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

Citation for the original published paper (version of record):
Cohen, J., Gil, J. (2021). An entity-relationship model of the flow of waste and resources in city-regions: Improving
knowledge management for the circular economy. Resources, Conservation and Recycling Advances, 12. http://dx.doi.org/10.1016/j.rcradv.2021.200058

12 (2021) 200058

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

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

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

Jonathan Cohen *, Jorge Gil

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

ARTICLE INFO

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

ABSTRACT

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

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

Introduction

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

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

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

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

[1] http://circularcitieshub.com

https://doi.org/10.1016/j.rcradv.2021.200058
Received 23 July 2021; Received in revised form 2 September 2021; Accepted 8 September 2021
Available online 13 September 2021

that integrates knowledge from different domains.

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

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

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

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

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

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

Related work

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

Industry 4.0 applications

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

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

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

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

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

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

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

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

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

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

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

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

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

Data management and standards in waste and resources management

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

[4] https://senseable.mit.edu/trashtrack/
[5] https://www.unwaste.io/
[6] https://www.litterati.org/
[7] http://h2020repair.eu/
[8] http://metabolismofcities.org
[9] https://www.geofluxus.com/
[10] https://dsposal.uk
[11] https://github.com/OpenDataManchester/Open3R

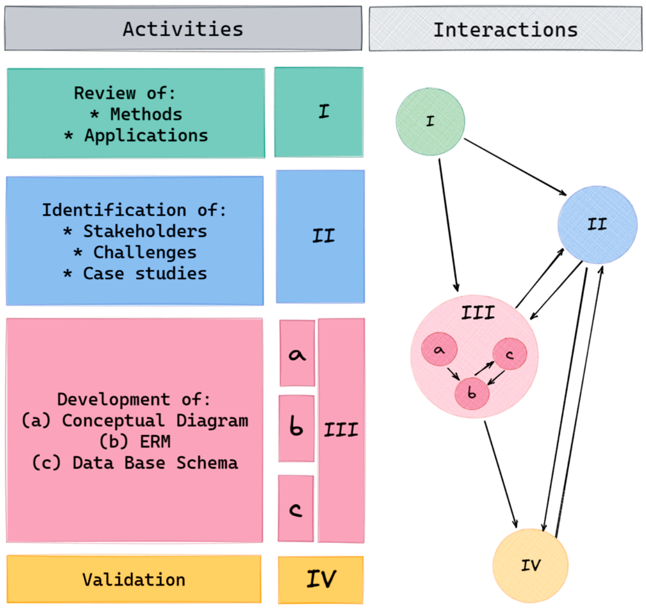

Fig. 1. Methodological stages and their interactions.

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

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

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

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

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

Methodology

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

Desk literature survey

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

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

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

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

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

Table 1
Interviews with stakeholders.

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

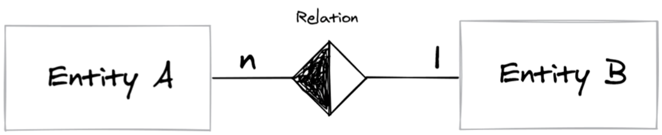

Fig. 2. ERM - notation Rein85.

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

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

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

Engagement with Stakeholders

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

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

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

Data model development

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

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

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

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

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

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

Validation using case studies

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

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

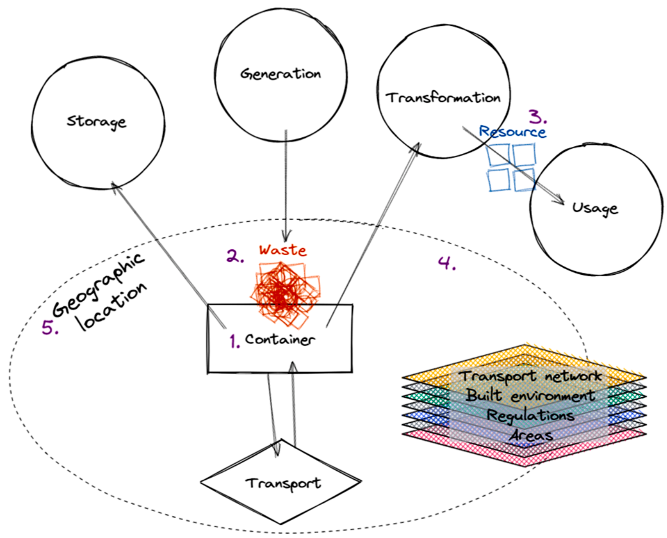

Fig. 3.. The Conceptual diagram of Circular Flow of Waste and Resources.

Results

Conceptual diagram of circular flow of waste and resources

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

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

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

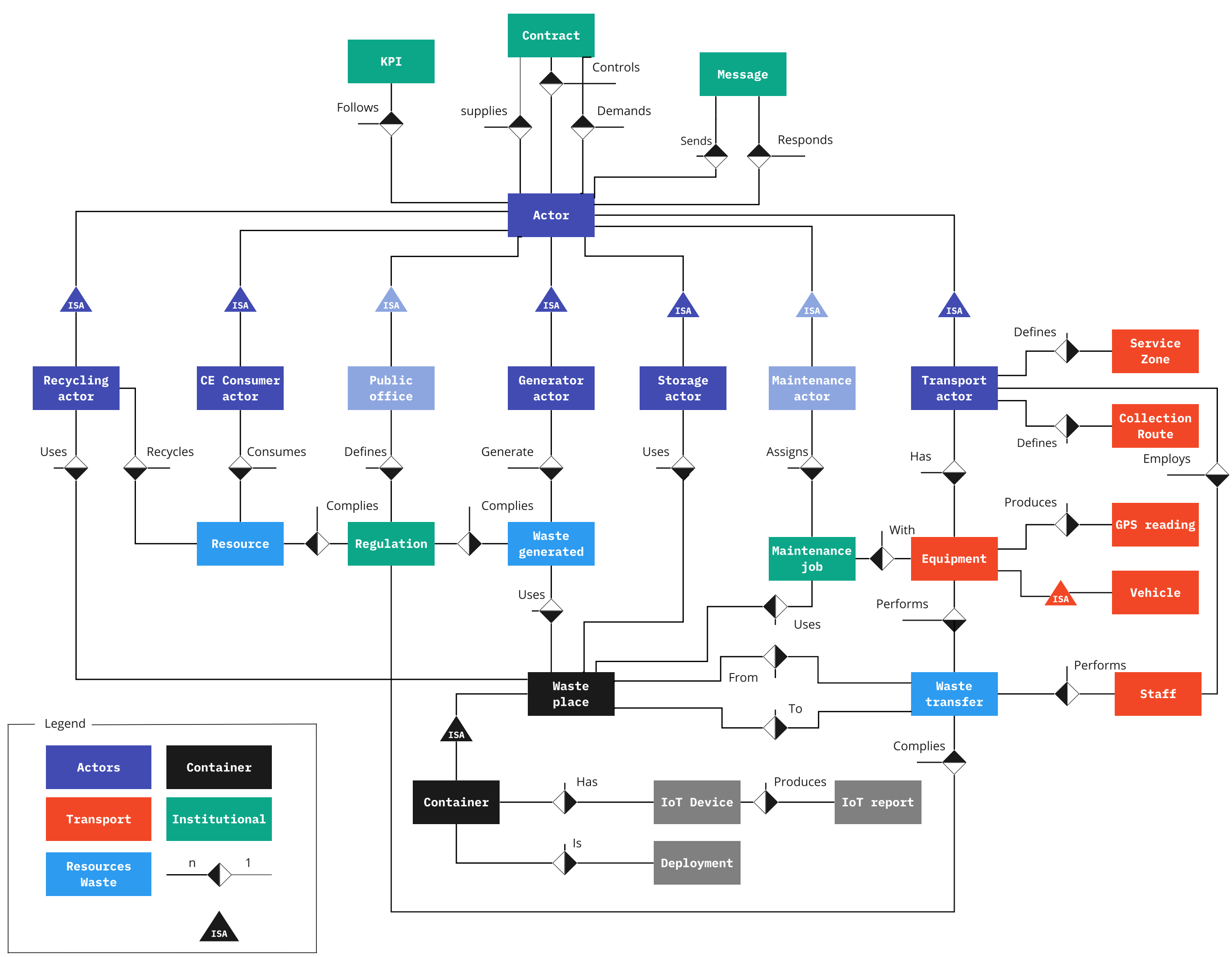

Fig. 4.. Entity Relationship Model (ERM) for waste and resources management - Rein85 notation.

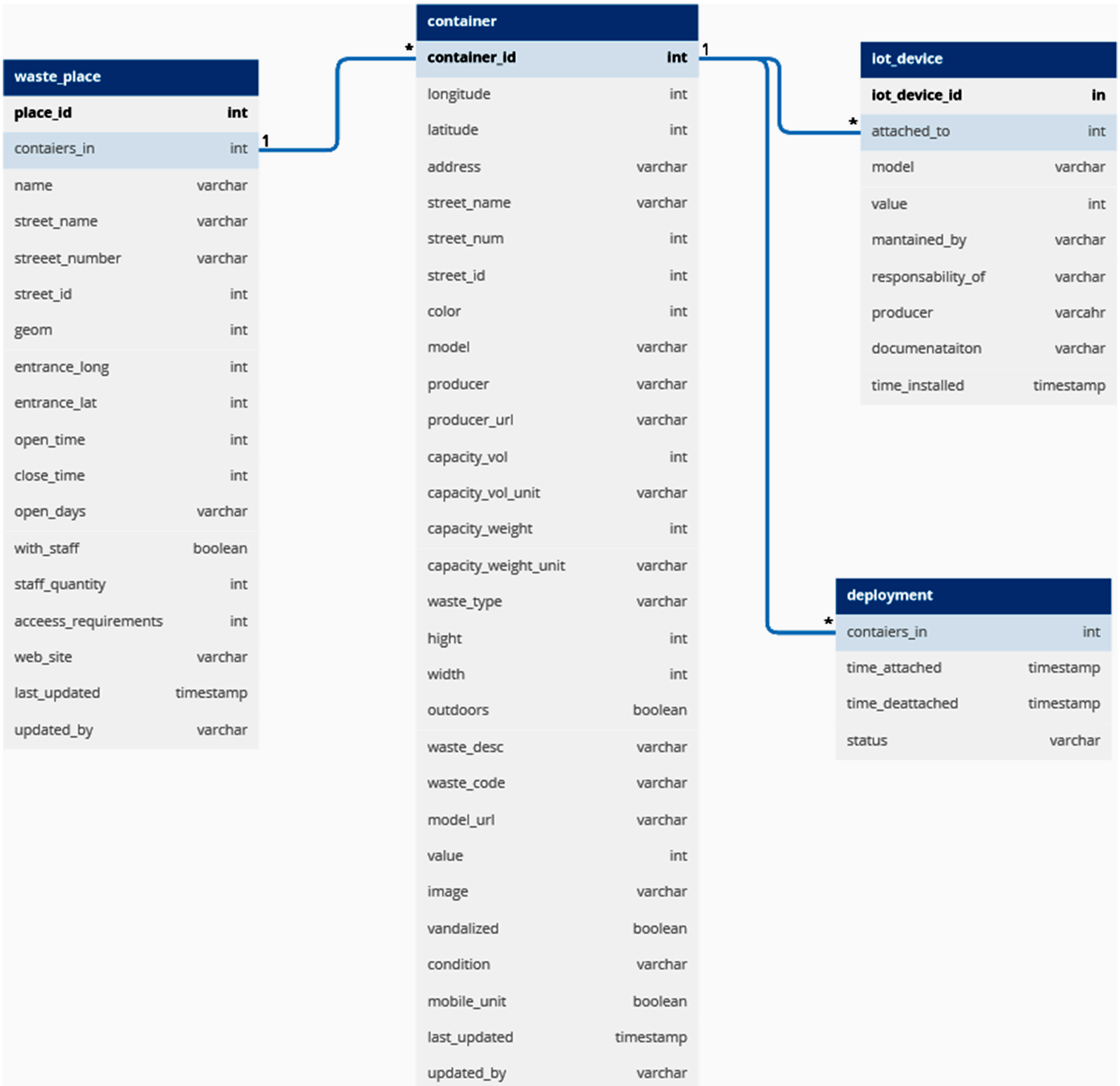

Fig. 5.. Relational data model schema for containers.

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

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

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

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

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

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

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

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

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

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

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

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

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

Relational database schema

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

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

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

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

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

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

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

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

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

[17] https://github.com/Urban-JonathanCohen/GeneralWasteDataModel
[18] https://dbdocs.io/Urban-JonathanCohen/Waste2Resources

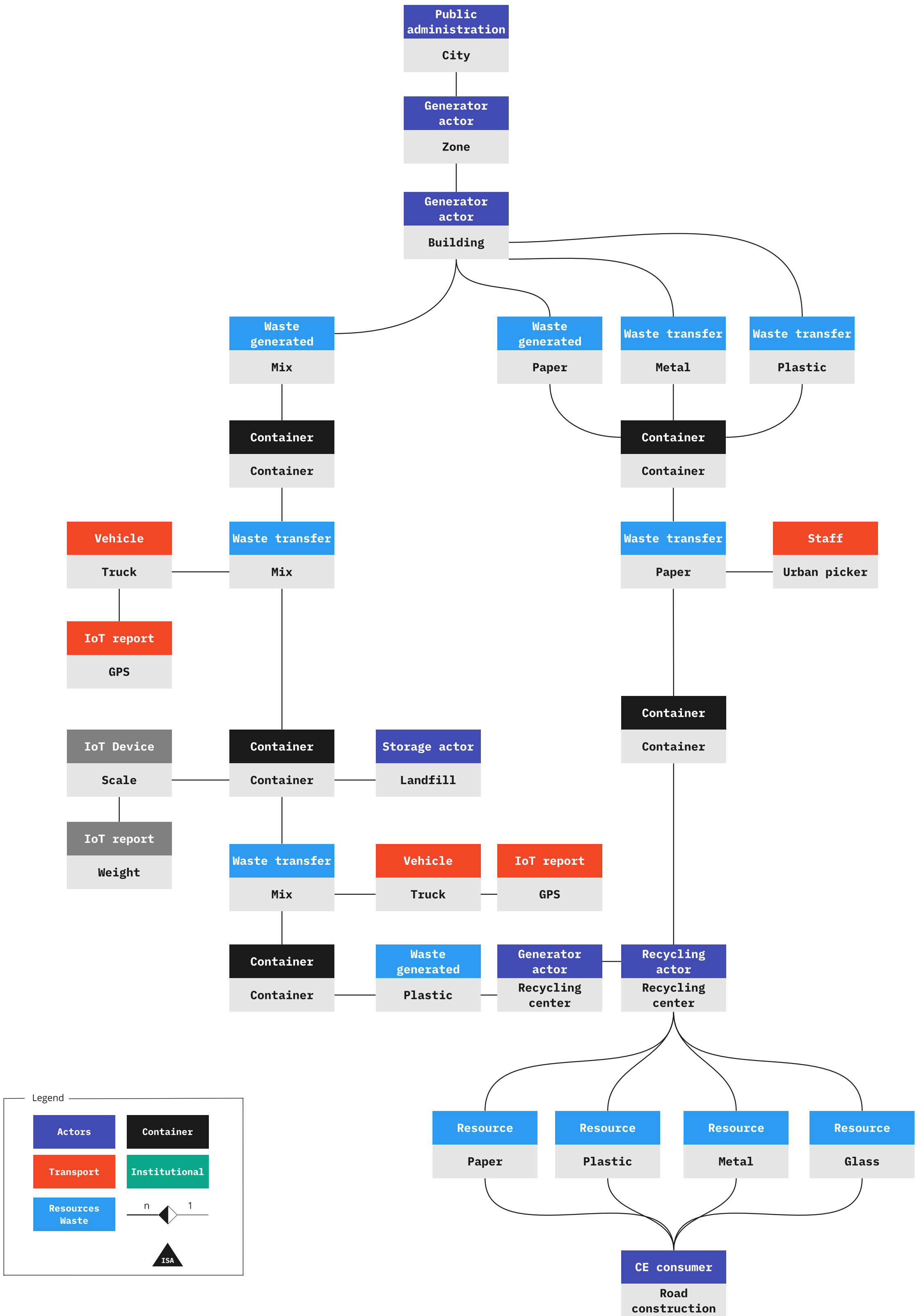

Fig. 6.. Recycling: Material recovery in Buenos Aires City.

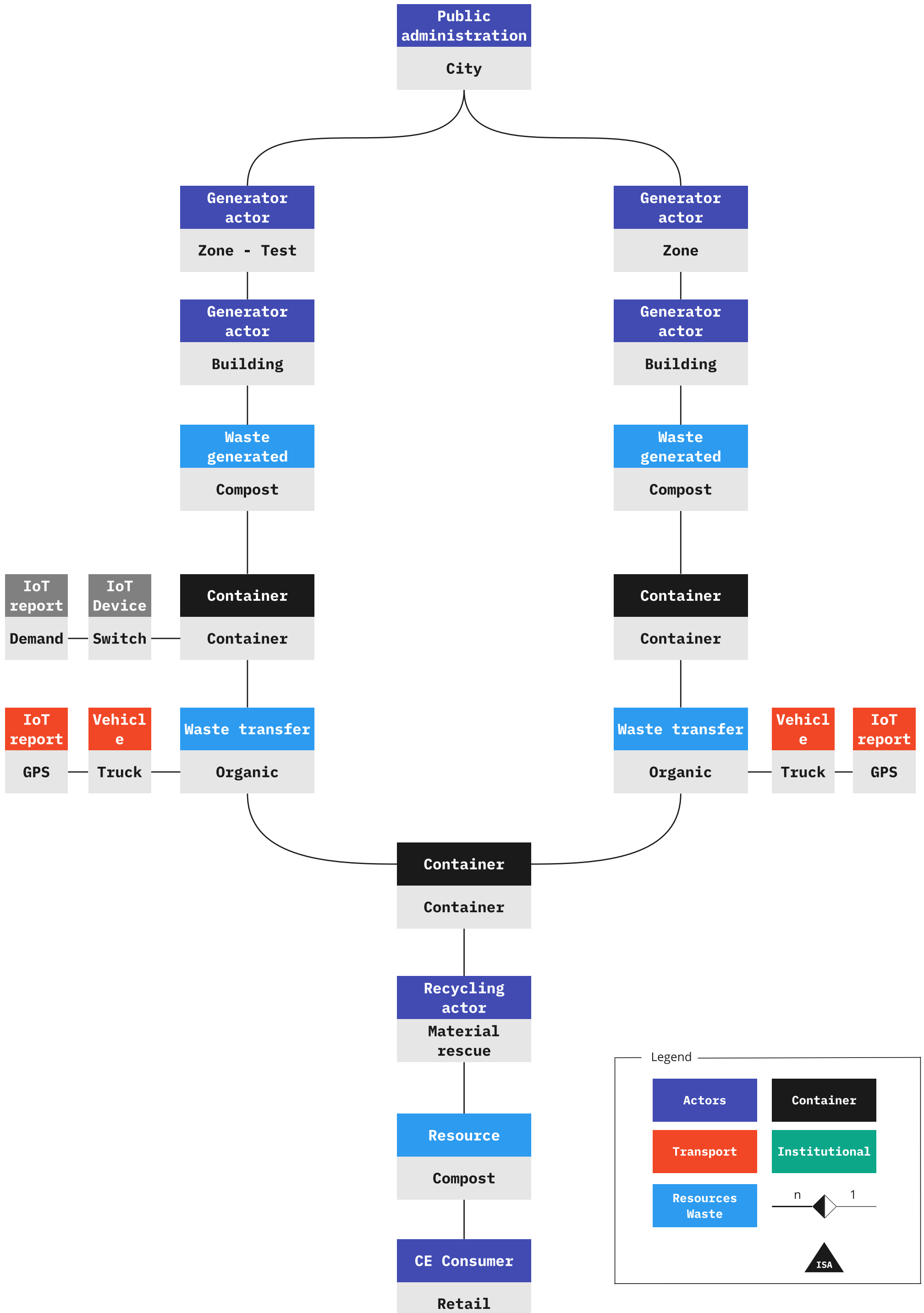

Fig. 7.. Optimization: IoT in waste management operations in Helsingborg.

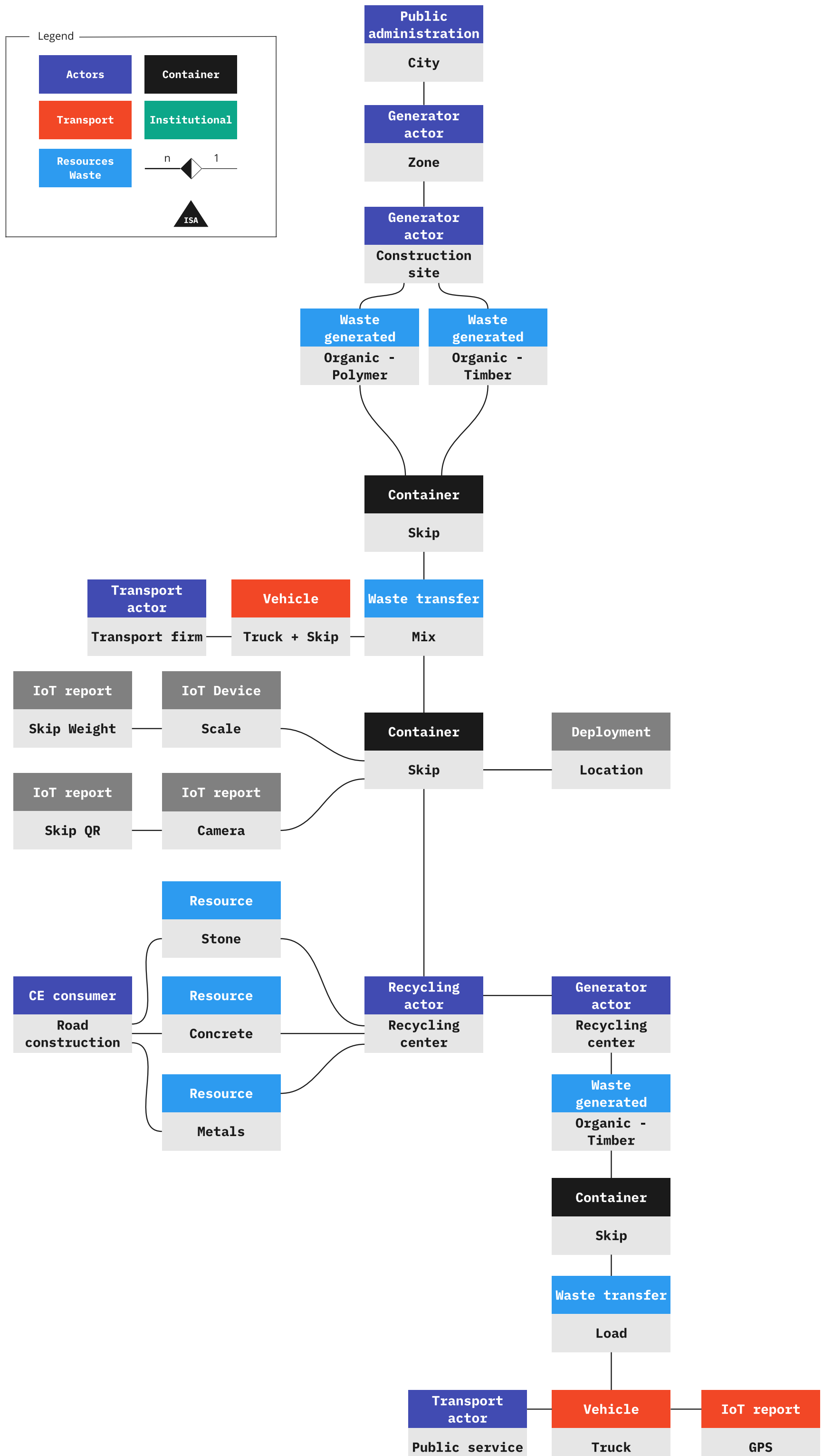

Fig. 8.. Reuse of materials: Construction and demolition sector in Buenos Aires City.

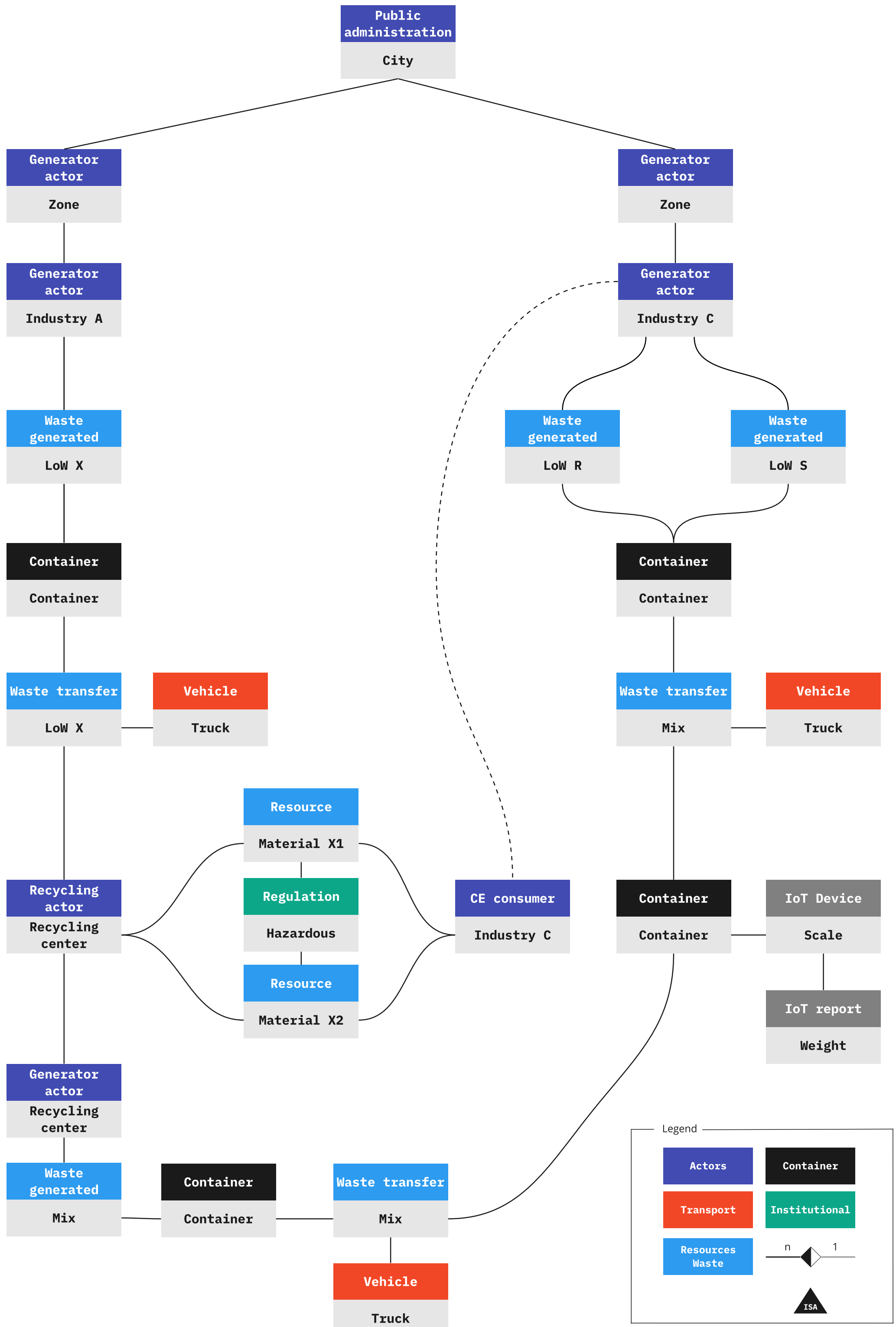

Fig. 9.. Regional waste exchanges: A general implementation.

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

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

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

Recycling: material recovery in Buenos Aires city

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

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

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

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

Optimization: IoT in waste management operations in Helsingborg

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

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

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

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

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

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

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

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

Regional waste exchanges: a general implementation

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

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

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

Discussion

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

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

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

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

Contributions of the CFWR data model as a standard

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

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

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

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

Limitations

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

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

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

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

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

Future work

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

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

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

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

Conclusion

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

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

Acknowledgments

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

Appendix A: Relational database schema

Figure 10, 11 & 12 Should be here

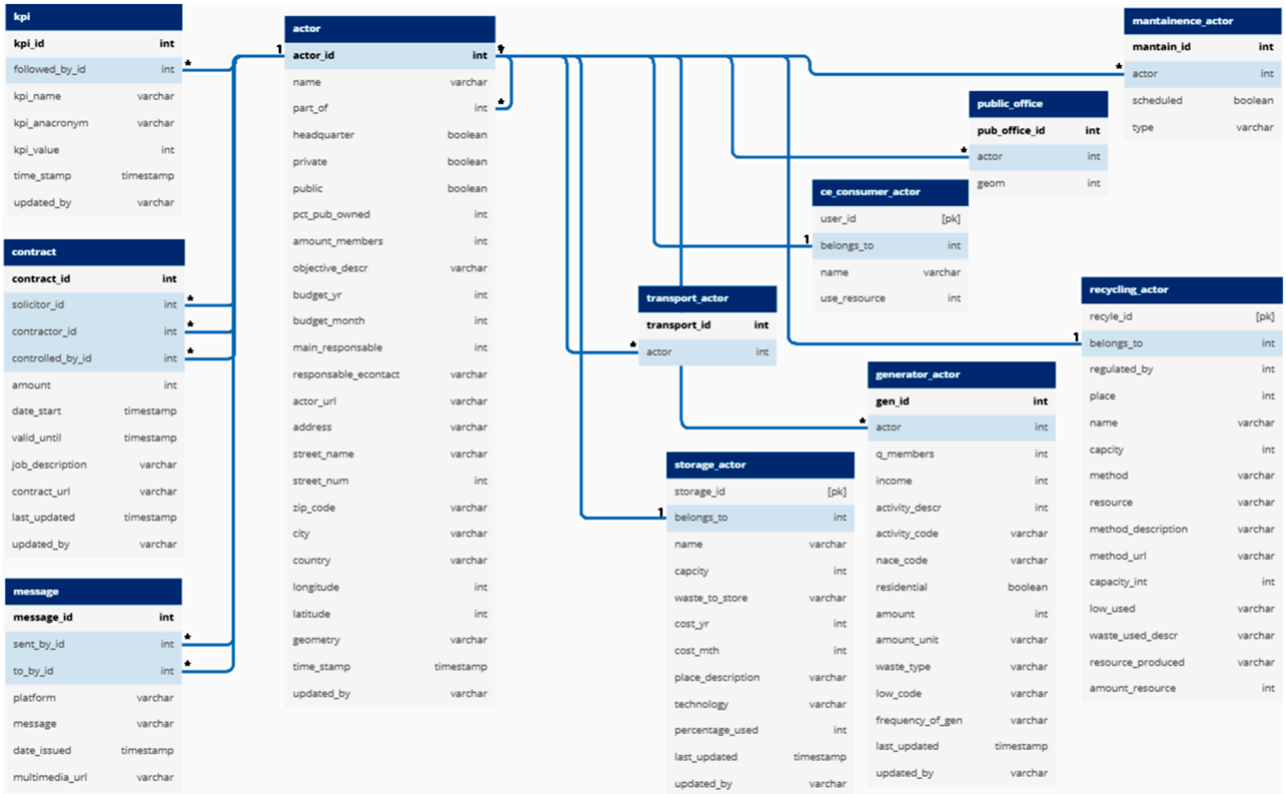

Fig. 10.. Relational data model schema of actors and roles.

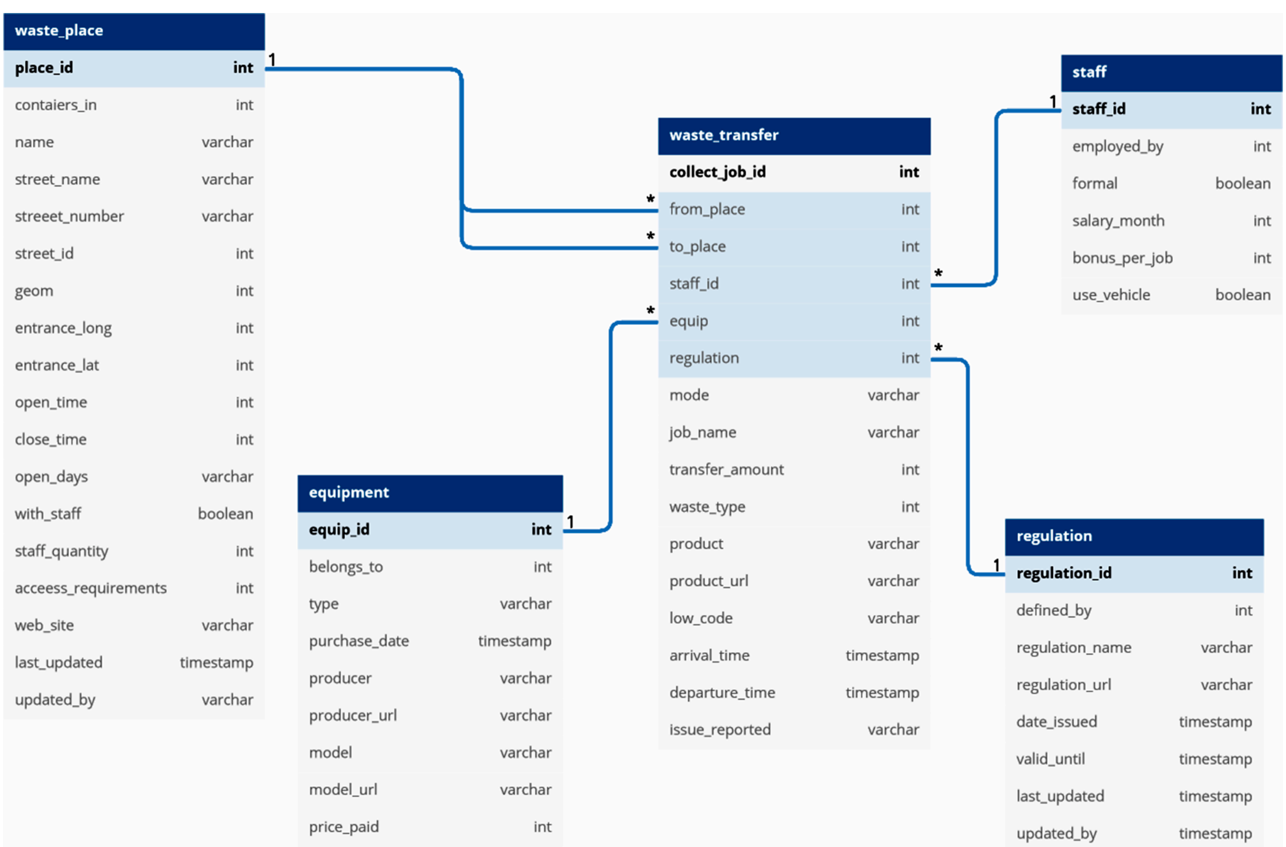

Fig. 11.. Relational data model schema of waste generated.

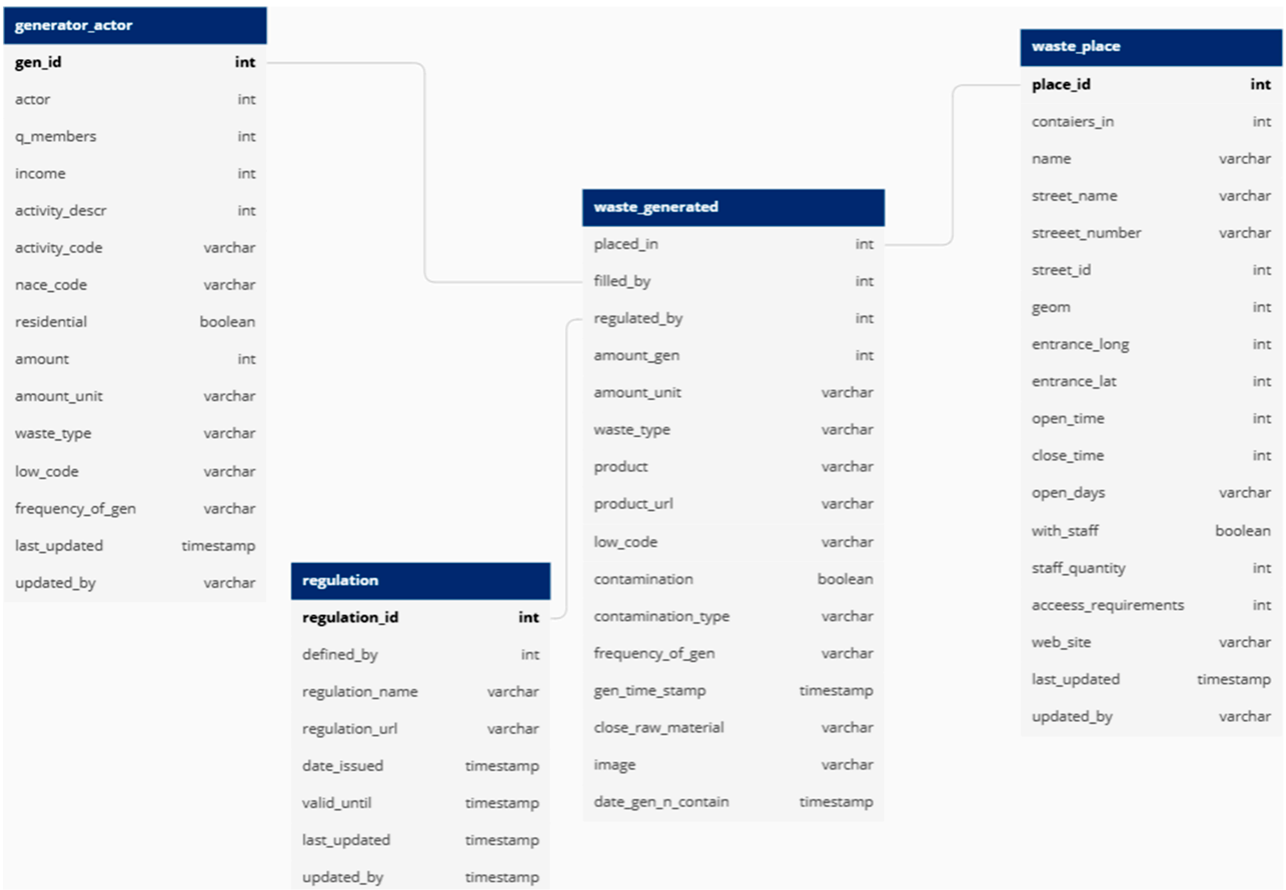

Fig. 12.. Relational data model schema for waste transfers.

Appendix B: Case Studies implementation

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

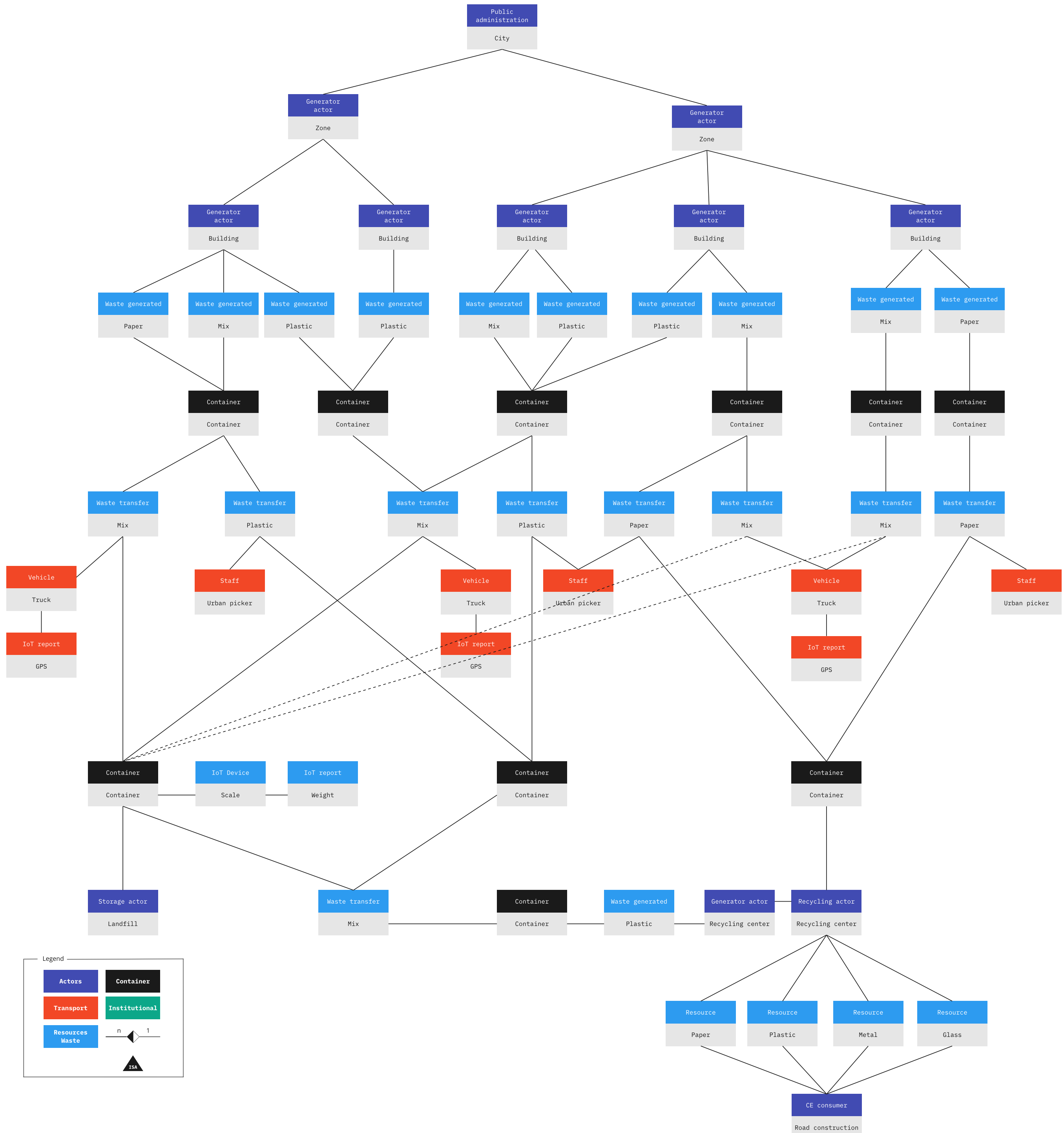

Fig. 13.. ERM for Recycling: Material recovery in Buenos Aires City.

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

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

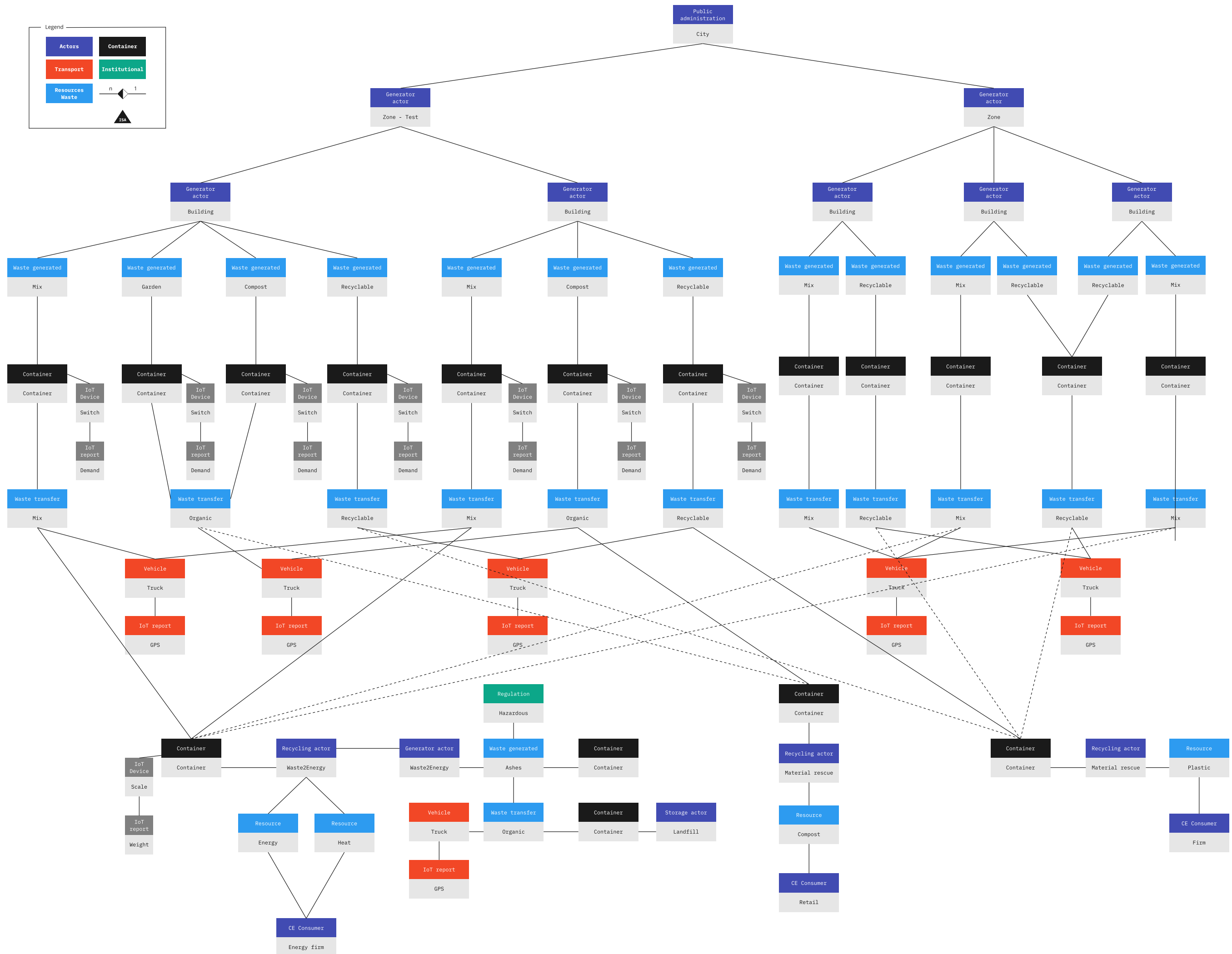

Fig. 14.. ERM for Optimization: IoT in waste management operations in Helsingborg.

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

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

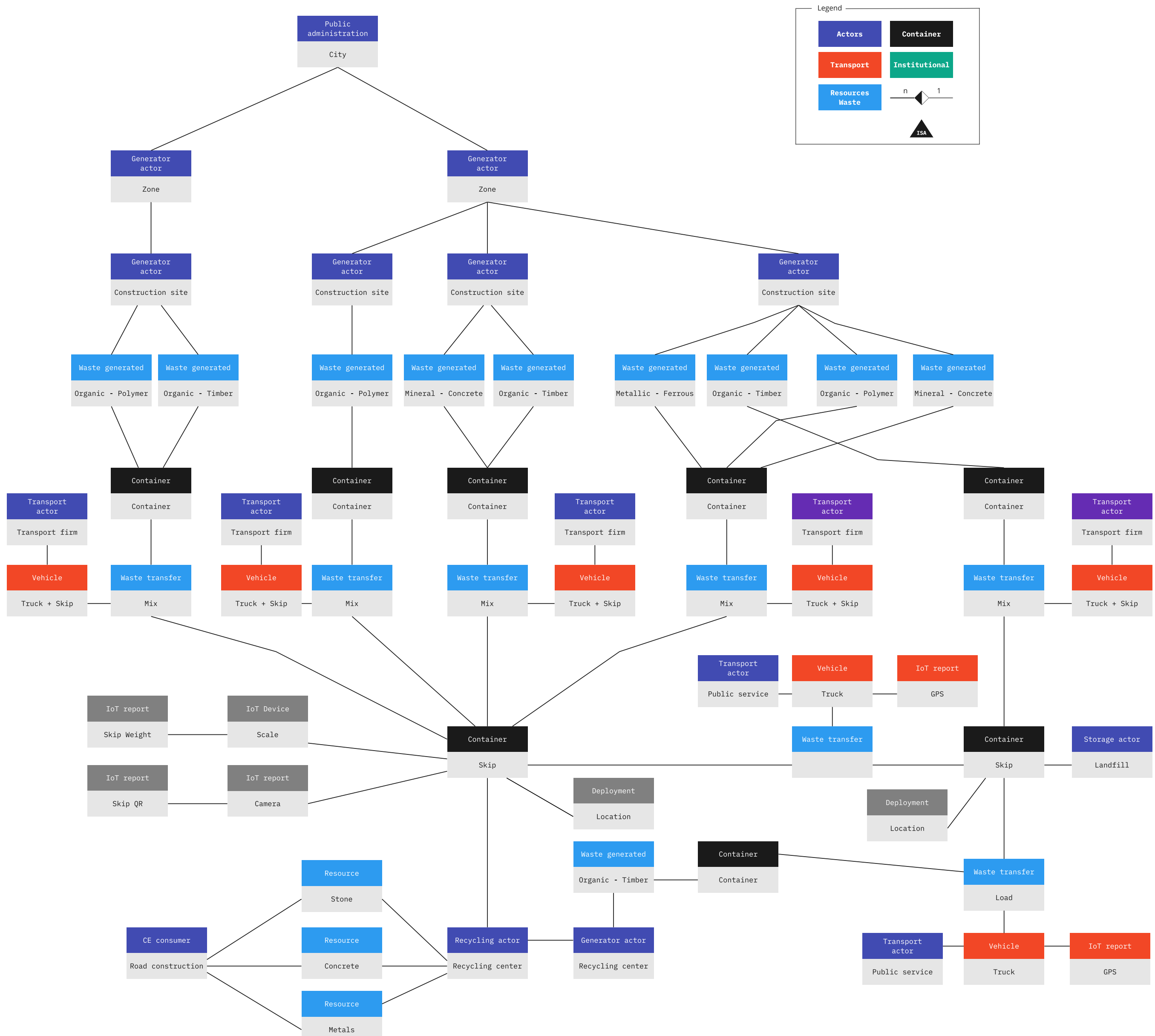

Fig. 15.. ERM for Re-use of materials: Construction and demolition sector in Buenos Aires City.

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

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

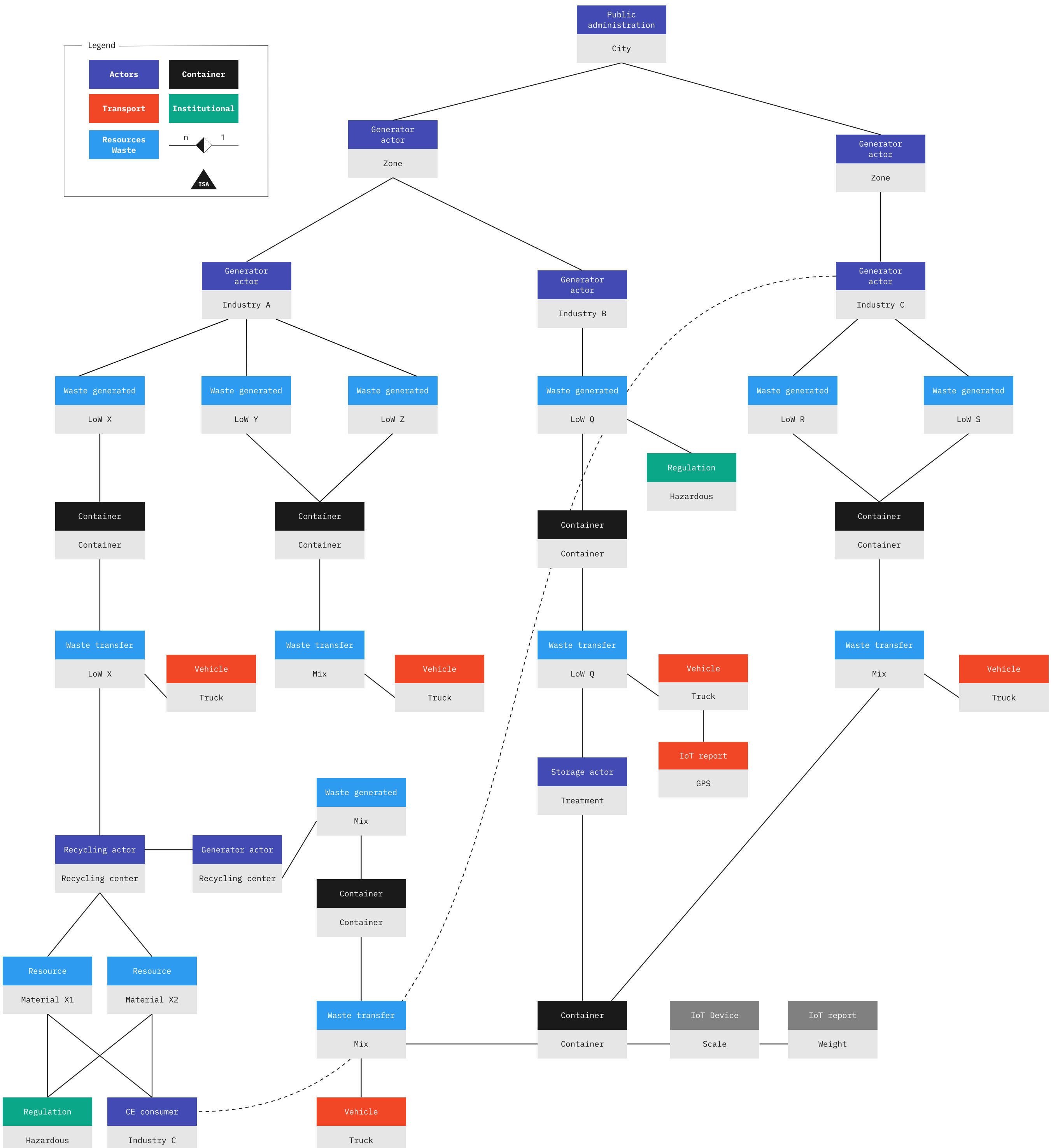

Fig. 16.. ERM for Regional waste exchanges: A general implementation.

Table 5
Competency questions for Regional waste exchanges.

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

References

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Hall, P. 1992. Urban & Regional Planning.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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