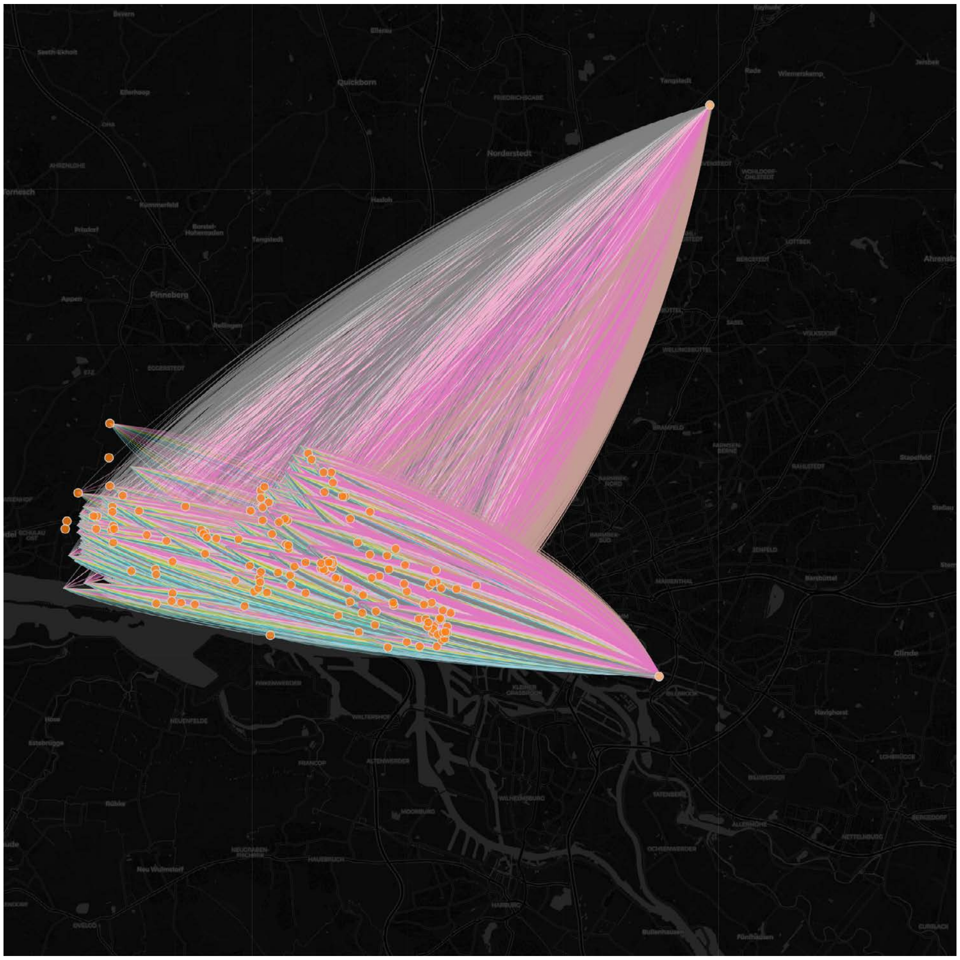
8.2.2 Ghent, Belgium

Waste type focus	Organic waste
Data provider	OVAM (Openbare Vlaamse Afvalstoffenmaatschappij)
Time	Aggregated per year
Space	Waste produced and treated in Flanders region, waste collection sector level of detail
Process	Household / company separation; company economic activity according to NACE code; waste processing method according to OVAM
Object	Separated/not separated organic waste in household or company residual waste
Unit	Waste mass



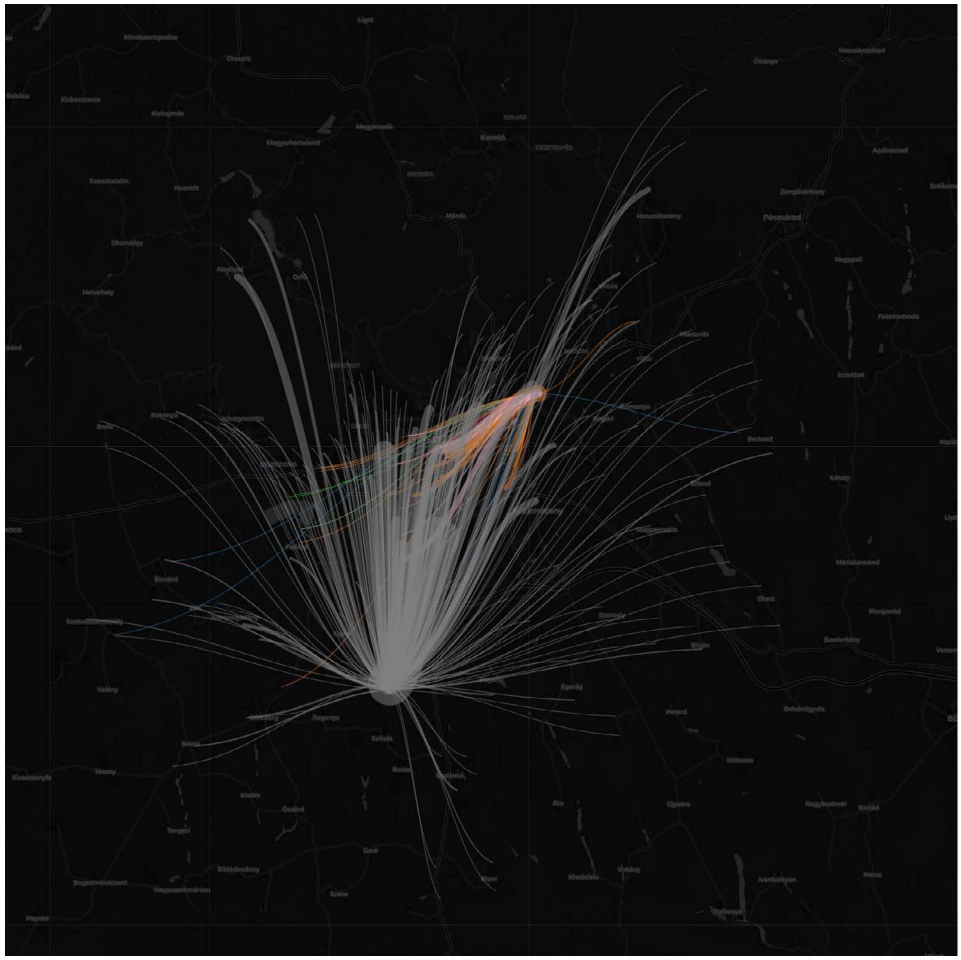
8.2.3 Łódź, Poland

Waste type focus	Municipal solid waste
Data provider	Central Statistical Office of Poland
Time	Aggregated per year
Space	Waste produced and treated in Łódź Metropolitan Area, city district level of detail
Process	Recycling / composting / other
Object	LoW, 4 codes
Unit	Waste mass



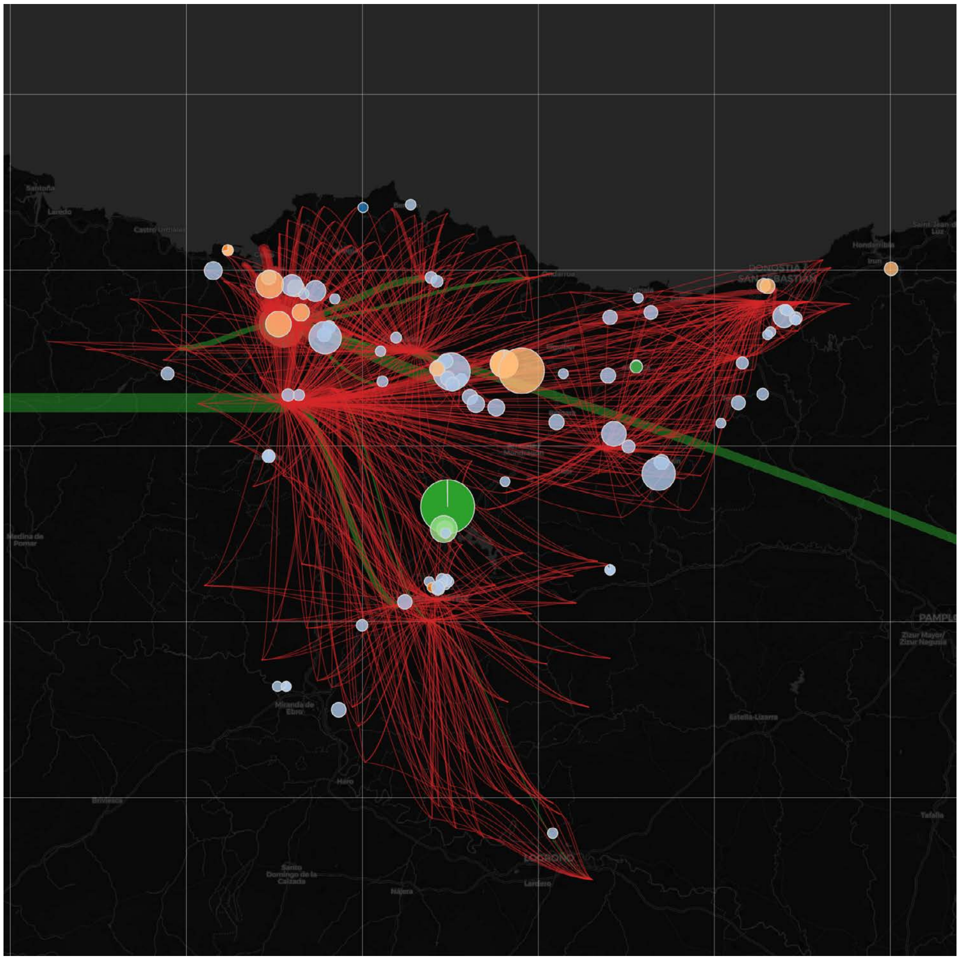
8.2.4 Hamburg, Germany

Waste type focus	Organic household waste
Data provider	Extrapolation based on a sample study of 22 housing types
Time	Aggregated per year
Space	Waste produced in the focus area; housing type level of detail
Process	Recycling/composting/incineration
Object	Detailed waste composition per housing type
Unit	Waste mass



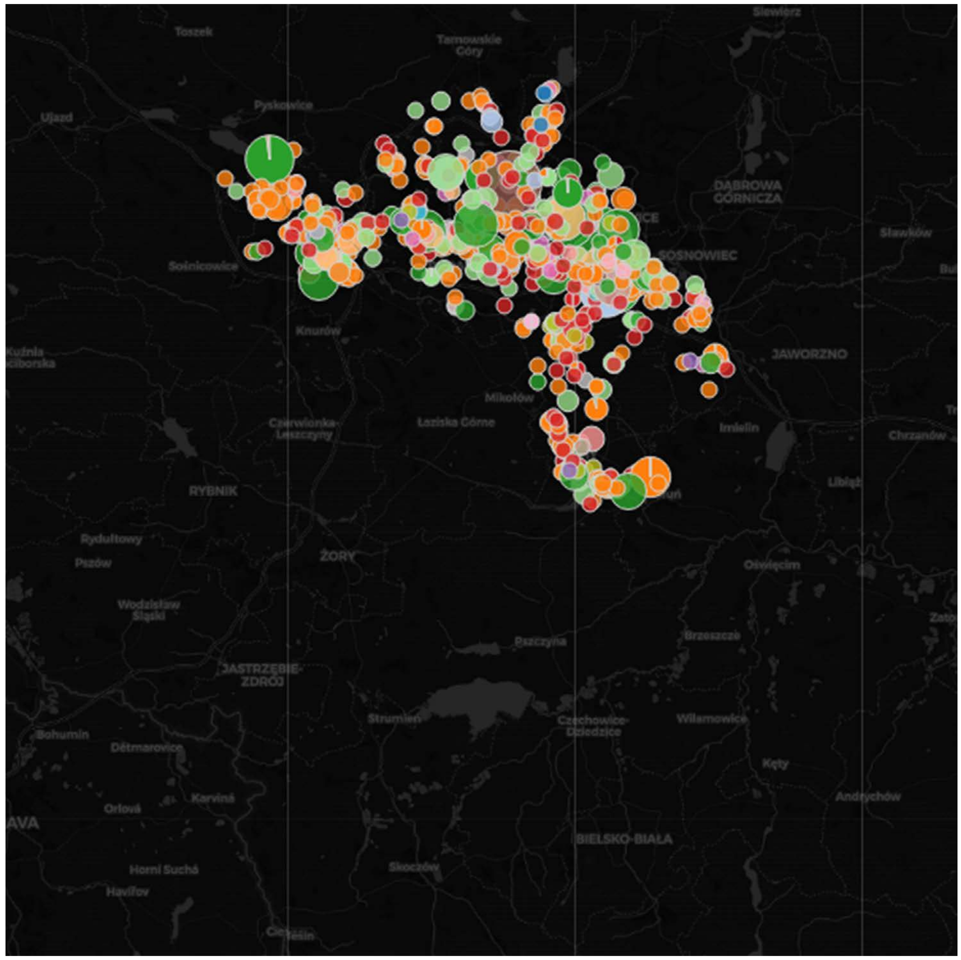
8.2.5 Pécs, Hungary

Waste type focus	Plastic and packaging waste, Organic waste
Data provider	Waste public service provider BIOKOM
Time	Aggregated per year
Space	Waste treated in the focus area; settlement/company address level of detail
Process	Economic activity according to the NACE code
Object	LoW codes
Unit	Waste mass



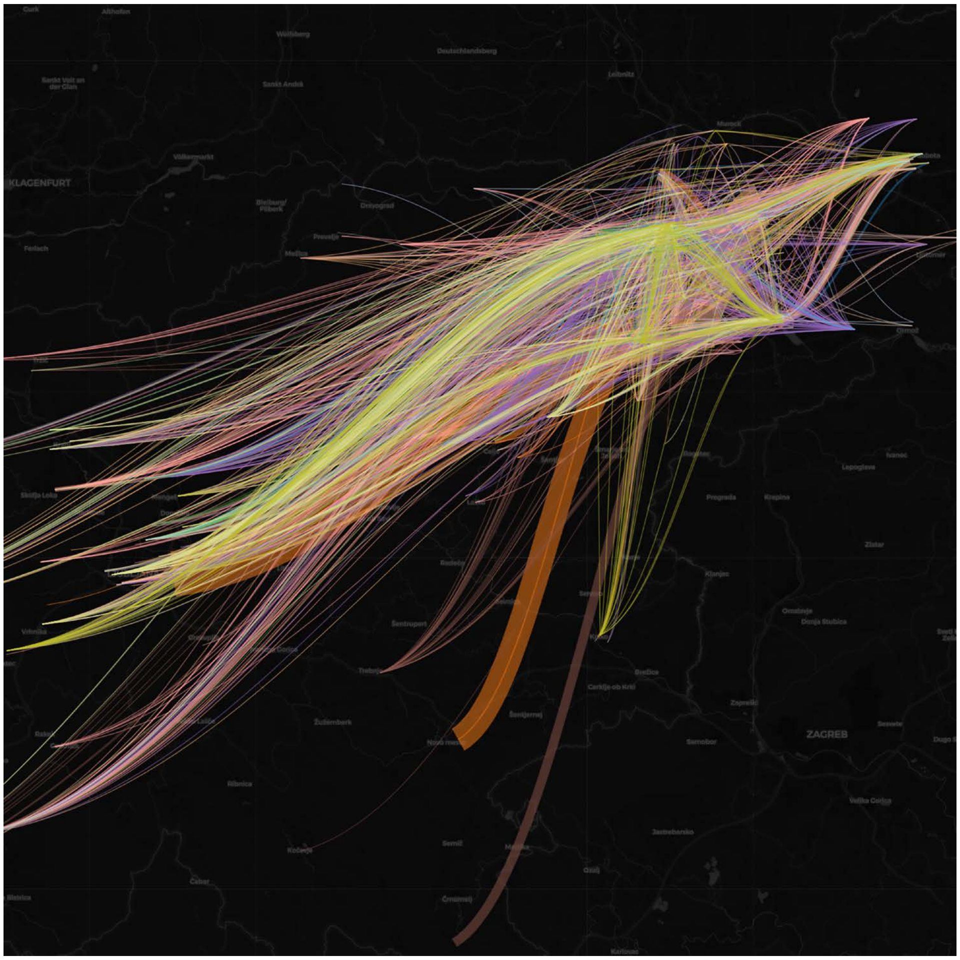
8.2.6 Bibao, Spain

Waste type focus	Construction and demolition waste
Data provider	The Environmental department of the Basque government
Time	Aggregated per year
Space	Waste produced and treated in the region; company address level of detail
Process	Economic activity according to the NACE code
Object	LoW codes
Unit	Waste mass



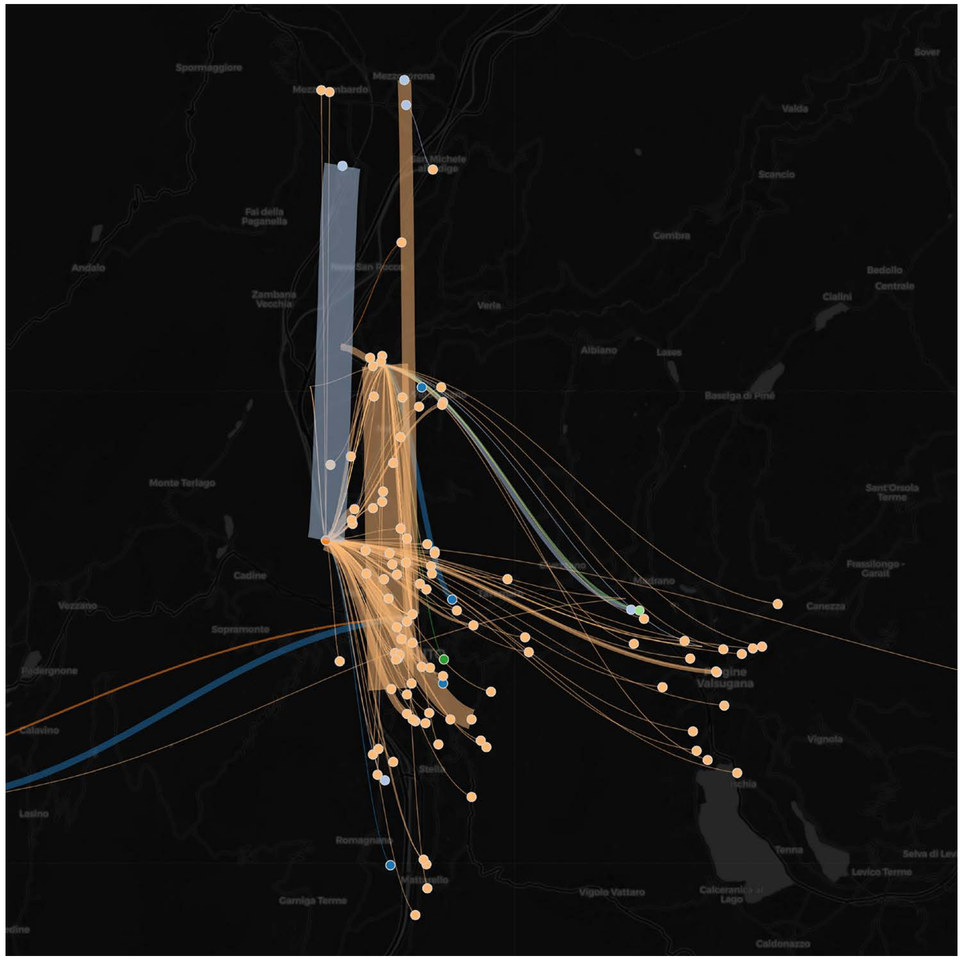
8.2.7 Katowice, Poland

Waste type focus	Construction and demolition waste
Data provider	Voivodeship reports on waste management
Time	Aggregated per year
Space	Waste produced in Silesia voivodeship; company address level of detail (no flow data available)
Process	Economic activity according to the NACE code
Object	LoW codes
Unit	Waste mass



8.2.8 Maribor, Slovenia

Waste type focus	Construction and demolition waste
Data provider	State register of the Environmental Agency of the Republic of Slovenia (ARSO)
Time	Aggregated per year
Space	Waste produced in Maribor municipality; company address level of detail
Process	Economic activity according to the NACE code
Object	LoW codes
Unit	Waste mass



8.2.9 Trento, Italy

Waste type focus	Construction and demolition waste
Data provider	ARPAT (Agenzia Regionale per la Protezione Ambientale in Trentino)
Time	Aggregated per year
Space	Waste produced in Trento city; company address level of detail
Process	Economic activity according to the NACE code
Object	LoW codes
Unit	Waste mass

8.2.10 Umag, Croatia

Waste type focus	Construction and demolition waste
Data provider	Croatian Agency for Environment and Nature (HAOP)
Time	Aggregated per year
Space	Waste produced in focus area; company address level of detail (no flows available)
Process	Economic activity according to the NACE code
Object	LoW codes
Unit	Waste mass

REFLECTION ON THE FINDINGS

The waste flow data sets from the different European regions are not directly comparable with the Dutch National Waste Registry, as they have been obtained from different institutions using different methods and queries. If certain regions have only chosen to use data extrapolated from a sample (e.g. Hamburg), it does not mean that industrial waste data set, comparable to the Dutch data set, does not exist in that region. At the same time, given that all regions have uploaded data already aggregated per year, nothing can be said about the granularity, coverage, and quality of the time dimension. The same applies to the unit dimension as the GDSE data structure only permits uploading waste mass; therefore, even if data in different units was available, it has not been used and reported for practical reasons. However, some of the patterns observed and discussed while analysing the Amsterdam case can be nevertheless observed in other regions, too.

First, it can be seen that the waste flows visualised on the maps always remain within national boundaries. It is not realistic that no waste is exported or imported from other countries. At the same time, it does not mean that there is no data available on the international flows of waste, as finding these data was not part of the exercise. However, the lack of international flows in every region, regardless of whether the data have been modelled, obtained from a national agency, or directly from waste treatment facilities, means that these data are typically kept separately from the general waste statistics. The question remains as to what extent international waste flows are included in reported waste statistics and circular economy monitoring indicators.

Second, detailed waste registries, very similar to the Dutch National Waste Registry, can be found in Slovenia and Italy. It cannot be concluded that the other countries and regions analysed do not have such registries as they might exist, but not be accessible for research purposes. The three comparable registries have also not been compared in detail to determine their differences. However, the observed similarities between them (detailed reporting of waste flows from waste producer to waste treatment facility using company addresses, use of LoW and NACE taxonomies, and reporting of the first applied waste treatment method only) suggest that these reporting fields are chosen because of an overarching supranational policy document.

The Waste Statistics Regulation evidently has a large impact on the choice of fields to be reported. This can be seen in the countries' choice to use LoW and NACE taxonomies to register waste type and economic activities. However, more regions have observed in their descriptions of the AS-MFA analysis that the LoW chapter, which shows which industry has produced waste, does not correspond to the NACE activity of the company that is considered a waste producer. For example, in the case of Maribor, where construction and demolition waste is analysed, researchers have observed that waste is registered by companies that invest in construction works; therefore, their NACE codes do not refer to construction-related services.

Another observation can be made regarding the lack of unified taxonomy to register waste processing methods. Although there is no large variety of processing methods used and most of them are described using the same terms (e.g. aerobic/anaerobic composting, incineration with energy recovery, landfilling), the biggest ambiguities can be observed in the usage of terms that indicate material recovery. Terms like “recycling”, “reuse as resource”, “separation” and others mostly indicate preparation for recycling and reuse. They are not enough to decide whether they can be considered as effectively closing the loop and to which extent the materials are again reused for different or the same purposes.

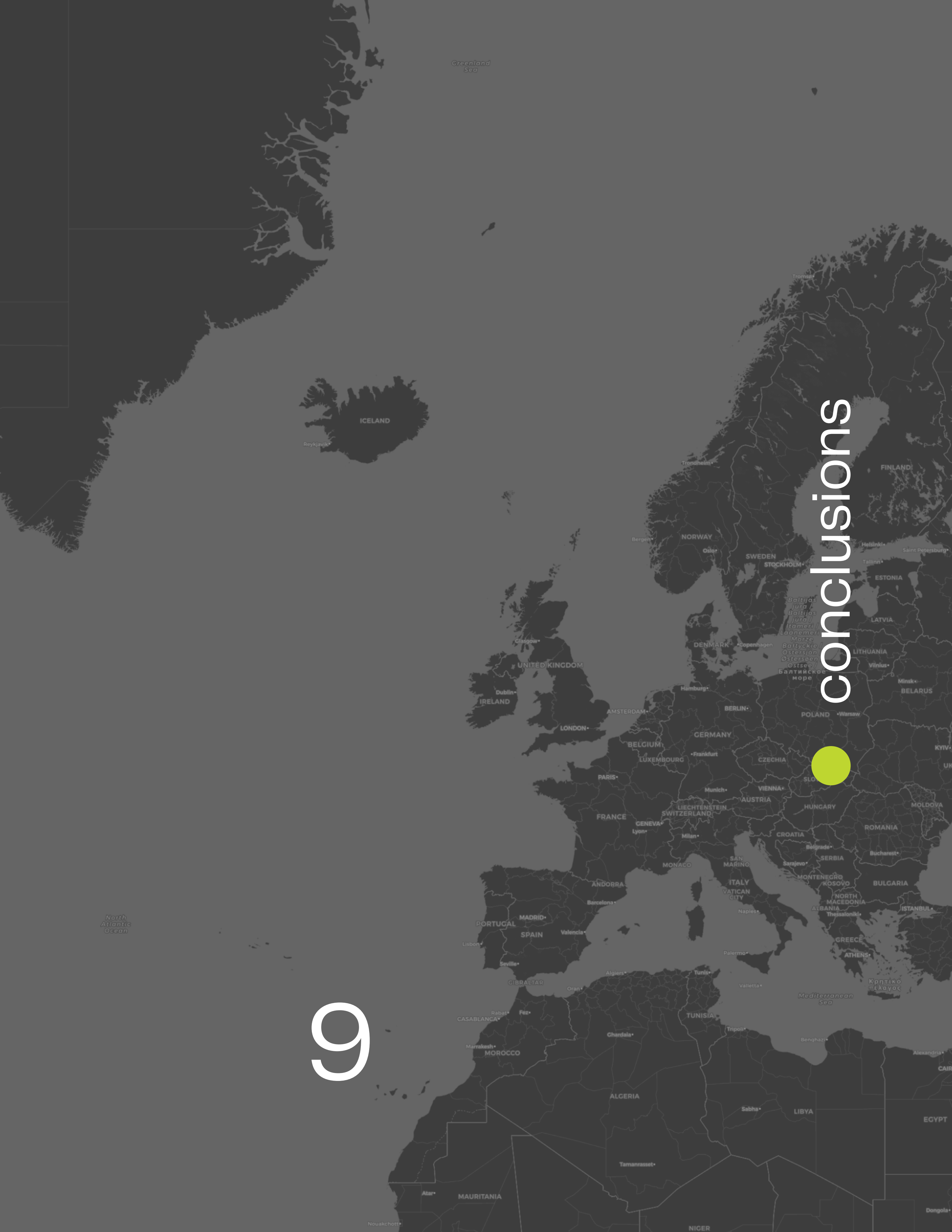
The similarities mentioned above between the different European regions prove that most observations regarding waste statistics suitability for circular economy monitoring are applicable beyond the Amsterdam Metropolitan Area. Furthermore, the European Waste Statistics Regulation and other related directives have a great influence on the national and local waste data collection choices. Therefore, the right changes made to these policies and related regulations have great potential to accelerate high-quality data collection that is able to support local decision-making in pursuit of a circular economy.

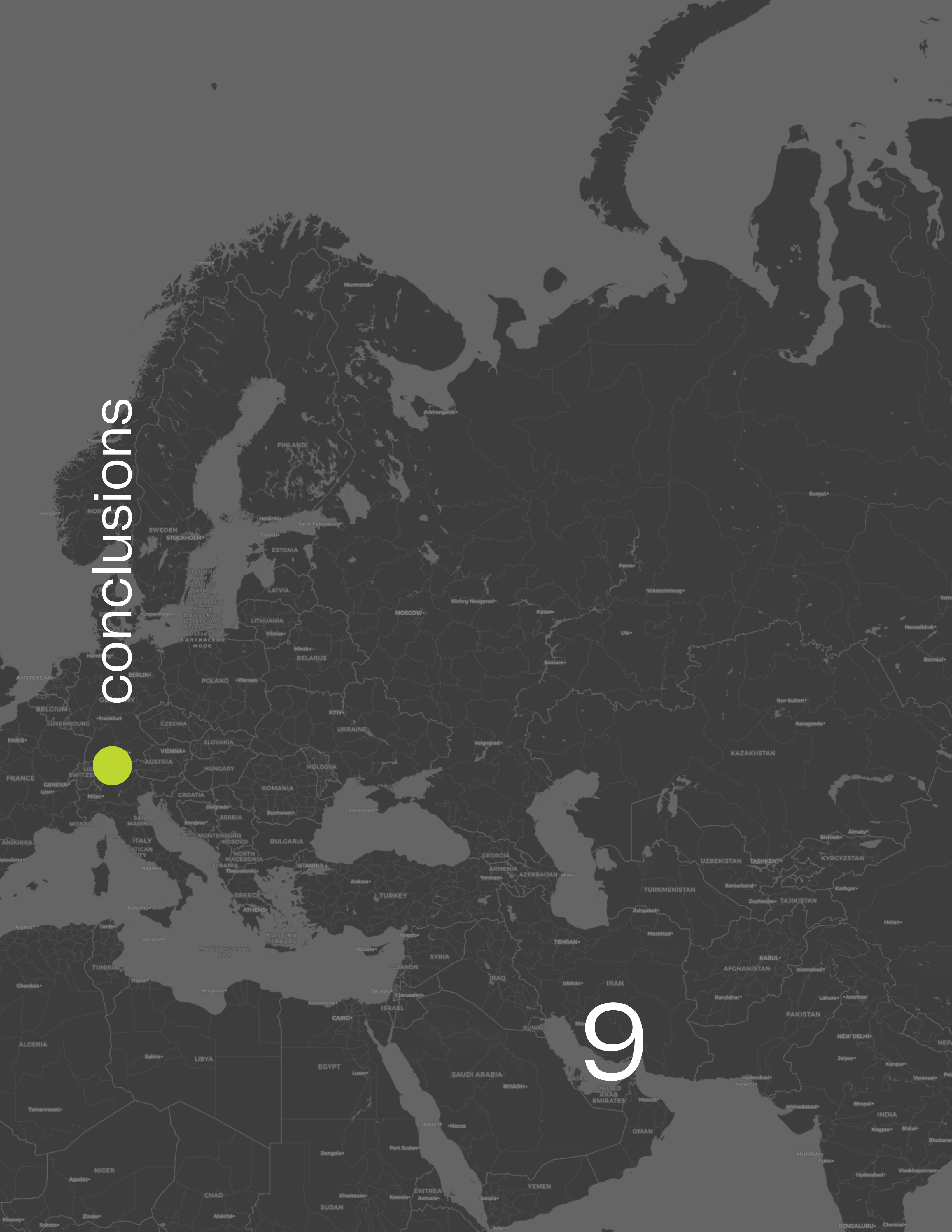
DATA AND SOFTWARE AVAILABILITY

All data sets used for this chapter have been accessed under the framework of two Horizon2020 projects: REPAiR and CINDERELA. The data that support the findings of this study are available from the data providers indicated in each subsection. Data are not available from the authors and can only be accessed directly from the providers.

9

conclusions





conclusions

9

CONCLUSIONS AND RECOMMENDATIONS

The five chapters of this thesis have explored different perspectives of why the European Waste Statistics is currently not providing adequate data for circular economy monitoring. Identifying existing institutional lock-ins and path dependencies has helped provide key recommendations to overcome barriers.

This chapter answers the main research question by describing the identified reasons and providing recommendations for reviewing current regulations. In addition, it reflects on the research methodology and discusses the direction of future research. Given that each chapter is based on answering a set of research subquestions, the answers to the subquestions are already provided in the conclusions of the corresponding chapters. To avoid repetition, the subquestions are not repeated in this chapter and only references to the previous answers are provided where necessary.

9.1 Why is European Waste Statistics not responding to the key challenge of data availability to advance the transition towards a circular economy?

The concept of a circular economy has a multitude of definitions of varying breadth and value range originating from academia, policy documents, media, and business communications. As long as there is no consensus on the exact meaning of the term, every official communication that mentions the circular economy provides an explanation of what the term is supposed to mean in that specific context. This research takes the position that the circular economy is rather an umbrella concept for diverse theories and divergent policy intentions, which encompasses the determination to reduce overall virgin resource extraction, material disposal, and externalities related to material flows and usage. Therefore, advancing the transition towards a circular economy within the scope of this research means the structured pursuit of the three simultaneous reductions.

The transition is supported by an increasing number of policy documents, ranging from a single company to supranational bodies. Along with setting targets, defining values, and outlining future actions, most of the policy documents express the intention for circular economy monitoring, which is meant to guide decision-making processes. However, several reports reviewing monitoring efforts conclude that one of the key challenges of monitoring lies in the availability of adequate data.

At the same time, large amounts of data are collected under the European Regulation (EC) 2150/2002 on Waste Statistics, which obliges member states to report statistical data on the generation and processing of waste. Although circular economy monitoring is concerned with a much wider spectrum of data than just waste statistics, and the regulation was created about a decade earlier than the first European circular economy policies appeared, waste data is a necessary monitoring component, which reveals the potential of closing material loops. However, policy makers at different administrative levels still lack guidance on which policies will make the greatest contributions to the set targets. Thus, so far, the European Waste Statistics falls short of responding to the key challenge and providing data for the circular economy monitoring, which is meant to advance the transition towards a circular economy.

To identify the reasons why data collected under the EWS framework do not sufficiently inform local and regional decision-making, the following steps have been taken followed by the described outcomes:

1. A theoretical framework for the significance assessment of decision impacts has been defined based on a literature review and further refined based on the exploration of available data and interviews with policy makers. The framework can be summarised as follows:

   Significance Assessment is part of a decision-making process that allows varying prioritisation of alternatives depending on the context in which a decision would be implemented or have effects. The magnitude of significance depends on the characteristics of an impact and the characteristics of the context in which that impact occurs. As these characteristics might vary along different dimensions, the magnitude of significance varies accordingly.

   The assessment of decision impacts means assessing whether a certain decision is bringing the situation closer to the predefined goals in comparison to the other possible decisions. The significance assessment in this case requires the definition of a goal or a target, and the significance magnitude is found in relation to the set goal considering distinct values in all relevant dimensions. In the case of circular economy monitoring, significance assessment should be carried out along these five dimensions: space, time, process, object, and unit.

To allow the significance assessment according to the defined framework, the data and models used to estimate the impact characteristics must have sufficient granularity, coverage, and values along the five dimensions. To qualify as "sufficient" they must be aligned with the granularity, coverage, and values of context importance. If the significance of decision impacts needs to be assessed, context importance is expressed as set goals and targets.

2. An ontology development process has been carried out to identify and resolve misalignments between monitoring expectations, theory, and available data. Amsterdam Circular Economy Monitor has been used as a case for ontology development. Four ontology development methods have been used to develop separate formal ontologies: user-centred, data-centred, tool-centred, and theory-centred. The user-centred ontology has captured the concepts future CEM users expect to find in the monitor. Data-centred ontology has recorded which concepts can be found in waste and product statistics. The tool-centred ontology has been based on a prototype application developed as a decision support environment to assess circular economy strategies. Finally, the theory-centred ontology has been based on the theory of socio-economic metabolism, which is deemed the most relevant domain for studying material flows and stocks.

   After merging and aligning the four ontologies into a single one, it has become apparent that although waste statistics do cover such core concepts as waste flows, processes, and actors, it lack semantic granularity to support interpretation of impacts, values, and potentials deemed important by the CEM users. The conclusions strongly relate to the theory of significance assessment, which requires that decision-makers be able to make judgments about impact importance along the different dimensions. If they set goals and targets using specific units or values in time and space or considering specific materials or processes, yet those units or values do not appear in the monitor, then the significance assessment will not be able to sufficiently inform the decision-making.

3. User requirements captured in the form of a formal ontology have been used to explore whether concepts that cannot be found directly in waste statistics can still be derived using data mapping. The mapping experiments have been carried out on the subset of the Dutch National Waste Registry used for EWS reporting. The subset has been limited to waste flows reported in 2018 and either produced or treated within the Amsterdam Metropolitan Area. Four mapping experiments have been carried out: geospatial mapping,

mapping waste producers to economic sectors, semantic mapping of waste content, and mapping waste transport needs to carbon emissions.

Mapping experiments have revealed that the Dutch National Waste Registry already has great potential to support decision-making. It provides very high granularity values in spatial and temporal dimensions, and occasionally granular values in object dimension. The registry has full national spatial coverage, temporal coverage since 2013, and covers most of the waste streams produced and treated in the Netherlands. It covers all legal waste processing methods, including temporary storage and transshipment.

At the same time, based on the targets, concepts and questions raised in the user interviews, the most prominent limitations that prevent a fair significance assessment are lack of international coverage, limited information on waste flow content in terms of material, and limited traceability of waste flow chains from their producer to an eventual (re)user. Additionally, significant confusion exists in the process dimension as the same terms are used interchangeably in policy documents to describe both processes and economic sectors (e.g. catering, demolition, logistics), often without specifying which of them is considered.

4. Finally, waste statistics from ten European regions spread across eight countries have been investigated to validate the transferability of research findings. First, it can be observed that each member country has different institutional arrangements for the collection, processing, and publication of waste data. Therefore, the data sources used are not directly comparable to each other. Moreover, data requirements have been based only on user interviews conducted in the Municipality of Amsterdam and not in the other regions. However, the main limitations in the waste statistics observed in the Dutch National Waste Registry (i.e. lack of international coverage, limited information on waste flow content in terms of material, and limited traceability of waste flow chains) have also been observed in the waste data sets from the other European regions.

As a result of the steps described above, seven reasons have been identified that cause the EWS not being sufficient to advance the transition towards a circular economy despite the large amounts of collected data and supranational reach and influence on waste data collection. The list of reasons is not exhaustive and resolving them does not guarantee success in circular economy monitoring. However, the identified reasons should serve as a starting point for discussions of the necessary changes to the EWS to support the desired transition. The reasons are divided into two groups: technical and conceptual, for which recommendations of political, scientific, and organisational nature are provided, as shown in Figure 9.1.

Figure 9.1. Summary of reasons why European Waste Statistics is not responding to the key challenge of data availability to advance the transition towards a circular economy and recommendations to overcome the mentioned barriers

BARRIERS

TECHNICAL

1. Path dependency
2. Limited data interoperability
3. Data incompleteness and fragmentation
4. Semantic asymmetry between raw resources, products and waste

CONCEPTUAL

5. The ambiguity of waste producer-responsibility
6. Conservative definition of waste
7. Insufficiently defined goals of the circular economy monitoring

RECOMMENDATIONS

POLITICAL

- Initiating EWSR amendment:
  - Expanding definition of waste
  - Expanding reporting obligations
- Ensuring financial support to national agencies

SCIENTIFIC

- Using and promoting open-source standards
- Aligning product/waste taxonomies
- Creating taxonomies for waste disposal roles and reasons

ORGANISATIONAL

- Providing access to expertise, guidelines and training
- Setting up international data infrastructure
- Enabling community involvement and feedback

REASON 1. Path dependency

The European Waste Statistics Regulation was first adopted by the European Parliament and the Council of the European Union in 2002, more than a decade before the European Commission had first mentioned the term circular economy in its policy documents. The regulation was not yet a result of the need to overcome material scarcity, but rather a result of the need to avoid harmful environmental impacts caused by waste disposal. The Regulation was revised for the last time in 2010, at the time when the circular economy had only started gaining traction in research and policy documents. It employs a broad definition of waste, framed as a burden rather than a commodity. Furthermore, the regulation is designed with supranational monitoring in mind, while the organisation of material flows in every city and region depends on the local conditions.

Being the remnant of the linear economy, the regulation uses terms, taxonomies, and definitions that have been selected to support a different purpose than what is expected from it at this point in time. As a widely adopted policy document and waste reporting standard, it has created path dependencies for the data collection infrastructures in each member country. Path dependencies still prevail over innovations in data collection.

RECOMMENDATION 1: Providing financial and expert support to institutions with the old regulatory legacy.

Overcoming path dependency first of all requires acknowledgement of its existence and of reluctance to commit to change due to cost implications. It requires a thorough investigation of the required changes, the identification of the most significant costs given the financial vulnerability of the different institutions across Europe, and adequate support to adopt the transformation. Changes in the European Waste Statistics Regulation will have implications on the national waste registries and their data infrastructures, but also on the companies that have to submit the waste reports and their technologies and operations. It must be acknowledged that path dependency exists not only in the technological realm, but also in social structures such as expertise, training, and internal policies, all of which require additional resources and guidance to be changed.

REASON 2. Limited data interoperability

It is not realistic to expect that all information necessary for circular economy monitoring could be provided by setting up a single data collection infrastructure. However, to support monitoring and decision-making, waste statistics should allow data enrichment using other data sources. When such enrichment is not possible, the waste data set cannot adequately support monitoring and decision-making.

The lack of data interoperability in waste statistics is due to two main underlying reasons. The first is caused by not using standard identifiers to describe unique objects. The data mapping experiment that has attempted to connect the Dutch National Waste Registry to the National Trade Registry has provided a quintessential example of low interoperability between two data sets that relate to the same real-world entities.

The second reason is related to the lack of semantic interoperability. Information fields such as waste processing methods, material content, transport methods, and economic sectors require the use of controlled vocabularies. However, currently used vocabularies lack meta-level definitions and therefore are not easily translatable to the vocabularies used in other relevant data sets, e.g. impact databases or vocabularies used in policy documents.

RECOMMENDATION 2: Creating an international standard for waste reporting that involves community feedback and participation

Data interoperability issues are typically solved by adopting (meta)data standards, controlled vocabularies, and shared object identifiers. These principles should be applied to record information on at least five dimensions of the circular economy monitoring: waste content, production and treatment processes, time, location, and measurement units. The amount of effort necessary to enhance the interoperability of the data sets is not equal in all dimensions.

The spatial dimension is already well covered by using standard addresses. The temporal dimension uses standard timestamps, although metadata is missing to determine whether provided time information relates to the reporting time, the waste transport time, or the disposal time. The same applies to measurement units. Although standard units are used, metadata on the exact measurement (or estimation) method is missing.

Waste content and processes already use controlled vocabularies; however, the vocabularies themselves are not aligned or standardised between relevant domains, countries, or institutions. A joint research effort is necessary to establish such vocabularies that would serve circular economy monitoring and decision support. Standards for describing waste content have already been suggested by the initiatives of material passports and material cadastres. Taxonomies and classifications of waste production and treatment processes are discussed within, among others, the domains of Industrial Symbiosis, Life Cycle Analysis, and Socio-Economic Metabolism.

Standardisation efforts initiated by a variety of institutions for different purposes could be combined into a single standard, comparable to that of INSPIRE[1] (Infrastructure for Spatial Information in the European Community), which aims to ensure that the spatial data infrastructures of the member states are compatible and can be used in a transboundary context. Including those standards in the EU Knowledge Graph [2] which provides Linked Open Data for the EU would also significantly reduce data fragmentation and reduce semantic ambiguities. Finally, the adopted standards should be based on an open and transparent discussion and allow community feedback and participation.

REASON 3. Data incompleteness and fragmentation

At this point, it is not known how well the European Waste Statistics represent the actual amount of waste produced or treated within the member states. However, since waste is a legal rather than a physical concept, most materials that are purposefully discarded by their owners are expected to end up in a formal waste management system and therefore be reported. However, apart from informal unreported waste movements, waste reporting itself is still rather fragmented.

First, EWS is limited to reporting a flow between the waste producer and the waste processor. However, in cases where the waste content is not destroyed or discarded in place, material flows extend beyond the waste processor to either secondary production, storage, or secondary waste treatment. These flows are only reported using waste statistics, as long as their content is legally considered waste. As soon as the status changes from waste to product, further tracking within the economy is not possible. This causes waste data to be insufficient for estimating which part of resources in the economy is made up of primary resources and which of

[1] https://inspire.ec.europa.eu/
[2] https://linkedopendata.eu/wiki/The_EU_Knowledge_Graph

secondary resources and therefore the actual contribution of circular economy strategies to the reduction of primary resource use.

Second, the tracking of waste on international borders within or outside the European Union is not integrated into national waste registries. Although the total amounts of waste exports and imports are known on a national level, the same level of detail as for flows within the national boundaries is not available or is not accessible. Data accessibility also plays a role in limiting data usability in circular economy monitoring. Due to the sensitivity of trade data sets, there are a number of mappings that are able to enrich the available data sets; however, they are not possible between the different countries.

RECOMMENDATION 3: Expanding reporting obligations without compromising data sensitivity

The first recommendation to overcome data incompleteness and fragmentation is related to the definition of waste, since waste statistics only require the reporting of substances that qualify as waste according to the official definition. As soon as materials are no longer discarded, but traded by their owners, their registration is no longer required for the sake of waste statistics. To allow detailed analysis of which waste types, locations, actors, and processes have the biggest untapped potential for the circular economy, waste statistics should require reporting of a subsequent flow after waste treatment. That is, waste reporting should include not only a flow of secondary waste but also a flow whose receiving party is using the former waste as a secondary resource.

The second recommendation relates to the separation of international waste trade statistics from national waste statistics. The current separation between the two means that detailed circular economy monitoring is only possible considering waste that is produced and stays within the national boundaries. To allow local or regional decision support, international waste trade registrations should meet the same data requirements as national waste data registries.

The implementation of both recommendations mentioned above is hindered by the sensitivity of the trade data. Detailed information about the trade of former waste products or trading partners may be considered commercially sensitive for the trade value, quantity, or unit value, which can be considered a proxy for the price. Therefore, before the recommendations can be implemented, a safe European circular economy data collection and sharing infrastructure should be considered, possibly based on distributed database technologies with encrypted end nodes and statistical querying capabilities.

REASON 4. Semantic asymmetry between raw resources, products, and waste

The unidirectional movement of resources in the linear economy has caused a unidirectional translation of controlled vocabularies used to register and report raw resources, products, and waste. It means that it is easier to determine what can be produced from a certain resource and what type of waste the product will end up as than to determine which products can be found in a specific waste and what resources have been used to produce them. The asymmetry can be clearly observed by simply comparing the number of elements in product and waste taxonomies. For example, the most widely used Harmonised Commodity Description and Coding System has about 5000 commodity groups, while the most detailed waste taxonomy, the European LoW, distinguishes about 800 waste types.

Due to the existing asymmetry, it is not possible to estimate with sufficient precision which types of waste should be targeted first to have the most significant impact on primary resource extraction. At the same time, estimation of the potential for circular economy in waste is hindered by the lack of correspondence between waste types and primary resources they can substitute.

RECOMMENDATION 4: Aligning taxonomies used to describe raw resources, products, and waste

Eliminating semantic asymmetry requires alignment of ontologies used to describe raw resources, products, and waste. Alignment efforts will require that new classes be introduced in downstream ontologies to adequately represent more detailed upstream ontologies. Intermediary ontologies of processes that change material status and characteristics, i.e., turn resources into products or products into waste, will have to be introduced as well. From a practical perspective, those ontologies should be introduced in a form of taxonomies that can be directly used in various registries and would substitute rather than supplementing the currently used ones.

It is important not only to restore semantic symmetry downward, starting from material extraction to their disposal, but also to create semantic loops that connect waste taxonomy to secondary resources. As these secondary resources do not always substitute the same raw resources from which they originate (that is, spoilt food used as animal feed does not substitute food intended for human consumption), it is more important to relate waste taxonomy directly to the processes for which waste can provide an alternative input.

This recommendation is strongly related to Recommendation No. 2, which suggests overcoming limited data interoperability by adopting standard vocabularies. The same additional recommendations regarding open standards and community participation in their creation apply to this recommendation as well.

REASON 5. The ambiguity of the responsibility of the waste producer

The experiment on mapping waste producers to their economic sectors has revealed that in the majority cases, there are (at least) two legal entities involved in the industrial waste disposal process: an entity that pays for and reports the disposal and an entity that carries out the process which causes waste. Regarding the definition of waste that includes the discarding entity as a deciding factor for waste status, the Regulation on Waste Statistics states that "waste should be attributed to the sector that generates it and gives it to the waste management sector or takes it directly to a landfill or treatment site". However, this rule is not consistent with the operational reality in which the process of waste generation and the process of transfer to the waste management sector are performed by different entities.

The existing ambiguity pertains to the ambivalence towards decision impacts. As long as it is not possible to determine which economic sectors require targeted circular economy policies to accelerate the transition, it is also not possible to estimate with sufficient certainty which economic sectors will be affected by the suggested policies. Therefore, the significance assessment of the discussed decisions misses the necessary values in the process and, accordingly, in spatial dimensions.

RECOMMENDATION 5: Creating taxonomies of different roles in waste discarding process and reasons of disposal

Resolving ambiguity requires a clear definition of what is expected from an actor who is considered responsible for waste production in a circular economy and during the transition period. The polluter-pays principle of the environmental law that currently applies to the responsibility for waste production also works in the opposite direction. The one who agrees to pay for the pollution is considered responsible, even if the actual responsibility is shared between multiple parties.

For example, in the case of demolition waste, the responsibility could be shared between as many parties as the building component producer, architect, builder, building owner, renovation architect, contractor, and demolisher. However, legally and, therefore, statistically, only one of the parties will be considered a waste producer.

The transition towards a circular economy adds an additional perspective to the focus on waste as a threat to the environment. In a circular economy, a waste producer is not only responsible for not polluting, but also for adapting its behaviour and operations to either prevent waste from happening or to ensure that waste can be reintroduced back into the economy. The role of statistics in this case is to provide support to policy decision-making and to ensure that the right economic sectors are stimulated to take up the responsibility and initiate changes.

As it is not always evident which party is responsible for the occurrence of waste (as in the above example of demolition waste), waste reports should rather include the reason why materials are discarded. For example, 'waste due to the expiration date of the product' places the responsibility on the final vendor, while 'waste due to the deprecation of the product' places the responsibility on the product designer. Reasons for waste occurrence are already partially included in the LoW taxonomy to describe waste due to production or maintenance processes, for example, '02 01 01 sludges from washing and cleaning", "03 03 10 fibre rejects, fiber-, filler- and coating-sludges from mechanical separation", "20 01 41 wastes from chimney sweeping". However, more granular reasoning would allow for a better estimate of who within the waste production chain is in a good position to act.

Another improvement to waste reporting is related to describing different roles in the waste discarding process and reporting relevant entities accordingly. Purchasing, task execution, administration, or brokerage functions are often performed by different entities, which should be registered as waste producers.

The taxonomies of the waste occurrence reasons and roles should be based on open standards, pursuit for interoperability, and community involvement as well.

REASON 6. Conservative definition of waste

Waste statistics is one of the most relevant data sources that can inform about the potential to close material loops and save primary resources. At the same time, prevented disposal into the environment reduces environmental damage. However, as long as the waste disposal rate is lower than the rate at which natural resources are extracted, waste is more a legal than a physical notion. Therefore, the concept of waste changes its meaning depending on the context and narrative in which it is discussed.

As a relic of the linear economy, the Regulation on Waste Statistics defines waste from the perspective of environmental protection rather than the potential of the circular economy. The current definition of waste requires the owner of the waste to actively discard it in the waste management system to report certain materials. However, if the main motivation for waste (material) reporting is not to prevent its disposal into the environment, but to estimate its best potential for being introduced back into the economy, the definition should include materials before they are effectively discarded. This would not exclude materials that fall under the current definition of waste, as environmental considerations and regulations remain relevant regardless of the transition.

RECOMMENDATION 6: Expanding the definition of waste to include underutilised resources before they are discarded in the waste management system

It has been established that preventing waste disposal and material value loss by reintroducing waste materials back into the economy is insufficient to achieve a fully circular economy and solve the challenge of material scarcity. Therefore, waste statistics can only reveal a limited part of the potential for the circular economy embedded in a given region. Besides strategies for general reduction in material consumption and its decoupling from economic growth, the untapped potential lies in the current material stocks. Large amounts of material stocks are dormant underutilised resources that are neither actively employed by their owners nor discarded as waste.

To allow the mining of secondary resources and reverse the approach of waste management as a post-factum problem, a separate part of waste statistics should be dedicated to the registration of underutilised material stocks. Investigating what hinders efficient use of already extracted resources, which economic sectors own them, how they are distributed spatially, and for how long they remain underutilised would provide decision support for policy making aimed at increasing material turnover and, in this way, preventing the extraction of new resources.

REASON 7. Insufficiently defined goals of the circular economy monitoring

The final reason why the EWS does not respond to the challenge of data availability to support the circular economy transition is not related to the EWS itself but to the unclear data requirements. It must be acknowledged that although circular economy monitoring is high on policy agendas, monitoring goals are still vaguely defined. Interviews with policy makers and future CEM users have revealed that they have highly varying expectations of the questions that a monitor should help answering. Although it is agreed that the CEM should support policy decision-making, the task is still rather abstract. During the course of this research, no concrete use cases have been encountered that would provide a clear formulation of alternative decisions related to circular economy strategies.

For as long as the circular economy concept is in a state of divergence and there is no consensus on goals and targets, all the more so on what exactly must be monitored, the challenge of data availability cannot be fully responded to. However, the presence of high-quality data can itself advance the paradigm divergence by answering contested queries, accelerating research, and pointing to the most significant risks.

RECOMMENDATION 7: Advancing the new CEAP-orientated amendment to the European Waste Statistics Regulation

The most important recommendation that can be given to the European Waste Statistics Regulation as a result of this research is that an amendment to the current regulation should be initiated as soon as possible. As proven by the earlier changes in the European regulations, the revision itself is a lengthy process that needs to go through many layers of institutional approval until it is published. After it is published on the supranational level, it needs to be further adopted by the member states and implemented in the national policies. This means that the time until high-quality data suitable for circular economy monitoring is available in most member states must be counted in years.

Previous recommendations have outlined several potential changes that should be considered for the amendment. They can be summarised as follows: financial, infrastructural and expertise-based support for overcoming path dependencies, revision of the waste definition, and, finally, development of new and alignment of currently used taxonomies based on open standards and community participation.

9.2 REFLECTION ON THE METHODOLOGY

A variety of methods have contributed to investigating the reasons why European Waste Statistics is not sufficiently responding to the data availability challenge. The applied methods have helped to identify seven reasons that currently hinder the effectiveness of EWS in circular economy monitoring and policy decision support. At the same time, this research has contributed new insights and innovative methods to the relevant research disciplines.

The necessary variance of significance assessment in five dimensions (time, space, object, process, and unit) brings a new perspective to the impact assessment discipline. To date, impact significance assessment has remained a single-dimensional exercise and has rarely been considered from both perspectives: context and impact magnitude at the same time.

Although ontology development has been used earlier for the purpose of aligning user needs and expectations with application development, to date this method has not been applied to the circular economy domain. Ontology development is also scarcely used to study socioeconomic metabolism and data applicability for urban metabolism research.

The most important interdisciplinary contribution connects policy and data sciences by demonstrating how path dependencies and lock-ins created by past policies influence data-based decision-making in a new sociopolitical context. This research has proven that limitations of data analysis cannot be handled strictly by data science and require a greater participation of disciplines and responsible institutions.

Waste mapping is not an innovative idea on its own; however, to date, it has not been executed on such a large scale as done by this research. Moreover, the comprehensive comparison of waste maps from several European countries has opened up a precedent for a new branch of resource geography, namely waste geography. Several GIS methods have been demonstrated to be applicable to waste geography studies, and a wide range of methods are still required to be developed in the future to fully explore and define this emerging discipline.

As not all aspects of the circular economy transition have been considered and investigated, the list of reasons discussed in the previous section is not exhaustive. The following paragraphs summarise research limitations and indicate future research directions.

9.2.1 Data needs beyond circular economy monitoring

This research has explored circular economy monitoring as the main data-intensive activity to advance the transition. However, high-quality waste data are not only necessary for monitoring and government decision support. Data from waste registries could be used directly in industrial symbiosis matching platforms, to grant material passports to secondary resources, in transparent supply chain management, etc. It has not been explored which data requirements exist for those applications, to what extent EWS is able to satisfy those requirements, and to what extent these other needs would collide with the provided recommendations.

Furthermore, it has not been investigated to what extent circular economy monitoring is effectively able to influence policy making and how far it helps to advance the transition. Therefore, future work on the topic should first aim to validate the assumption that monitoring is indeed the primary purpose that EWS should serve, while at the same time exploring alternative data uses and comparing their effectiveness in the transition.

9.2.2 Circular economy transition outside Amsterdam Metropolitan Area

It must be acknowledged that the Amsterdam Metropolitan Area is not a typical region and therefore findings based on this geographical area are not necessarily applicable in other EU regions.

First, due to its particularly voiced ambition to be a front-runner in the circular economy transition, Amsterdam is setting more ambitious and bold targets related to sustainable development than other European regions. It is part of the city's identity and, therefore, its development strategy, to prioritise low negative impact on the environment combined with a growing economy and social well-being. Other cities and regions are not motivated by the same ambitions and, therefore, are likely to have different priorities and more pragmatic targets related more to financial rather than ideological incentives for the circular economy transition.

Second, AMA is not an administrative region but a collaboration between municipalities with Amsterdam city as its economic and geographic centre. Although AMA has been chosen as the geographic extent for data analysis and data-related experiments, only policy makers from the municipality of Amsterdam have been interviewed for ontology development. Therefore, their questions and concerns do not reflect the concerns of the non-central, less urbanised municipalities that accommodate more industrial activities than the Amsterdam city.

To validate the data needs for circular economy monitoring that apply to the majority of local governments in Europe, interviews for the ontology development process should be repeated with policy makers from the regions that are not urban metropolitan centres, do not set more ambitious targets than those required by the European Commission, and are more engaged in industrial activities and, therefore, more dependent on the changes in resource and material flows.

9.2.3 Legal and economic aspects of waste ownership and reporting

Computational methods for the built environment have been used as the basis for the design of this research. This means that there has been a very limited analysis of the legal and policy documents that influence multiple aspects discussed in the conclusions. At the same time, only physical material flows have been considered to monitor the circular economy, while “monitoring economy” implies monitoring of price and value fluctuations, sales and logistics costs, return on investments, and several other economic indicators related to changing material flows and resource needs and distribution.

Before the suggested changes and recommendations can be implemented, an in-depth analysis is necessary to anticipate the legal (and, therefore, financial) consequences and barriers of changing the definition of waste, clarifying the ambiguity of waste ownership and responsibility for production, and increasing the transparency of waste trade.

9.2.4 Demonstration of the impact significance assessment in decision-making

The theoretical framework of the impact significance assessment has not been applied to a specific case, and the practical applicability of the theory developed based on the literature review has not been demonstrated. Although multiple examples have been provided throughout the thesis that illustrate the use of the framework, no comparative analysis has been performed with other impact significance assessment frameworks. To verify the usefulness of the framework in the decision-making process, future work should consider using this framework in comparison with other decision-making frameworks on multiple examples of policy decision alternatives related to the circular economy transition.

As the developed framework has only been used for theoretical guidance and is not implemented in a tool or applied to a specific case, the data requirements of the framework might not be fully accounted for and new requirements might arise. The requirements might be related to both the capacity of waste data to assess various decision impacts and to describe the characteristics of the context in which the decision is made.

9.2.5 Detailed assessment of related data sets

The research has been built on the detailed analysis of the Dutch National Waste Registry, which is the most comprehensive, however, not the only available data set related to waste flows in the Netherlands. Waste trade data are kept in a different registry and should be used in the future to supplement the analysis. Household waste, small company waste, and sorted mono streams were also excluded from the analysis, as they do not need to be reported. However, these types of waste are also relevant to the circular economy monitoring and therefore should be investigated.

Future research should consider data collection efforts to integrate all existing waste streams into a single monitoring system. This system would allow identifying overlaps and eliminating double counting that are currently likely to occur if waste statistics are integrated after a ggregation. Double counting caused by secondary waste being repeatedly reported to the Waste Registry is even likely within a single registry, and future work should focus on identifying and resolving this issue.

9.2.6 Circular Economy Monitor not as a decision support tool

Data requirements for a Circular Economy Monitor have been based on the assumption that CEM is primarily a decision support tool or a Spatial Decision Support System. Due to the lack of existing examples of active CEMs to date, no analysis has been done on other alternative uses and purposes of a monitoring application. Moreover, the application that has been used as a starting tool for the development of Amsterdam CEM, the Geodesign Decision Support Environment developed by the REPAiR project, is not a widely used tool but a prototype.

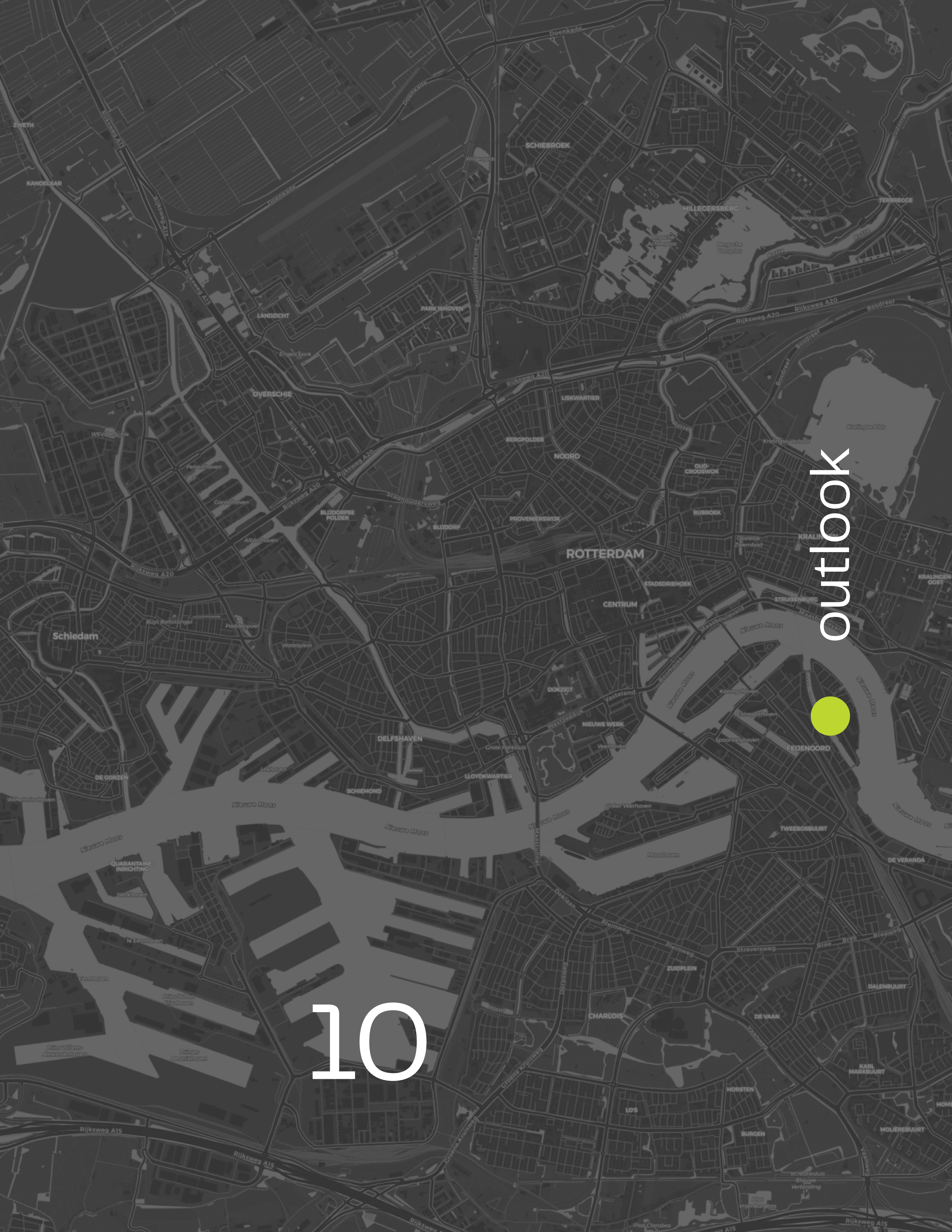
Therefore, future research should be done on the analysis and comparison of currently emerging CEMs in different countries, regions, and cities, their goals, use, development process, and data needs. Besides evaluating how a CEM is able to influence policy making, it should be examined how monitoring effectively influences public awareness, transparency, and communication related to the transition.

9.2.7 Practical implementation of the ontology in a digital tool

The ontology development process has been used as a method to identify misalignments between theory, data, and user expectations for monitoring. However, the final ontology has not been implemented in a monitoring tool to demonstrate its usefulness beyond the development process. Furthermore, although the merged ontology has been made public and, in theory, could be reused for other related purposes, to date it has not been used neither in different academic research nor in CEM development. Therefore, the data requirements captured in the ontology have not been verified in practise.

Related to the above, due to not having been implemented in a practical setting, the developed ontology has not been tested for its usability and ease of integration with existing tools, libraries and databases. It is probable that for practical reasons it would need to be further adapted to fit a widely used upper-level ontology, e.g. DOLCE , BFO, GFO, UFO, YAMATO or others.

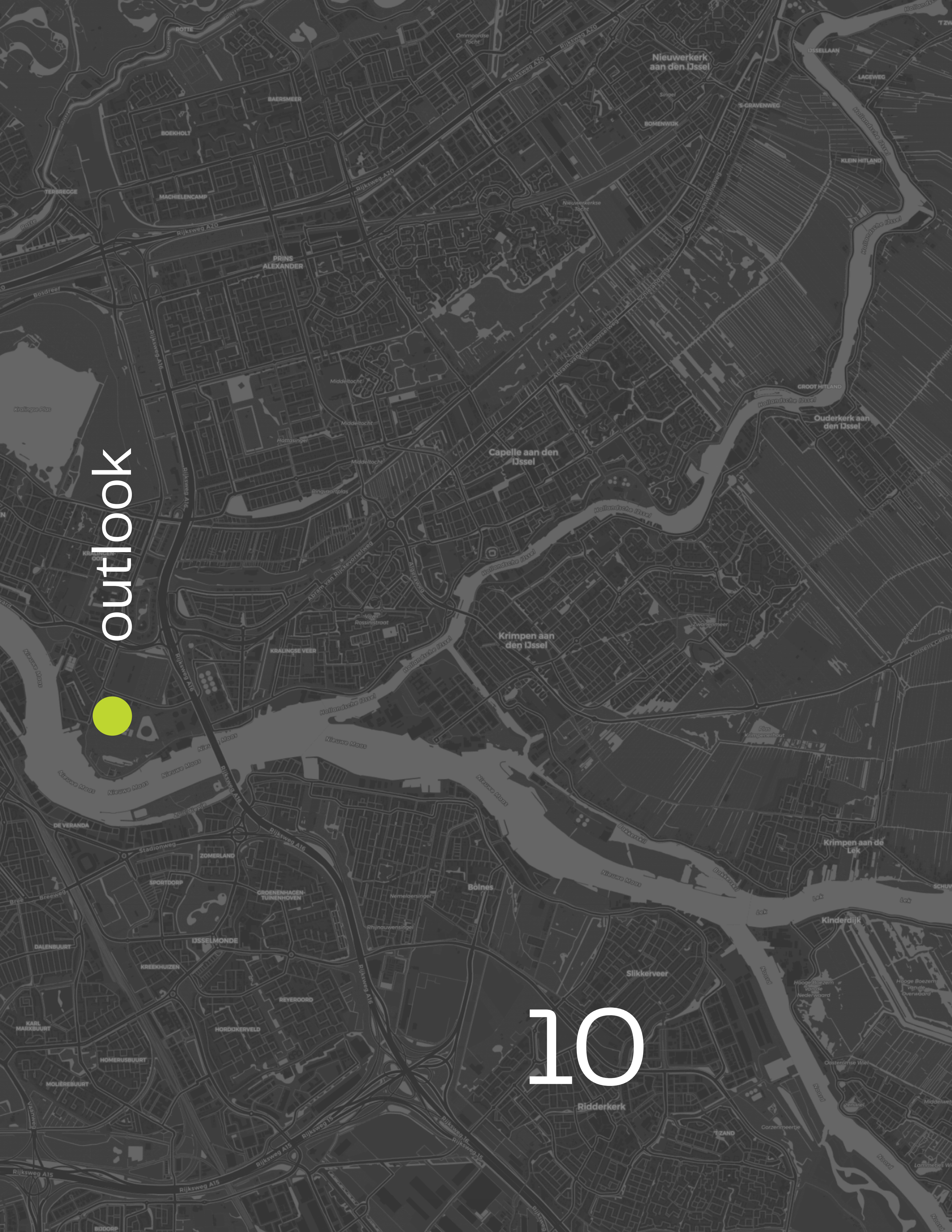
Finally, domain-specific user questions captured in user interviews only include primary queries. For example, a question about carbon emissions from material consumption in Amsterdam cannot be answered on the basis of waste statistics alone. To answer this question, new subqueries will have to be created that will include classes and properties not yet captured in the ontology. Therefore, the development of new and expansion of already used taxonomies, as pointed out in the recommendations for EWS improvement, needs to correspond not only to the data requirements already captured in the ontology but also to the technical requirements of the underlying subqueries. Examples of such subqueries include environmental impact assessment, interoperability with LCA databases, balancing out material flows on a systemic level, etc. Therefore, future work should unpack user questions by defining subqueries and including their semantic elements in the ontology.


ROTTERDAM
Schiedam
CENTRUM
NOORD
OVERSCHIE
SCHIEBROEK
HILLEGERSBERG
DELFSHAVEN
FEIJENOORD
CHARLOIS
Nieuwe Maas

10

outlook

10 outlook


Nieuwerkerk aan den IJssel
PRINS ALEXANDER
Capelle aan den IJssel
Ouderkerk aan den IJssel
Krimpen aan den IJssel
Krimpen aan de Lek
Kinderdijk
Bolnes
Slikkerveer
Ridderkerk

10.1 THE (NEW) ROLE OF STATISTICS IN THE CIRCULAR ECONOMY TRANSITION

Clearly, this research might seem as if it suggests that data-based policy making is the holy grail of the circular economy transition. It might read as if waste statistics, or statistics in general, is what defines the success of the transition, and having incomplete statistics means that we are not only blindly trying to hit the target but might also simply miss the fact that we hit it if it was not reflected in concrete numbers. This narrow point of view is not uncommon in technocratic understanding of progress and order, where data-based insights are presented as indisputable, apolitical, impartial truth.

On the contrary, the objective of this research was quite the opposite. The goal of this research was to demonstrate that looking at the world through the lens of statistics provides us with a limited image, and understanding its limitations is crucial to interpretation and judgment. Moreover, it is about manifesting that numerically based facts and objectivity are, after all, socially produced (Daston and Galison, 2007). The seven reasons presented in the conclusions of this research show how the public attitude towards waste influences the way waste statistics are collected and how statistical insights shape the measures taken to handle it. Construction and demolition waste might not receive as much attention if mass was not the chosen unit of comparison, and mixed waste could already have better treatment if only the name indicated what is in the mixture.

The results of this research do not request more data (although having more data increases the chances of having the right data), the results ask for more criticism, transparency, and approachability regarding existing data sources. Due to being handled by dedicated institutions, guarded by data sensitivity standards, and restricted by the costs of infrastructure and expertise, statistics appear to be a given. As a result, more effort is being spent in discussing methods to process, combine, and interpret the available data than methods to change the data collection.

Not acknowledging the limitations and subjectivity of data-based insights is probably even more dangerous to society than not having those insights. It creates the illusion of control, as everything that needs to be observed is already tracked and reported upon. Yet, just as Alexander and O'Hare (2020) have described five methods to cause waste to disappear, the same methods can be used to make circular economies appear. The danger lies in being assured by the numbers that the desired transition is happening while the actual transition occurs in registration and communication of data. The conclusions of this research suggest that to reduce oblivion beyond data and statistics, its role should change from being **means to control** to being **means to advance** the transition.

Open data initiatives are already widely promoted by the European Union (e.g., by European Open Data Portal[1]). However, openness goes beyond publishing open data sets. It includes information about data that is not publicly open but available with restricted access, openness of metadata, openness of taxonomies and vocabularies, etc. Furthermore, there is a need for openness regarding the usage of (open) data and transparency of decision-making. The science reproducibility movement currently includes only academic publications. However, a great number of computational methods are applied to governmental data sets for decision support purposes. Given that they have direct impact on societal changes, those computations should apply the same level of transparency and requirements for reproducibility as any scientific publication.

Another difference between statistics as control mechanisms and statistics as means of advancement lies in collaborative design and maintenance. Institutions responsible for data registration, management, and distribution to users should not be the only ones involved in the data collection design process. The data and statistics produced using the raw data need to follow user needs; therefore, not only the primary users, but also the subsequent users, must be involved in decision-making regarding the database schemas, taxonomies, units, and other characteristics of the collected data. Since it is not always possible to identify all data users in advance, feedback mechanisms should be set up for future users to request changes and updates. Technological solutions for community-based data curation, design, and maintenance already exist and are widely used by open-source communities. Therefore, the same practises should be used by public institutions at different levels of governance.

Finally, data collected from public resources should be given back to the public and, more importantly, to the community that has contributed to its collection. This does not mean that data sensitivity standards should be removed; in contrast, it means that data should be "as open as possible, as closed as necessary". In case of waste statistics, the waste registry data can be used not only for overviews and insights but also to practically promote circular solutions by matching supply and demand using the full overview of all available waste materials with all available secondary uses in a given area. This way instead of being a bureaucratic task, waste reporting brings mutual benefits to both the reporting and the controlling party at the same time motivating provision of high quality data.

[1] `https://data.europa.eu/en`

10.2 GEOFLUXUS: ENTREPRENEURIAL ACTIVISM

At the beginning of 2020 this research received commercial interest from one of the biggest startup accelerator programmes Techstars. Since 2006, the programme has reached a combined market capitalisation of $18.2bn USD and by 2019 has already helped launch more than 1600 companies into the market. Fewer than 1% of the over 17,000 applicants are accepted yearly.

To realise the potential of research commercialisation, Techstars provided an investment of $120 000 USD upon which geoFluxus was created by me and a fellow PhD candidate Arnout Sabbe. In 2022 geoFluxus is a team of seven whose mission is to get rid of the concept of waste. We undertake this mission by serving two web-applications, one of them for companies, the other one for governments. Our "Waste Profile" provides companies with all existing alternatives for their waste and suggests the most environmentally and financially friendly solutions. Our "Circular Economy Monitor" provides an overview of all waste, its production and treatment patterns and insights into the potential for a circular economy for local governments at different administrative levels.

Both products are based on the Dutch National Waste Registry and use algorithms and methods developed during this PhD research, specifically, ontology development and semantic querying discussed in Chapter 5, entity linkage discussed in Chapter 6, semantic mapping and carbon emission assessment discussed in chapter 7, and mapping and visualisation methods that have not been included in the thesis (Figure 10.1).

In its still short existence, geoFluxus has attracted acclaim for green innovation by winning the EU Datathon Green Deal Challenge (2020), the EIC accelerator excellence award (2020), being selected for the Dutch trade mission to New York (2019), being runner-up at the EIT Climate-KIC National Finals (2019), and selected as the Top 100 most promising Software-as-a-Service companies in the Netherlands (2022). Furthermore, regional circular economy analysis produced by geoFluxus platforms is currently being used in preparation of the upcoming Integral Circular Economy Report (ICER, NL: *Integrale Circulaire Economie Rapportage*) to be published in 2023.

Being an academic spin-off geoFluxus operates in the space where activism and business enterprise converge. We are committed to create the highest positive social and environmental impact remaining a business entity that operates and competes on capitalist markets chasing innovation, profitability and expansion. This way we ensure that all knowledge produced during the years of research does

Figure 10.1. geoFluxus is using waste flow visualisation methods and algorithms developed during this research.

not end up in academic archives but enhances products which solve real world problems.

At the same time, we work closely with governments and use data sets that are not available to the public. Our vision is to bridge the gap between administrative burdens and societal and business benefits by giving the data back to its producers. This way data producers are also motivated to provide higher quality waste reports as a warranty for higher quality waste solutions.

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summary

summary

SUMMARY (EN)

More than half a century ago, Kenneth Boulding conceptualised Earth as "a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution". Since then, the circular economy has been seen as a new paradigm that solves two major problems in one shot: the burden of waste and the scarcity of resources. Since 2015 in Europe, the transition has been supported by an increasing number of policy documents affecting us all: from consumers and small and medium-sized enterprises, to multinationals and supranational institutions. These documents stress the importance of circular economy monitoring, not only to track progress and priorities in terms of set goals, but also to assess the impact of decision-making processes.

At the same time, several reports reviewing monitoring efforts conclude that one of the key challenges lies in the availability of adequate data. Although circular economy monitoring is concerned with a much wider spectrum of data than just waste statistics, waste-related data is a necessary monitoring component which reveals the potential of closing material loops. Large amounts of this data are collected under the European Regulation (EC) 2150/2002 on Waste Statistics, which obliges member states to report to the European Commission statistical data on waste generation and processing.

In this context, the research asks why European Waste Statistics is not responding to the key challenge of data availability to advance the transition towards a circular economy. The research is based on the case of the Amsterdam Metropolitan Area using data from the Waste Registry Division of the Dutch Ministry of Infrastructure and Public Works (NL: *Landelijk Meldpunt Afvalstoffen (LMA)*). The research revolves around three topics: assessing the significance of policy decision impacts, the semantics of waste and circular economy, and evaluating the adequacy of waste statistics to circular economy monitoring.

First, a theoretical framework for impact significance assessment is developed based on the review of related literature. According to the developed framework, Significance Assessment is part of a decision-making process that allows the prioritisation of alternatives depending on both the context in which a decision would be implemented or has effects, and the magnitude of the effects themselves.

This framework is suggested as the basis for a circular economy monitor.

Monitoring requirements are further defined using a formal ontology development method. Following this method, prospective monitor users within the municipality of Amsterdam are interviewed and the questions important to them are compared with the available data, tools and the theory of socio-economic metabolism. This process helps to identify misalignments between monitoring expectations, theory, and data quality. The process has exposed that although waste statistics cover the core concepts of resource flows, they primarily lack semantic granularity and coverage to support the interpretation of waste-related impacts, values, and circularity potentials.

Finally, an in-depth investigation is conducted on the Dutch National Waste Registry which follows the guidelines of the European Waste Statistics. Waste registry data is explored with the help of four queries related to the goals of circular economy monitoring. Although data mapping experiments reveal several limitations present in waste data collection and a number of gaps present in circular economy theory, innovative computational methods used for the experiments demonstrate how the data is already able to support significant insights into the current waste system and its potential.

In conclusion, seven reasons are formulated that act as barriers to the effectiveness of EWS in circular economy monitoring. Each of the reasons is followed by concrete recommendations for the next amendment to the European Waste Statistics Regulation. Financial, infrastructure and expertise-based support is recommended to overcome linear-economy-induced path dependencies. A revision of the waste definition is suggested to overcome semantic ambiguities and fragmentation of waste statistics. Finally, the development of new and alignment of currently used taxonomies based on open standards and community involvement is recommended to acknowledge and employ the observation that numerically based facts and objectivity are, after all, socially produced.

SAMENVATTING (NL)

Meer dan 50 jaar geleden bedacht Kenneth Boulding de aarde als "een solitair ruimteschip, zonder eindeloze reserves van wat dan ook, noch voor extractie, noch voor vervuiling". Sindsdien wordt de circulaire economie gezien als een nieuw paradigma dat twee grote problemen in één keer oplost: het probleem van afval en de schaarste aan grondstoffen. Sinds 2015 wordt deze transitie in Europa ondersteund door een toenemend aantal beleidsdocumenten die ons allen van belang zijn, van consumenten en ondernemers, tot multinationals en internationale instellingen. Al deze documenten spreken over het belang van monitoring van de circulaire economie, om zo besluitvormingsprocessen te sturen.

In al deze verschillende documenten en rapporten, wordt geconcludeerd dat een van de belangrijkste uitdagingen voor het monitoren van de circulaire economie de beschikbaarheid van kwalitatieve data is. Hoewel het monitoren van de circulaire economie betrekking heeft op veel meer dan enkel afvaldata, zijn afvalgerelateerde gegevens een essentieel monitoring onderdeel dat het potentieel van het sluiten van materiaalkringlopen blootlegt. Grote hoeveelheden van deze gegevens worden verzameld in het kader van de Europese Verordening (EG) 2150/2002 inzake afvalstatistieken, die de lidstaten verplicht om statistische gegevens over afvalproductie en -verwerking aan de Europese Commissie te rapporteren.

In deze context gaat het onderzoek in op waarom Europese afvaldata bieden geen antwoord op de belangrijkste uitdaging van de beschikbaarheid van data om de overgang naar een circulaire economie te bevorderen. Het onderzoek is gebaseerd op de casus van de Metropoolregio Amsterdam, gebruikmakend van data van het Landelijk Meldpunt Afvalstoffen (LMA). Het onderzoek draait om drie onderwerpen: het beoordelen van de betekenis of belang van de gevolgen van beleidsbeslissingen, de semantiek van afval en de circulaire economie, en het evalueren van de geschiktheid van afvaldata voor monitoring van de circulaire economie.

Eerst wordt een theoretisch raamwerk voor de impact beoordeling ontwikkeld op basis van het bestuderen van de wetenschappelijke literatuur. Volgens het ontwikkelde raamwerk maakt 'Impact beoordeling' deel uit van een besluitvormingsproces dat prioritering van alternatieven mogelijk maakt, afhankelijk van

zowel de context waarin een beslissing zou worden uitgevoerd of effecten zou hebben, als de omvang van de effecten zelf. Dit raamwerk wordt voorgesteld als basis voor een monitor circulaire economie.

Monitoring vereisten worden verder gedefinieerd met behulp van een formele ontologie-ontwikkelingsmethode. Volgens deze methode worden aspirant-monitor gebruikers binnen de gemeente Amsterdam geïnterviewd en worden de voor hen belangrijke vragen vergeleken met de beschikbare data, tools en de theorie van het sociaal-economisch metabolisme. Dit proces helpt bij het identificeren van verschillen tussen monitoring verwachtingen, theorie en datakwaliteit. Het onderzoek toont aan dat hoewel afvaldata de kernconcepten van grondstoffenstromen dekken, ze in de eerste plaats semantische granulariteit en dekking missen om de interpretatie van afvalgerelateerde effecten, waarden en circulariteit potentieel te ondersteunen.

Tenslotte wordt een diepgaand onderzoek uitgevoerd naar het Landelijk Meldpunt Afvalstoffen die de richtlijnen van de Europese Afvalstoffen Statistiek volgt. De data van het LMA worden verkend met behulp van vier vragen die verband houden met de doelstellingen van de monitoring. Hoewel deze data mapping-experimenten verschillende beperkingen aan het licht brengen die aanwezig zijn bij het verzamelen van afval data en een aantal lacunes in de theorie van de circulaire economie blootleggen, tonen de innovatieve digitaal methoden die voor de experimenten zijn gebruikt aan hoe de data al in staat zijn om significante inzichten in het huidige afvalsysteem en haar potentieel te visualiseren .

Tot slot worden zeven redenen geformuleerd die de effectiviteit van de Europese Afvalstoffen Statistiek bij monitoring van de circulaire economie in de weg staan. Elk van de redenen wordt gevolgd door concrete aanbevelingen voor de volgende wijziging van de Europese verordening afvalstoffen statistiek. Financiële, infrastructuur- en expertise gebaseerde ondersteuning wordt aanbevolen om de door lineaire economie veroorzaakte pad afhankelijkheden te overwinnen. Een herziening van de definitie van afval wordt voorgesteld om semantische dubbelzinnigheden en versnippering van afvaldata weg te nemen. Ten slotte wordt de ontwikkeling van nieuwe en afstemming van momenteel gebruikte taxonomieën op basis van open standaarden en betrokkenheid van de maatschappij aanbevolen om de observatie te erkennen en te gebruiken dat numeriek gebaseerde feiten en objectiviteit uiteindelijk sociaal geproduceerd zijn.

SANTRAUKA (LT)

Daugiau nei prieš penkiasdešimtmetį Kenneth Boulding apbibūdino Žemės planetą esant "vienišu erdvėlaiviu, neturinčiu begalinių rezervuarų, nei išgauti medžiagoms, nei talpinti taršai". Nuo tada žiedinė ekonomika laikoma nauja paradigma galinčia išspręsti dvi esmines problemas vienu metu: tiek atliekų naštą, tiek išteklių trūkumą. Europos Sąjungoje nuo 2015 metų perėjimas nuo linijinės prie žiedinės ekonomikos remiamas nuolatos augančiu kiekiu teisės aktų, aprėpiančių tiek pavienes kompanijas, tiek viršnacionalines įstaigas. Šiuose aktuose nuolatos reiškiami ryžtingi ketinimai sukurti žiedinės ekonomikos monitoringą ir šiais stebėjimais paremti tolimesnius sprendimų priėmimo procesus.

Tuo pat metu dauguma monitoringo ataskaitų konstatuoja, kad vienas didžiausių iššūkių yra stebėjimui tinkamų duomenų trūkumas. Nors žiedinės ekonomikos monitoringas aprepia daug platesnį duomenų spektrą nei su atliekomis susiję statistiniai duomenys, skaitmeniniai faktai apie atliekų susidarymą yra būtini norint nustatyti išteklių pernaudojimo potencialą. Dideli tokių duomenų kiekiai yra renkami pagal Europos Parlamento ir Tarybos Reglamentą (EB) Nr. 2150/2002 dėl atliekų statistikos, kuris įpareigoja visas valstybes nares rinkti ir perduoti Europos Komisijai statistinius duomenis susijusius su atliekų susidarymu ir tvarkymu.

Šiame kontekste šio darbo tikslas yra ištirti kodėl duomenys renkami Europos Atliekų Statistikos pagrindu yra vis dėlto nepakankami paspartinti perėjimui prie žiedinės ekonomikos. Šis tyrimas remiasi Amsterdamo metropolinės zonos duomenimis, kuriuos renka Nyderlandų Infrastruktūros ir Viešųjų Darbų Ministerijos Atliekų Duomenų Registro skyrius (NL: *Landelijk Meldpunt Afvalstoffen (LMA)*). Šiame darbe tiriamos trys pagrindinės temos: pirma, su žiedine ekonomika susijusių politinių sprendimų reikšmingumo vertinimas; antra, atliekų ir žiedinės ekonomikos semantika; ir trečia, atliekų statistikos tinkamumas žiedinės ekonomikos stebėsenai.

Pirma, remiantis literatūros apžalga išvystomas teorinis modelis politinės veiklos sprendimų reikšmingumo vertinimui. Pagal šį modelį Reikšmingumo Vertinimas turi būti dalimi sprendimų priėmimo proceso, kurios dėka būtų galima prioritizuoti nuosprendžius, įvertinant tiek kontekstą, kuriame sprendimas būtų įgyvenditas arba kuriame jis turėtų padarinių, tiek pačių padarinių mastą.

Reikšmingumo Vertinimo modelis siūlomas kaip pagrindas žiedinės ekonomikos monitoringui.

Monitoringo reikalavimai toliau apibrėžiami naudojant formaliosios ontologijos sudarymo metodiką. Pagal ją apklausiami būsimi monitoringo sistemos naudotojai Amsterdamo savivaldybėje ir jiems svarbūs klausimai palyginami su turimais duomenimis, skaitmeniniais įrankiais ir socio-ekonominio metabolizmo teorija. Šis procesas padeda identifikuoti semantinius neatitikimus tarp monitoringo lūkesčių, teorinių žinių ir turimų duomenų. Ontologijos sudarymas atskleidė, kad nors atliekų statistika ir apima pagrindines atliekų srautų sąvokas, jai pirmiausia trūksta semantinio detalumo ir pakankamos aprėpties. Dėl šių trūkumų neįmanoma pakankamai gerai nustatyti atliekų sistemos poveikio masto, vertės ir neišnaudoto potencialo.

Galiausiai atliekama išsami Nyderlandų Nacionalinio Atliekų Duomenų Registro, atitinkančio Europos Atliekų Statistikos reikalvimus, analizė. Atliekų duomenų registro duomenys nagrinėjami naudojant keturis skaitmeninius eksperimentus, susijusius su monitoringo tikslais. Nors duomenų kartografavimo eksperimentų metu išryškėja tiek atliekų duomenų rinkimo ribotumai, tiek spragos egzistuojančias pačioje žiedinės ekonomikos teorijoje, eksperimentams atlikti siūlomi skaitmeniniai metodai, kuriuos taikant jau dabar galimos reikšmingos įžvalgos į dabartinę atliekų tvarkymo sistemą ir jos potencialą.

Apibendrinant suformuluotos septynios priežastys, trukdančios atliekų statistikos veiksmingumui siekiant stebėti žiedinę ekonomiką. Po kiekvienos iš priežasčių pateikiamos konkrečios rekomendacijos būsimiems Europos Atliekų Statistikos Reglamento pakeitimams. Norint įveikti linijinės ekonomikos paveldimumą ir tolimesnį plėtojimą, rekomenduojama teikti finansinę, infrastruktūros ir žiniomis paremtą paramą su atliekų statistika dirbančioms institucijoms. Kad būtų pašalintos semantinės dviprasmybės ir atliekų statistikos fragmentiškumas, siūloma peržiūrėti patį atliekų apibrėžimą. Taip pat rekomenduojama į naujų taksnonomijų kūrimą ir senųjų vienodinimą įtraukti jas naudojančias bendruomenes ir naudoti atviruosius standartus, taip pripažįstant ir panaudojant pastebėjimą, kad statistika grindžiami faktai ir objektyvumas vistik turi gilias socialines šaknis.

CURRICULUM VITAE

Rusnė Šilerytė (1989) was born in Klaipėda, Lithuania. She has studied BSc in Architecture at Vilnius Gediminas Technical University (Lithuania) and University of Florence (Italy). For a year, she has worked as a junior architect in PILIS Design Studio in Klaipėda.

In 2015, she obtained her MSc in Geomatics from the Delft University of Technology (The Netherlands). During her MSc studies, she has published two conference papers with the Association of Geographic Information Laboratories in Europe. As part of her studies, she has also completed an internship at CycloMedia, a Dutch company specialising in the large-scale and systematic visualisation of environments based on 360° panoramic photographs.

After her studies she has continued working at the Delft University of Technology in Design Informatics groups under the supervision of Dr. Pirouz Nourian and Prof. dr. Michela Turrin. Her work on supporting exploration of design alternatives using multivariate analysis algorithms was awarded the Best Paper Award at the annual SimAUD conference in 2016. At the beginning of the same year she has won a research grant to continue her work at the University of Lisbon, Design and Computation Group under the supervision of Prof. dr. Jose Beirao.

In 2016, Rusnė returned to Delft to continue her research as a Ph.D. candidate under the supervision of Prof. dr. Arjan van Timmeren and Dr. Alexander Wandl at the Chair of Environmental Technology and Design. Her research has contributed to two H2020 projects related to advacing the transition towards the circular economy. During her PhD she has been also involved in teaching a Geomatics MSc course 3D Modelling for the Built Environment.

Since 2020 Rusne has been a co-founder and CTO of geoFluxus, a spin-off company based on Ph.D. research of her and her co-founder Arnout Sabbe. geoFluxus helps companies and governments find the quickest, cheapest and most circular solutions for their waste using mandatory waste reports.

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ISBN/EAN 978-94-6366-655-8

Published by TU Delft Open

Printed by Jubels BV in Amsterdam

On paper 120gsm Arena Rough / Natural

Cover designed by the author. The image shows 1000 largest construction and demolition waste flows (EWC Chapter 17) that have originated in Amsterdam Metropolitan Area in 2018

An electronic version of this dissertation is available at
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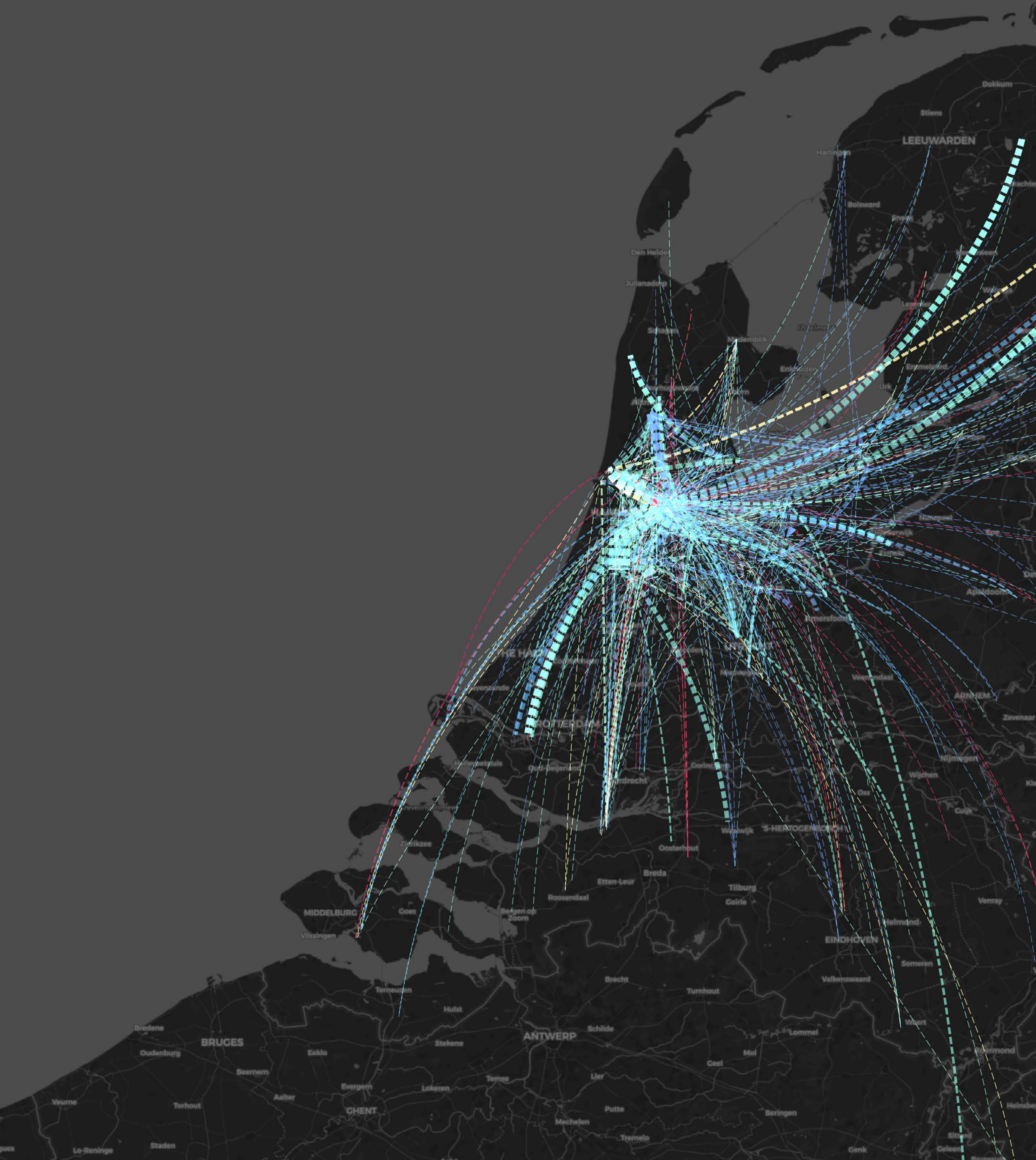
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