A Holistic Sustainability Framework for Waste Management in European Cities
Concept Development

Taelman, Sue Ellen; Tonini, Davide; Wandl, Alexander; Dewulf, Jo

DOI
10.3390/su10072184

Publication date
2018

Document Version
Final published version

Published in
Sustainability

Citation (APA)
Taelman, S. E., Tonini, D., Wandl, A., & Dewulf, J. (2018). A Holistic Sustainability Framework for Waste Management in European Cities: Concept Development. *Sustainability*, *10*(7), Article 2184. https://doi.org/10.3390/su10072184

sustainability

MDPI

Article

A Holistic Sustainability Framework for Waste Management in European Cities: Concept Development

Sue Ellen Taelman [1,*], **Davide Tonini** [2], **Alexander Wandl** [3] **and Jo Dewulf** [1]

[1] Department of Sustainable Organic Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, 9000 Gent, Belgium; jo.dewulf@ugent.be
[2] Circular Economy and Industrial Leadership Unit, Joint Research Centre, European Commission, 41092 Seville, Spain; Davide.TONINI@ec.europa.eu
[3] Department of Urbanism, Faculty of Architecture, Technical University Delft, 2628 BL Delft, The Netherlands; A.Wandl@tudelft.nl
* Correspondence: sueellen.taelman@ugent.be; Tel.: +32-9-264-58-71

Received: 22 May 2018; Accepted: 14 June 2018; Published: 26 June 2018

Abstract: Waste management represents a challenge for public authorities due to many reasons such as increased waste generation following urban population growth, economic burdens imposed on the municipal budget, and nuisances inevitably caused to the environment and local inhabitants. To optimize the system from a sustainability perspective, moving the transition towards a more circular economy, a better understanding of the different stages of waste management is necessary. A review of recently developed sustainability frameworks for waste management showed that no single framework captures all the instruments needed to ultimately provide a solid basis for comprehensive analyses of the potential burdens associated with urban waste management. Bearing this limitation in mind, the objective of this research is to propose a conceptual and comprehensive sustainability framework to support decision-making in waste management of European cities. The framework comprises a combination of methods capable of identifying future strategies and scenarios, to assess different types of impacts based on a life cycle perspective, and considers the value of waste streams, the actors involved, and possible constraints of implementing scenarios. The social, economic, environmental, technical and political domains are covered, and special attention is paid to impacts affecting foremost the local population.

Keywords: urban waste management; circular economy; life cycle thinking; sustainability; framework

---

1. Introduction

The linear economy is a wasteful system: many valuable materials are "lost" to landfills, and the products that are manufactured are consistently under-utilized. This is amplified in the urban context where many studies have highlighted a structural problem with waste generation and management in key sectors such as mobility, food, and the built environment (e.g., [1,2]). The waste generated through these ineffective processes brings about additional costs due to waste management (WM) and collection spending which increases pressure on municipal budgets and possibly harms the natural environment and society as a whole. In contrast to a linear economy, a circular economy aims to decouple growth from finite resource consumption and is restorative and regenerative by design [3]. The transition towards a circular economy is challenging as only 9 percent of the goods and product of the global economy loop in one or the other way [4]. Moving towards a circular economy in cities requires an involvement of many sectors and stakeholders. Such a multi-disciplinary and multi-facets process inherently needs evidence-based and scientific sound information on the potential consequences of the decisions made. On this basis, establishing an overarching sustainability framework is crucial to support such a cohesive model for change. With this in mind, the main objective of this study is to propose a holistic sustainability framework for urban waste management (UWM) in European cities. To do this, the authors identified and described the recent framework developments in the field of (urban) waste management, analyzed their comprehensiveness and proposed advancements.

1.1. From Linear to Circular Economy

Simultaneously with industrial growth, increasing population, rapid urbanization and improved community living standards, enormous quantities of materials are being wasted in the European Union (EU) in the last decades. EU statistics illustrate that up to 2.6 billion tons of waste (specified by Directive 2008/98/EC) was generated in 2014, of which most originates from economic activities such as construction (34.7%), mining (28.2%) and manufacturing (10.2%), while households contributed for 8.3% [5]. Consumption patterns, economic wealth in combination with the projected population growth will likely lead to an increased amount of municipal solid waste in the near future. Overall, waste generation indicates the limited ability to use primary resources efficiently. The linear economy is a basic structured model that relies on the extraction of raw materials and their processing into products and potential by-products which, after usage, are treated as waste and mainly disposed of into landfills or dumpsites (Figure 1a). In the past, this model has been considered as a successful and effective approach, able to manufacture products at competitive prices, boosting the economies of developing and industrialized countries, and encouraging human consumption. However, concerns about the depletion of natural biotic and abiotic resources (coal, minerals, metals, wood, etc.), with consequent challenges in supply, have brought increased attention to the way we should manage the available resources. In this respect, waste disposal not only results in significant losses of materials but also incurs significant impacts on the environment finally reducing the quality of life [6]. Ultimately, this may lead to exceed certain environmental thresholds or tipping points, defined as “planetary boundaries” by [7], affecting the current ecosystem irreversibly. Therefore, waste should be managed so that it does not poses risks to air, water, soil, plant and animals e.g., by the release of methane or leachate, eventually leading to impacts on human health and well-being which is absolutely to be avoided [8]. Therefore, changing this linearity of material flows is high on the agenda as it is one of the profound challenges the EU is facing today.

The linear “take-make-dispose” model of economic growth we relied on in the past is no longer suited for the needs of today’s socio-economic European system (Figure 1a). A shift towards a circular economy as an industrial system that is restorative or regenerative will increase resource efficiency and reduce waste significantly [9]. Furthermore, the circular economy model aims to create secure jobs in Europe, to boost innovations giving competitive advantages to EU industry and to provide increased level of protection to humans and the environment. It should also provide consumers with more durable and innovative products that provide monetary savings in a life cycle perspective and a better quality of life.

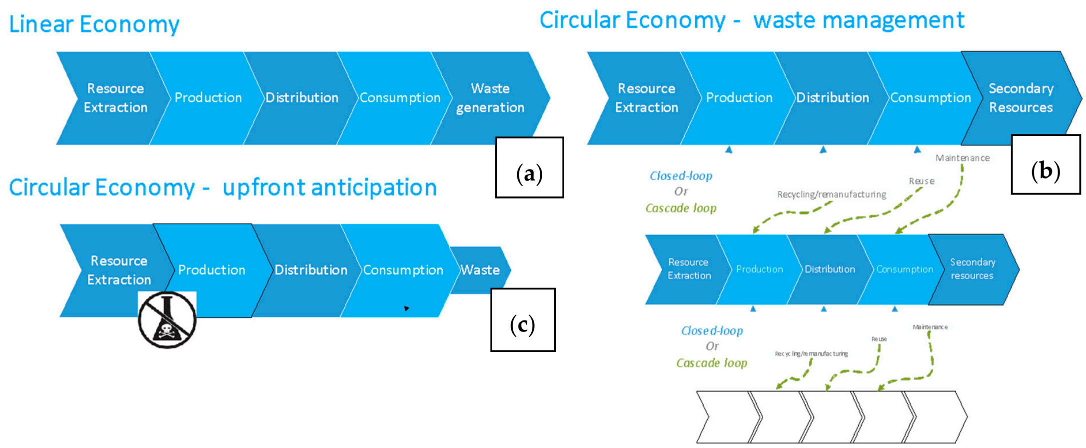

Figure 1. Linear economy (**a**) and Circular economy: upfront anticipation (**b**) and waste management (**c**).

In essence, two main perspectives can be distinguished regarding the circular economy. The first perspective focuses on the value of products and materials which should be maintained for as long as possible, by prolonging the lifetime of products and hence postponing the end-of-life phase (Figure 1b; upfront anticipation). Additionally, consumables in the circular economy should be largely made of biological ingredients or "nutrients" that are at least non-toxic and possibly even beneficial, and can safely be returned to the biosphere, either directly or in a cascade of consecutive uses. Such upfront anticipation could contribute greatly to reduction of waste, when done in a safe and smart manner. Re-conceptualization and re-design of products and processes is paramount, enabling materials to be used and reused at their highest utility for the intended performance, while either circulating through man-made systems as long as possible or through natural systems in pure, shorter and longer cycles.

The second perspective is based on a proper WM system. By following the waste hierarchy and applying enhanced end-of-life processes, it can contribute largely to preventing waste and keeping materials in the economy loop (Figure 1c). However, only very few materials can be reused repeatedly in their "highest utility and value" (cfr. closed loop). When the inherent properties of recycled material are not considerably different from those of the virgin material and can be used in the identical type of products as before, it is also referred to closed loop recycling. In open-loop or cascade recycling, the inherent properties of the recycled material differ from those of the virgin material in a way that it is only usable for other product applications, mostly substituting other types of materials. As illustrated in [10], this ultimately reduces the benefits of recycling. Avoiding this so-called quality downgrading as much as possible is key to achieve successful circular economy solutions. Overall, according to the European Environment Agency [11], there is still large potential for improvements throughout the full product life cycle, from the choice of materials, to the product design, or the end-of-life phase.

1.2. *Responsibilities and Current Practice of Waste Management in European Cities*

Over the last 30 years, efforts at European policy level resulted in a series of environmental action plans, directives, reports and a framework of legislation aiming to reduce negative environmental and health impacts of waste and improve Europe's resource and energy efficiency [12]. For example, the Waste Framework Directive (2008/98/EC) sets out basic concepts and principles for waste management across the EU, such as the five-step "waste hierarchy", the "producer responsibility" and the "polluter pays principle". The waste hierarchy framework ranks priorities for WM with the preferred option of waste prevention, followed by re-use and recycling which closes the loop of product life cycles. Lower on the ranking to be found is the recovery of energy from waste, with landfilling the least desirable option.

A multi-level governance model is applicable in Europe (Figure 2); e.g., the EU Waste Framework Directive describes how member states should deal with waste collection and treatment, but it is up to the municipalities and regions to establish and control the implementation of the waste and materials policy as they are typically in charge of waste collection and treatment. As an example, in Belgium waste/resource management is regionally determined, e.g., the Flemish government independently exercises its authority in the domain of waste/resources management in the region of Flanders. It also has the power to establish and maintain foreign relations and to act internationally for its own competencies. Flanders has its own policy on waste management in which the municipalities are imposed to be legally responsible for the implementation of the policy regarding municipal waste and to ensure that the citizens can easily carry out the outlined municipal (solid) waste policy. They have a "duty of care" for the collection of household waste, but it does not apply for industrial waste. Though, in practice, very often the municipalities delegate their authority for the collection and treatment of household waste to small- or medium-scale (inter)municipal waste associations or companies. The latter collect waste from one or multiple neighboring municipalities (amalgamation), i.e., these partners are responsible for the collection of one or multiple types of waste in a specific geographic area, further referred to as the focus area. These focus areas are often characterized by heterogenic urbanization patterns from sparsely populated rural to dense urban and all forms of in-between, which often have different collection strategies applied. However, a share of the waste generated and collected in the focus area may not always be treated in the focus area, due to e.g., lack of space or facilities or social pressure, and may be thus transferred to another location for treatment. For instance, treatment and processing can be organized at the regional level, meaning in collaboration by several municipalities and/or provinces or metropolitan areas, an intergovernmental form of collaboration that very often coordinates action of larger cities, with their surrounding municipalities, or somewhere else within the same country or even exported abroad.

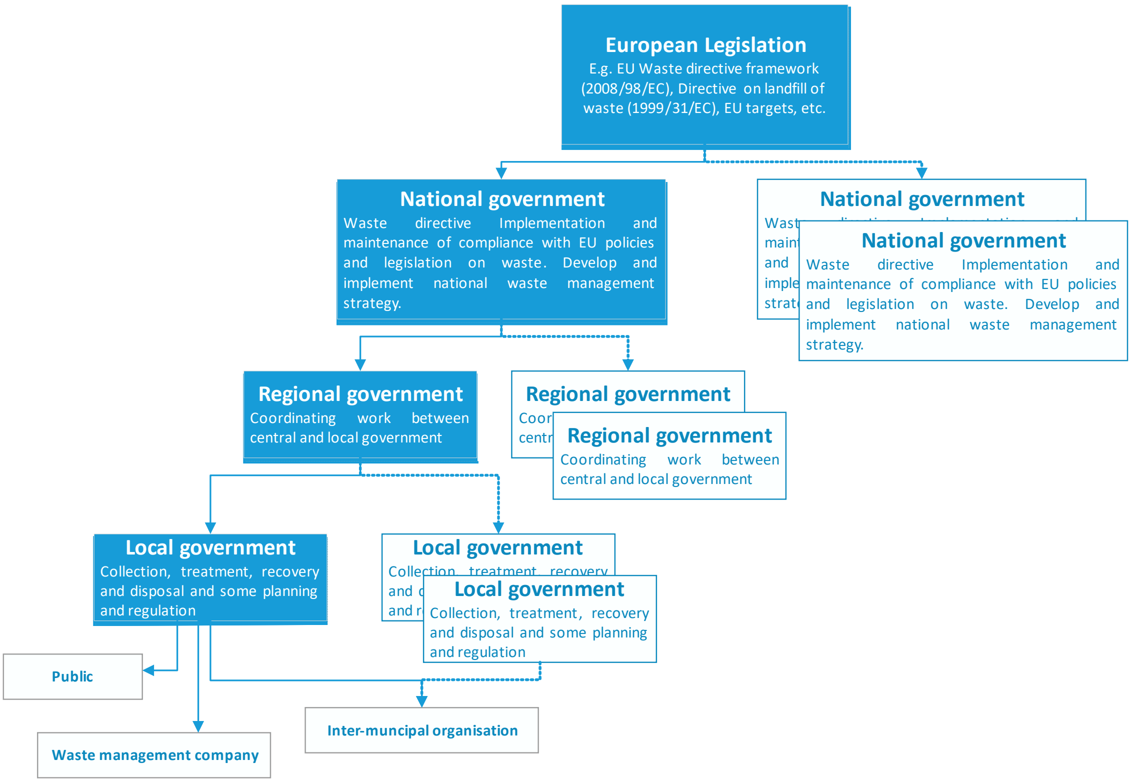

Figure 2. Multi-level governance structure and roles in Europe regarding municipal waste management.

1.3. Sustainable Urban Waste and Resource Management

Although multiple waste policies and targets have been established since the 1990s, in practice the status of the EU economy remains far from being circular or sustainable. A good cooperation between local, national and EU authorities and their stakeholders is needed to tackle the challenges effectively. A key objective will be to apply the circular economy principles to European cities and metropolitan areas, because cities are at the heart of Europe's economy, they are large consumers of goods and services, including the utilization of primary energy, and generators of waste. Urban systems are open structures depending on the hinterland for several resources such as people, materials, water, food and energy. Consequently, cities tend to produce large amounts of waste, of which most is often transported back to the hinterlands because the urban environment has typically a limited amount of space and to avoid that nuisance and emissions of waste management processes affect densely populated areas, i.e., the impact of European cities extends well beyond their geographic boundaries [13]. Cities with their need for resources are driving engines in a linear economy. However, it is also in cities, particularly growing ones, where critique on a linear economy accumulates and where there is experimentation with new, more circular economic models. Civil actors and consumers express their concerns and engage. Companies see, in the transition to a circular economy, opportunities for innovation, new exportable production techniques and business models, while reducing dependency on imports. City governments and their administrations are following and supporting this trend with dedicated policies to establish a more resource-efficient system. The importance of urban settlements will only grow in the near future, as it is estimated that by 2020 almost 80% of EU citizens will be living in cities, which will make proper WM even more challenging, specifically with the tendency that growing cites become less dense and more dispersed [14]. On this basis, more sustainable urban development and local waste management may improve not only the quality of life in a city, including ecological, cultural, political, institutional, social and economic components, but indirectly generate effects in regions located outside the city boundary.

When the objective of decision making in waste management is to contribute to sustainable development, it is important to quantify and understand the actual impact on the environment, on society and the economy, the short- and long-term investments and effects, and the synergies and trade-offs across different domains [15]. After all, (local) waste management is a complex system as it both comprises spatial and temporal variability. Waste composition and quantity change over time due to several external factors (change in human diet, increase of human welfare, etc.) and the WM system is spread over different geographic locations. This means that the consequences associated with the treatment of urban waste must be considered to avoid burden shifting among different regions. In this respect, life cycle thinking approaches are useful to holistically assess performance and highlight burden shifting among the involved processes and regions. Equally important is to not only consider global but also local impacts in the case of collection and treatment of waste, as it often leads to complaints from the inhabitants regarding smell, dust, flies, increased traffic, etc.

A common agreement on a consistent sustainability framework for urban waste management could allow an assessment and comparison between current systems and prospected changes, thereby stimulating the current and future developments towards targeted circular economy objectives. In this study, a framework is defined as a layered and conceptual structure, a system of interlinked rules, ideas, or beliefs, which supports a particular approach to a specific objective. As yet there is no consensus on how to holistically assess the sustainability of urban waste/resource management, therefore, the main *objective of this paper* is to develop and propose a comprehensive, overarching sustainability framework to support decision-making in this area, which covers social, economic, environmental, technical and political pillars, considers local to global scale impacts, recognizes the importance of burden-shifting between processes and locations, allows a comparative analysis among cities, acknowledges the importance of stakeholder involvement, considers temporal changes, identifies potential synergies among sectors, recognizes value differences between waste types, accounts for possible constraints towards implementing new strategies and provides a basis for policy making. The framework is supported by the concept of life cycle thinking but it is restricted to the second perspective of circular economy as described above, i.e., focusses on the WM system, including prevention, treatment, and production of secondary products and is applicable to European cities in particular. Clearly, optimizing waste management alone does not solve the linear economy problem—to "close the loop" and achieve a circular economy, it is equally important for example to examine product designs, production systems, and consumption habits. Nonetheless, this framework can be used to advance the assessment of urban waste management in the endeavor of a transition towards a circular economy in Europe. The intended targeted users are the local authorities that need to develop new strategies in relation to waste management and circularity.

Section 2 of this paper deals with a critical and systematic review of recently developed sustainability frameworks regarding (urban) waste management to understand their specific objectives and underlying methodology. Although none of these frameworks are developed to cover the multitude of objectives in a holistic way (as intended by this study), it is important to investigate the integrated methods and tools currently used, and to carefully select and adopt those methods in a conceptual sustainability framework [16]. A consistent sustainability framework may stimulate the development of the WM sector towards the ambitious European circular economy targets, ultimately supporting local and regional authorities in the identification and implementation of optimal waste and resource management strategies.

2. State-of-the-Art Overview of Sustainability Frameworks in the Context of Waste Management

There have been many attempts to analyze the sustainability of WM systems over the past decades. The state-of-the-art review performed in this study focused on identifying existing sustainability frameworks formulated to guide decision making in waste/resource management during the period 2007–2017 (i.e., last decade), and is therefore not exhaustive; however, it is sufficiently representative of today's developments in the field. The systematic review performed in ScienceDirect and Web of Science included the following search terms: sustainability, waste, secondary resources, framework and/or model in several combinations (minimum 2 terms), to be found in title, abstract or keywords and further selected based on relevancy. The search for articles was done in December 2017. In total, 22 literature studies were retained (a combination of two databases), and shortly discussed as shown in Table 1 (alphabetical order) according to following subjects/criteria (as derived based on the objectives as mentioned in Section 1.3):

- Key objectives: the aim(s) of the study.
- Urban/city focus: framework especially made to inform local authorities?
- Methods/tools: which methods, indicators and eventual tools used.
- Life cycle thinking approach: whether life cycle thinking was integrated.
- Multi-dimensional: social, economic, political, technical, legal, environmental, or other.
- Temporal variability: in terms of data collection, impact assessment, or other.
- Spatial variability: in terms of data collection, impact assessment, or other.
- Stakeholder involvement: during data collection, impact assessment, criteria selection, etc.

Table 1. Description of recently developed sustainability frameworks for (urban) waste management (as mentioned by the respective authors), based on 8 topics as shown per column.

Reference	Key Objectives	Urban/City Focus	Methods/Tools	Life Cycle Approach	Multi-Dimensional	Temporal Variability	Spatial Variability	Stakeholder Involvement
[17]	Development of a methodology to design multiple technology bioenergy supply chains and to select the optimum technology, considering economic and environmental sustainability aspects.	No, case study on West Midlands region from the United Kingdom	fuzzy multi-objective modelling, constraint optimization techniques	Partly, considering the main supply chain	Economic (capital investments costs and benefits), Environmental (greenhouse gas emissions), Technological (capacities, etc.)	No	Location of technology and energy demand nodes, Territorial Units for Statistics (NUTS) 3 level	No
[18]	A preliminary web-based information system is developed to analyze material flows (resource use, waste generation) both on national and industrial levels. The four-layer framework integrates information on physical flows and economic activities with material flow accounting and waste input–output table analysis.	No	Economy wide Material Flow Analysis (MFA), Input Output analysis	Yes, material life cycle	Environmental	No	No	No
[19]	Proposing a framework of sustainability indicators and a metric of sustainability that can serve as a reference for sustainability studies of waste-to-energy systems.	No	Life Cycle Sustainability (LCA), substance flow analysis, Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA), (life cycle sustainability assessment (LCSA)	Yes	Social, Economic, Environmental	No	No	No
[20]	Development of a Sustainable Operations framework to guide projects to make a proper contribution to sustainability without compromising on financial rigor, e.g., by integrating sustainable development (SD) into industrial plant design and operation.	No	LCA, social impact analysis, footprinting, multi-criteria analysis techniques, etc. (not a fixed-set of methods)	Partly, depending on the choice of methods used to address sustainability	Environmental (natural), Social (human), Economic (manufactured, financial capital)	No	No	Study team per project (different backgrounds)
[21]	Development of 3-stage consistent framework and application to the assessment and retrofit of several technological options for food waste management.	No	Data envelopment analysis (non-parametric linear programming), LCA, process retrofit	Yes	Environment	No	No	No
[22]	Introducing a multi-objective robust optimization model for municipal solid waste management system, by considering all three dimensions of sustainability.	Case study on the Municipal Solid Waste (MSW) management system of the city of Tehran	Multi-objective optimization model, robust optimization approach (uncertainty), constraint optimization, linear programming	No	Economic, Environmental, Social	No	Yes, optimal localization of disposal/recycling plants	No

Table 1. *Cont.*

Reference	Key Objectives	Urban/City Focus	Methods/Tools	Life Cycle Approach	Multi-Dimensional	Temporal Variability	Spatial Variability	Stakeholder Involvement
[1]	Development of a multilayer systems framework and scenarios to quantify the implications of food waste strategies on national biomass, energy, and phosphorus cycles, using Norway as a case study.	No	Substance flow analysis (biomass, phosphorous) and energy balances	Partly, considering the main supply chain	Technical (environmental)	No	Specific national data (mass/energy flows) used from Norway	No
[23]	This study proposes a novel, conceptual approach that seeks to assess how complex value is created, destroyed and distributed in resource recovery from waste systems. It combines scientific and engineering methods with a socio-political narrative grounded in the systems of provision approach, and provides a comprehensive, analytical framework for making the transition to a resource-efficient future.	No	Value stream mapping, industrial symbiosis	Yes	Economic, Environmental, Social, Technical	No	No	No
[24]	This paper presents a framework for examining the most sustainable processing options for green waste valorization in terms of the triple bottom line, People–Planet–Profit	No, case study on the region Flanders in Belgium	LCA, Analytical Hierarchy Process (AHP), multiple objective mixed-integer linear programming, (net present value)	Yes	Economic, Social, Environmental	No	No	Partly, stakeholders' experiences included
[25]	This paper proposes strategic positioning of pollution prevention and clean production projects via design of a sustainable environmental management system, ELECTRE III, that is responsive to regulatory requirements, and is relevant to industry culture and business structure.	No	Multi-criteria decision analysis method (electric iii)	No	Social, Economic, Environmental	No	No	Involving decision makers and experts to define problems, generate alternatives, performance criteria and indicators
[26]	Presented in this paper is an integrated ecological economic assessment considering the economic and ecological losses and a sustainability policy-making framework for 31 typical Chinese cities in view of spatial variations based on thermodynamic analysis	Yes	GIS, emergy analysis, LCA	Yes	Environment, Economic	No	Yes, representation of cumulative impacts in terms of emergy performance on a terrestrial map	No

Table 1. *Cont.*

Reference	Key Objectives	Urban/City Focus	Methods/Tools	Life Cycle Approach	Multi-Dimensional	Temporal Variability	Spatial Variability	Stakeholder Involvement
[27]	The "Wasteaware" Integrated Sustainable Waste Management (ISWM) indicators framework is described; an innovative combined evaluation approach is proposed in the present paper to deal with the issue of the performance measurement and comparison of UWM services in the context of cities.	Yes, case study based on 12 different cities from the Optimal Territorial Ambit of Palermo in Sicily.	ISWM indicators of Wilson et al., 2015, evaluation approach (electric iii outranking method), multi-criteria analysis in a non-compensative manner	No	Technical-Operational, Environmental, Financial, Economic, Socio-cultural, Policy-legal and Institutional	No	Yes, city-specific data collection.	Consultation process key stakeholders (citizens, local administrators, service providers), face-to-face survey
[28]	A waste elimination framework has been suggested as an approach for sustainability in manufacturing environment. The framework contains three consecutive phases: waste documentation, waste analysis, and waste removal.	No	Traditional and dynamic value stream mapping (VSM), root cause analysis, failure mode and effect analysis, AHP, Analytic Network Process (ANP), Data Envelopment Analysis (DEA), . . .	Partly, root cause-effect chain	Not stated.	Yes, DVSM, time recording	Yes, DVSM, location recording	Brainstorming with experts (root cause analysis)
[29]	A Hierarchical Analytical Network Process (HANP) model is demonstrated for evaluating alternative technologies for generating electricity from MSW in India	No	HANP, AHP	No	Technical, Financial, Environmental and risk (criteria, to inform policy makers)	No	Partly, site-specific primary data of the situation India.	WM experts involved (based on questionnaires) to identify weighting factors
[30]	This study aimed to establish a comprehensive framework to evaluate industrial and urban symbiosis scenarios.	Yes, Kawasaki City in Japan	Industrial and urban symbiosis, material flow analysis, emergy analysis, life cycle carbon footprint	Partly, carbon footprint	Environment	No	Case study: site-specific data (process flow data + geographical data)	Case study: discussion with stakeholders for data (interviews and surveys) and scenario design
[31]	The authors examine the factors that give rise to food waste throughout the food supply chain and propose a framework to identify and prioritize the most appropriate options for prevention and management of food waste.	No	Interviews	Partly, the main food supply chain	Social, Environmental, Economic	Partly, considers temporality of food (waste)	No	Interviews with food waste specialists, they give qualitative information, on which the framework is entirely built
[32]	The proposed framework, SWIT (Sustainable Wealth creation based on Innovation and Technology) has been developed to provide multiple businesses of zero-value residue industrial ecology processes, inserted into circular value ecosystems, all managed and governed by a sustainable sharing value system for the benefit of a community.	No	Value stream mapping, MFA, LCA, LCC, SLCA, Environmentally Extended Input Output analysis (EEIO), Cost Benefit Analysis (CBA)	Yes	Economic, Social-Political, Environmental	No	Regional level.	No

Table 1. *Cont.*

Reference	Key Objectives	Urban/City Focus	Methods/Tools	Life Cycle Approach	Multi-Dimensional	Temporal Variability	Spatial Variability	Stakeholder Involvement
[33]	A concept and action plan framework is proposed to evaluate issues surrounding the sustainability of solid waste management in Asian countries	No	Situation analysis	No	Political, institutional, legal, technical, (environment, social)	No	Partly, nationally aggregated urban information	Yes, public participation
[34]	In this paper, we develop and apply a methodology for stakeholder consultation regarding the selection of Life Cycle Sustainability Assessment (LCSA) impact categories. The methodology is based on decision science concepts and tools with an emphasis on the elicitation of stakeholders' perspectives depicted in cognitive causal maps	No	LCA, LCC, SLCA, Multiple-criteria decision-making (MCDA), Problem structuring methods, Strategic options development analysis, causal maps	Yes	Economic, Social, Environmental	No	Partly, national level.	Stakeholder involvement for the selection of impact categories (interviews, workshops)
[35]	A conceptual sustainability framework for near-to-site variations of cycle technological design (to reutilize waste streams) has been developed. Suitable structure and characteristics for initial technology assessment, specifically for these cycle technologies are presented	No	LCA, material, energy and waste modelling, cost indicators	Yes	Environment, Economic, Technical	No	No	No
[36]	The paper presents an indicator set for integrated sustainable waste management (ISWM) in cities both North and South, to allow benchmarking of a city's performance, comparing cities and monitoring developments over time. The comprehensive analytical framework of a city's solid waste management system is divided into two overlapping "triangles"—one comprising the three physical components and the other comprising three governance aspects.	Yes	/	No	Economic, Social, Environmental, Governance	No	Partly, city-specific data	Yes, inclusivity (allowing stakeholders to contribute and benefit)
[2]	This paper aims to establish a framework for assessing the eco-efficiency of construction and demolition waste management performance through eco-efficiency indicators, based on the particular practice of Hong Kong	No, case study on the region of Hong Kong	Eco-efficiency analysis, LCA, LCC or total cost of ownership, full cost accounting	Yes	Economic, Environmental	No	Partly, can be done on company level to supranational level	No

Out of the 22 articles which proposed frameworks or models that analyze the sustainability of waste management (Table 1), only five of them developed the methodology for urban systems or can be applied to case studies dealing with waste generation from a city or municipality. These few studies explore spatial variability, mostly by collecting site-specific data to analyze a particular situation in terms of flows, infrastructure, population, etc. The remaining literature studies did not have an urban focus; however, a few studies did consider spatial differentiation, often at higher levels such as the region (e.g., NUTS) or country. Temporal variability seems more challenging, as only two studies recognize the importance of changes over time (e.g., food quality losses over time, tracking of location of goods/materials). However, both spatial and temporal differentiation in impact assessment (cfr. location/time-specific characterization factors) seem to be out of the scope for the respective frameworks under review.

From Table 1, it appears that many frameworks were developed in a general way (applicable to multiple waste streams and systems) or focused solely on popular themes such as food waste, municipal solid waste and waste-to-energy systems. Methods/tools commonly used based on this review are life cycle analysis (LCA), multi-criteria and optimization techniques, flow and value analysis methods, Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA). This already implies that many frameworks integrate a life cycle approach, although not always executed according to the ISO 14040/14044 guidelines. Only 6 studies do not consider any burden related to supply chain networks. The frameworks developed are mostly applicable in the domains of environmental sustainability, followed by economic and social sustainability, and regularly complemented with technical or political-legal-institutional domains. Although most frameworks operate in multiple domains, i.e., are multi-dimensional, only half of the reviewed studies value stakeholder involvement (e.g., by consulting stakeholders and integrating their ideas, feedback, etc.). Overall, this review confirmed the lack of an overarching framework capable to support policy-makers in assessing the sustainability of urban waste management systems in a holistic way. For this reason, a conceptual framework is proposed in this study.

3. Development of a Holistic Sustainability Framework for European Urban Waste Management

The review allowed identification of key methods and tools that can be integrated fully or in a slightly modified way in the final framework, which serves the multiple objectives of the study. In the end, the framework developed is composed of different complementary methods that provide enhanced understanding of sustainability of current WM system and plausible eco-innovative scenarios, ultimately providing a fundamental support to policies and decisions.

3.1. Holistic Sustainability for Urban Waste Management: What Does It Mean?

The development of a conceptual sustainability framework for waste management based on a life cycle thinking approach can support business, local/regional authority and policy makers in finding resource efficient strategies to increase the economic, environmental and social performance. It is key to start with the analysis of the present WM system, how materials are flowing through the urban and rural parts of a city and beyond, the quantities and value of streams, the stakeholders/actors involved and their link and proximity details, the role of land and infrastructure, etc., which is different for each metropolitan area. Examining and mapping the current waste management system, i.e., the focus area where the waste is produced, and the pathways of treatment and production of secondary goods is a first step towards full transparency. The concept of life cycle thinking is introduced in waste policy (cfr., the Waste Directive Framework; EC, [8]) to avoid burden shifting among processes and regions [37]. It follows the 4 steps as defined in the International Organization for Standardization (ISO) 14040 guidelines: goal and scope definition, data inventory, impact assessment and interpretation.

The goal and scope phase includes a description of the intended objective(s), the chosen system boundaries, the functional unit (FU), which represents the function of the product/service under study which forms the basis for comparison between alternative products or services, and methodological choices (e.g., time scale, allocation procedures, assessment criteria, etc.).

The choice of the functional unit (FU) is fundamental; it represents the function of the product/service under study which forms the basis for comparison between alternative products or services, and methodological choices (e.g., time scale, allocation procedures, assessment criteria, etc.). The FU should account for the serious challenges posed by a continuation of the short-term and long-term trends of increasing waste flows. In this case, the FU can express the annual quantity of waste generated in a geographical area, a measure to facilitate the assessment of waste prevention and waste treatment options [6]. In principle, if the aim of the study is to assess the sustainability footprint of managing the waste which is generated in a focus area, possibly imported waste should not be part of the functional unit. This allows a fair comparison between management systems of different areas. Yet, accounting for eventual credits/burdens of treating imported waste may be necessary when assessing the sustainability of strategies involving changes in treatment capacity [38].

In addition, defining the system boundaries is crucial. Because the objective is to develop a framework for waste management to support the local government in making more sustainable choices, it is important to include not only the waste collection, treatment and possible secondary product-production processes (cfr. foreground system), but also the supply chain processes which support the activities of the foreground system in terms of providing energy, materials, etc. (cfr. background system), to embrace a life cycle approach. The foreground system of the framework consists of the core WM system, including collection of waste in the focus area, and linked with the area-specific generated waste, the transportation, separation, treatment and production of new products (secondary goods; energy, materials, nutrients) which are introduced to the market. Figure 3 shows a hypothetical and simplified example of household plastic waste from the focus area, which is exported to other regions for further treatment, involving many different actors and processes. Collection of household plastic waste takes place in the focus area, whereas the different treatment steps are located outside the territorial boundary. The supply chain processes can be in the proximity of the waste management processes, or in the extreme, on the other side of the globe. This implies that any burden and/or saving (or credit due to energy/material recovery) associated with the treatment of the waste should be accounted for regardless of the geographic location of the process to avoid burden shifting from one region to another and must be attributed to the overall impact of the waste generated in the focus area. For example, Cimpan et al. [38] illustrated how local strategies involving food waste diversion from incineration to biogas production may also incur environmental benefits in other countries, as the surplus capacity at incineration plants may be used to combust imported waste otherwise landfilled.

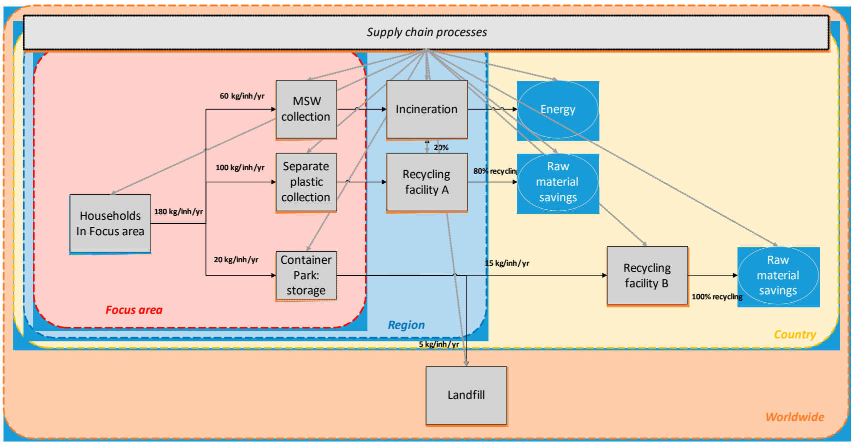

Figure 3. A hypothetical example for plastic household waste; collection in the focus area, transfer to the regional or national scale for treatment, and export to other countries for final disposal. Supply chain processes are represented as a black box system and may cover all geo-scales.

Regarding data inventory, different types of data are needed to holistically assess the sustainability of urban waste management. The data might be either quantitative, semi-quantitative or qualitative, either site-specific or generic data, from primary or secondary sources, though all in function of the goal and scope of the study and the data-availability. Examples of data needs are: material and energy flows, revenues, costs, land use and transformation, emissions and waste, social perception, nuisance experiences, etc.

A following step is the calculation of impacts based on the data inventoried. Each process, either foreground or background, associated with the generation of waste in the focus area generates impacts because of the interaction with the socio-economic and natural environment. It is extremely important to recognize the geographical spread of impacts associated with the treatment of the waste from the focus area, further referred to as multi-geoscale impacts, to avoid a possible shift of burdens to other regions. Another point of attention is the extent or magnitude of the impact of WM practices and processes in general, which can be very local (close to the point of emission) or regional or spread even further on a European or global scale. For example, the emissions of odorous compounds from a treatment plant have a very local (micro-) impact as it affects the surrounding population. Leaching of pollutants into ground or surface water due to landfilling can have an impact at the regional (meso-) scale, as eutrophication can occur tens of kilometers away from the point of emission. The emissions of greenhouse gases such as methane gas contribute to global warming, which is an impact affecting the global population (macro impact). Table 2 further explains the difference in magnitude or spread among the three types of multisize impacts.

Table 2. Different multisize impacts (micro/meso/macro) identified and described in terms of spatial area and length [39,40].

Scale	Length	Area	Description
Micro	1 m–10 km	1 m^2–100 km^2	Affects a local area
Meso	10 km–1000 km	100 km^2–1,000,000 km^2	Affects a regional/continental area
Macro	>1000 km	>1,000,000 km^2	Affect places all over the globe

On top, all these multi-geoscale and multisize types of impacts have a social, economic and/or environmental dimension, following the three pillars of sustainability and sustainable development, also referred to as the triple bottom line or the 3Ps: people, planet, prosperity [41]. When one pillar is weak, the system is unsustainable. Therefore, the waste management system must be environmentally, economically and socially sustainable. Figure 4 schematically shows that multi-geoscale processes generate multisize impacts which can be socially, economically of environmentally oriented (multidisciplinary impacts). Differentiating these impacts based on (1) the location of their cause, (2) their magnitude and (3) the type of impact, can help decision makers prioritize their action on those they can effectively reduce. In principle, all these impacts need to be accounted for to avoid burden shifting among different processes, actors and regions all over the globe.

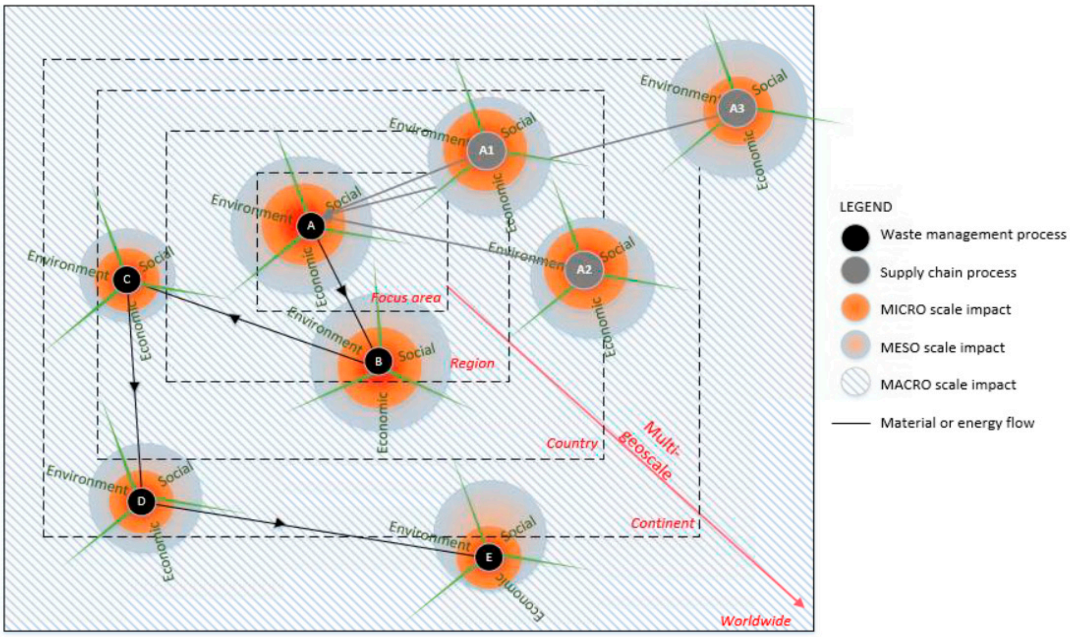

Figure 4. Overview of multisize (micro, meso, macro), multi-geoscale (processes located at different geographical scales) and multidisciplinary (social, economic, or environmentally oriented) impacts. Hypothetical example of 5 processes (A–F), that are part of a waste management production chain, while A1, A2, A3 represent supply chain processes in relation to process A.

Apart from the spatial variability in data-inventory and impact assessment which is extremely important for several impact categories such as eutrophication, land use, acidification, odor and noise, also the temporal variability is an issue of concern. For example, emissions occur at different moments in time during the life cycle of a product or service and the related impact may happen instantly or later. Temporal homogeneity of inventory data and impact assessment models is one of the major challenges in life cycle sustainability assessment studies as ignoring temporal differences may lead to large uncertainties and misleading conclusions in real practice [42]. It is also important to identify key parameters that are influenced by time, e.g., population density and waste composition, to estimate alternative scenarios or to predict future scenarios.

In addition to social, economic and environmental sustainability aspects, equally important is the technical performance of the system (e.g., recycling rates, energy recovery, frequency of collection, treatment capacities) and the political environment (e.g., the governance decision structure, regulatory control, existing national and European legislation and guidelines). Often, stakeholders are consulted during policy making to increase transparency and to make legislation more targeted and coherent. Consultations—together with impact assessments, evaluations and expertise—are a key tool for policy making [43]. However, stakeholder involvement (citizens, SMEs, big enterprises, local authority, etc.) is also important to collect full-scale technology data, to identify relevant impact categories and indicators, scenario development, complex-value assessment and to develop aggregation and weighting criteria. A stakeholder mapping exercise must be carried out in advance to carefully select individuals or organizations that would potentially be impacted by or have interest in the sustainable operation of urban waste management [44].

3.2. Selection of Methods According to the Objectives

3.2.1. Classification: Types of Methods

The ambition is to inform policy makers on urban waste management potentials by developing a holistic sustainability framework which integrates carefully selected methods that recently appeared in literature. The conceptual framework is built on 6 main types of methods as visualized in Figure 5.

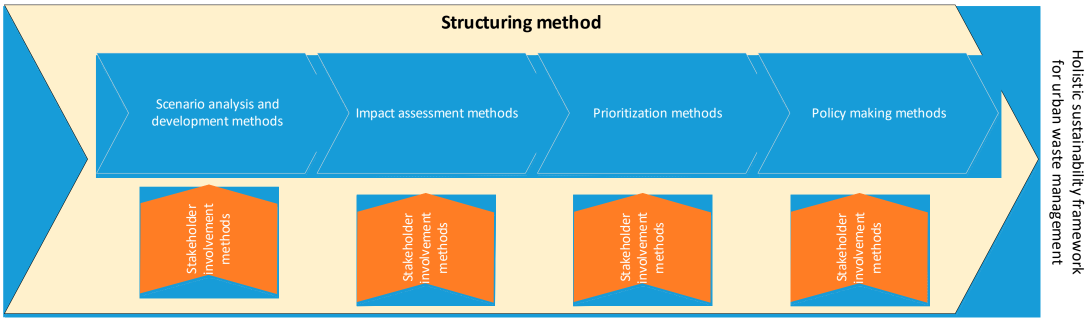

Figure 5. Comprehensive framework for sustainable urban waste management based on 6 types of methods; scenario analysis and development methods, impact assessment methods, prioritization methods, policy making methods, stakeholder involvement methods, and a structuring tool.

Scenario analysis methods describe a particular scenario: a situation fixed in time and space. These methods have the ability to quantify and/or visualize information flows (e.g., labor hours), physical (e.g., mass) or monetary (e.g., euro) flows (and stocks) and to identify the related processes and/or actors involved, while scenario development methods are able to identify other plausible scenario's, different from the current situation (e.g., in terms of geographical location, time period, technical parameters, political context, social capital, or other) [45]. Impact assessment methods quantify direct and/or indirect multi-geoscale, multisize and/or multidisciplinary impacts, considering the whole life cycle of the WM service or just part of it. Once the impact results are calculated, prioritization methods may help in scenario selection, by isolating the best scoring scenarios among different sustainability disciplines, or based on elimination by identifying current constraints that hinder the practical implementation of the most sustainable scenarios. Furthermore, policy making methods or tools are needed to formulate, adopt, and implement a strategy for addressing the unsustainable waste management practices. Further on, stakeholder involvement methods may be integrated among the latter methods, to ensure interaction with stakeholders. On top, a structuring method is needed to provide the framework with a solid configuration where the other methods (and indicators) can be integrated, to enable feedback from and to policy makers on sustainable urban waste management in Europe.

3.2.2. Retained Methods

The review of frameworks that aim to analyze the sustainability of waste management systems and screening of methods allowed identification and careful selection of those that fit the overall objective. In essence, each of the selected methods should provide further insight on the subject being explored, i.e., the methods are complementary rather than rival. Following paragraphs describe the selected methods, per category as identified before. The purpose of each of the selected methods within the final framework and their interrelations, i.e., how they complement each other to ultimately reach the objectives of the study, is broadly discussed.

Scenario Analysis and Development Methods

This category includes methods capable to visualize and/or (semi-)quantify flows or stocks or actors of a particular situation (the WM process of waste generated in a specific city), taking place in the past, present or future. Moreover, methods able to develop circular economy scenarios are included. These methods do not (or only indirectly) provide any information regarding possible impacts on the anthropogenic system and/or natural ecosystem.

- *Material and Energy Flow Analysis (MEFA)*

MEFA combines material flow analysis (MFA) and energy flow analysis (EFA), and is a method particularly used to quantify the inputs (material, thus substances and goods, and energy) and outputs (products, waste, emissions) of the processes of a particular scenario, defined in space and time (waste collection and corresponding treatment chain, and its supply processes) by focusing on one or several materials/substances [46]. Both methods must be applied at process level; however, likewise their system boundary can consist of geographical borders, which makes it interesting to quantify the total amount of a particular type of waste generated within specific city/district boundaries (Figure S1 in Supplementary Materials). MFA/EFA indicators can inform on the fate of materials or energy within the anthropogenic system, e.g., percentage of materials/energy imported/exported, the required volume of landfill [47] or recycling rates of materials [48]. They can evaluate how a region or a process chain performs in terms of material/energy management and cover therefore the technical performance of the system, but they do not characterize the impacts (cause-effect relationship) in a quantitative manner [15,49].

- *Value Stream Mapping (VSM)*

Additional to MEFA, Value Stream Mapping (VSM) can add flows of information to a product next to materials and energy flows as it makes its way through the value stream. Information flows may include statistics, data on frequency of collection, treatment capacity, high heating values, chemical compositions, number of employees, etc. The VSM perspective embraces a broader picture, not just optimizing the individual processes, but rather the whole system at once. VSM can model how value is transferred, transformed, created and destroyed across the system. For example, recycling processes are often responsible for material quality loss. It is, therefore, important to assess the quality of secondary resources, as this dramatically affects their technical functions and the related substitution effect on virgin market products [32].

- *Stakeholder Analysis (SA)*

Stakeholder analysis or stakeholder mapping identifies all the stakeholders that are the interested parties in a project/product/process/service—the people who affect and influence it, as well as those who will be influenced by it. Although this is a vital first step in any participatory exercise, stakeholders are often identified and selected on an ad hoc basis. This has the potential to marginalize important groups, bias results and jeopardize long-term viability and support for the process. Therefore, it is important to not overlook stakeholders (affected individuals, groups or organizations). Identifying stakeholders is usually an iterative process, during which additional stakeholders are added as the analysis continues. Commonly used methods to identify stakeholders are described in [50]. Combining MEFA/VSM and SA provides a holistic picture of a particular urban waste management scenario (a snapshot in time and space).

- *Urban and Industrial Symbiosis (UIS)*

This method is used to assist in the development of possible circular economy scenarios, by identifying symbiosis opportunities; specific possibilities arising from geographic proximity of urban and industrial areas to use physical resources discarded in urban areas ("wastes") as alternative raw material or energy. Overall, the exchange of products, materials, water, energy, waste, etc. (link with MEFA) between different actors such as households, small and medium-sized enterprises and neighborhoods, are visualized and improvements towards resource consumptions and waste treatment can be made (Figure S2 in Supplementary Materials). By this it provides information that is relevant to find spatial nearby possibilities for symbiotic use of resources and waste, which can go beyond traditional industrial symbiosis, but could include public and non-commercial actors. Moreover, it implies the development of new social interactions and technological innovations that offers different ways to meet society's demand for products and services [51].

- *Geographic Information System Based Spatial Analysis (GSA)*

Sustainable urban development and waste management requires insights into the specific spatial configurations to understand the current WM practices and future opportunities. Spatial analysis includes methods and techniques, which are used to study entities using their topological, geometric, or geographic properties.

Within waste and secondary resource management, Geographic Information System (GIS) traditionally supports tasks such as assessing the demand of waste disposal, optimizing waste collection routes, siting landfills or other waste treatment facilities. Furthermore, Vanderhaegen and Muro [52] recognized that GIS may potentially be beneficial in describing the baseline conditions, cumulative impact identification, prediction of impact magnitude, visualization, public consultation and participation and thereby link industrial economy and spatial planning. Spatial analysis allows the addition of location-specific data on flows and related activities. Moreover, it allows assessing the impacts not only of the whole system but also on sub-parts of the system, which is crucial for making spatial plans and actor involvement. As within spatial planning processes, different actors have different geographies of interest.

Further improvement, which is achieved through advanced spatial analyses, is acquiring a better understanding of the influence that specific spatial configurations of urbanized areas have on both the existing waste management system as well as the potential for urban and industrial symbioses. One example of overcoming the simplistic city/countryside models of the spatial organization of settlements is the classification of territories-in-between, having spatial and programmatic characteristics of both urban and rural areas, also referred to peri-urban areas. Wandl et al. [53] developed a spatial selection method to delineate urban, peri-urban and rural areas, based on demographic and land cover data. Identifying the more complex spatial structure of metropolitan areas is important, as it may provide information to spatial planners and local governments about opportunities for improvement regarding waste and resource management and its effect on livability and spatial quality, which is nowadays most often based on an urban/rural understanding of space.

- *Foresight Methods (ForeS)*

Foresight methods are important for future scenario development with reference to a particular situation, nowadays or in the past. The selection of a method depends on many factors—the context of the forecast, the relevance and availability of historical data, the degree of accuracy desirable, the period to be forecasted, the cost/ benefit (or value) of the forecast to the ordering party, and the time available for making the analysis. Mainly two types of methods exist: quantitative foresight methods such as S-curve analyses, analogies, experience curves, applying discount rates, and different sorts of extrapolations of time series [54–56], mainly applicable for short-term forecasting and qualitative foresight methods or judgmental methods such as literature reviews, expert panels, scenarios, futures workshops and Delphi surveys [57], applicable for long-term and tentative prospective analyses. Quantitative methods generate what-if scenario's, rather well-known situations based on existing data while the qualitative methods generate cornerstone scenarios which does not necessarily give quantified results.

Trends in technology innovation and development are measured by technology foresight techniques (such as road mapping), which does not only entail the forecasting of technology performances but provides a holistic approach to anticipate the future challenges and opportunities related to technological developments, e.g., in the field of waste management. The goal is to support current strategic discussion and decision-making rather than predicting precisely. Foresight methods develop a well-informed context for current decisions [58].

Methods for Impact Assessment

These methods perform the assessment of selected potential impacts in a sustainability framework (could include environmental, economic or social impacts, multisize and/or multi-geoscale impacts). Both risk assessment (RA) and life cycle sustainability assessment (LCSA) are commonly used analytical tools that proved their worth in supporting waste management decision-making processes [19,59,60]. On top, these methods can be applied in parallel to provide integrated assessment results.

- *Risk Assessment (RA)*

The aim of RA is to address the question of whether the risks from an activity or product are acceptable. According to [61], two types of risk assessment studies exist: accident risk assessment which evaluates the potential impacts associated with unexpected incidents (e.g., due to explosions, fires, etc.) on the studied site and is more related to safety measures and chemical risk assessment which quantifies the exposure (magnitude and duration) of the local environment and people to chemicals. On one side, RA can evaluate the potential adverse effects that human activities have on natural ecosystems, and indirectly the functioning of the ecosystem itself (ecological risk assessment (ERA)) or the potential human health risks to people, both workers and the public, that may now, or at some time in the future, be exposed to a certain chemical substance (Human health risk assessment; HRA). Because RA is used to evaluate potential risks of specific substances under specific conditions by taking local details into consideration, it provides a basis for comparing different waste management options from an environmental/human health point of view, enabling decision-makers to gain a better understanding and develop strategies for a sustainable development [62]. RA can be regarded as a tool that supports environmental impact assessment (EIA) as it identifies the frequency, causes, extent, severity of exposure to humans or ecosystems [63]. However, while having a dedicated focus on emissions of hazardous goods/substances and associated risks for specific targets, RA is not suitable to assess the fate of chemicals at higher geographic scales (region, continent, and global). In addition, RA does not assess the risks connected to resource extraction from the environment [64], as illustrated in Figure S3 in Supplementary Materials.

- *Life Cycle Sustainability Assessment (LCSA)*

A comprehensive life cycle-based assessment towards sustainability is represented by the LCSA assessment framework developed by [65], and recently updated by Valdivia et al. (2011), where LCSA combines life cycle assessment (LCA), environmental life cycle costing (ELCC) and social life cycle assessment (SLCA). The three methods (LCA, ELCC and SLCA) are often used in isolation, but under the requirement of keeping the same system boundary, they can be applied in parallel.

a. Life cycle Assessment (LCA)

This methodology compares the environmental impact of products, processes, systems or services over its entire life cycle (production, use and end-of-life phase) for predefined system boundaries and functional unit, cfr. product-LCA. Two types of LCA approaches exist: top-down and bottom-up (also referred to as process-based). The latter differs from top-down LCAs in the approach and related datasets used to model the system under assessment: while top-down uses national input-output (IO) economic tables to derive the impacts of a sector or industry, process-based (bottom-up) pieces together the individual unit-processes composing the supply/management chain. It is generally acknowledged that process-based LCA is most suited to assess the sustainability of WM systems because of: (i) the detailed process-specific analysis enabling to better describe technical performances; (ii) the intrinsic ability to identify potential trade-offs that occur between life-cycle stages; (iii) the possibility to rigorously assess and eventually optimize the performance of the individual unit-processes composing the system; (iv) efficiently comparing multiple similar products/services, etc. [66]. International standards for process-based LCA have been developed, e.g., the ISO standards 14040, 14044, and the Product Environmental Footprint (PEF) [67–69]. Furthermore, handbooks with guidelines on how to conduct LCA are available [70–72]. These documents explain the LCA terminology, principles and the four methodological phases (cfr. Section 3.1). However, despite the availability of a harmonized general LCA framework, it is important to be aware of the limitations of the methodology and to understand that the information it generates is neither fully complete, nor absolutely objective or accurate. Many (methodological) choices may be influenced by the values and perspectives of the LCA practitioner.

When LCA is applied to the waste management sector, further referred to waste-LCA, as opposed to product LCA, it aims at assessing the environmental impacts along the life cycle of interconnected waste management technologies based on a specific waste composition and starting from the generation of waste to the final disposal [73]. This type of LCA is typically used to compare various treatment options or technical solutions. An intrinsic part of a WM system is the co-production of several useful products, such as electricity, heat and secondary materials, i.e., there is a need to apply the attributional or consequential LCA approach [74]. In most of the cases, LCA studies on waste management prefer to apply system expansion (substitution principle) over allocation techniques, as highlighted in recent reviews [75–77], i.e., the consequential approach is preferred over attributional one. The choice follows the ISO guidelines [67]. Although the advantage of a consequential system expansion approach is the fact that it strives to represent the actual consequences of the waste scenarios assessed, i.e., of the potential decision to be taken, a major challenge is the identification of the affected market processes (i.e., the marginal technologies/products), as repeatedly highlighted in recent reviews of waste management LCAs [75–77]. The choice of the marginal suppliers typically brings along scenario uncertainties that need to be assessed with sensitivity analyses to test the criticality of the choices taken to the results [78,79].

Despite the high resolution on individual processes and technologies, process-based LCA is nevertheless often applied to provide a broad perspective, e.g., for global impact evaluation [80] as shown in Figure S3 in Supplementary Materials. However, many local impacts occur in the WM sector, such as odor, noise, etc., which are highly relevant for those living nearby the treatment facilities. In this context, RA could be used as it has a remarkably narrow and local focus and is more suitable for evaluation of site- and time-dependent conditions. Therefore, RA methodology can be integrated in the impact assessment step of LCA, for the development of spatially-differentiated characterizations factors which allows a better accounting of local impacts. On top, GSA and foresight techniques may be used in the LCIA step, to include temporal and spatial information in the characterization factors (CFs). For example, Taelman et al. [81] calculated spatially-differentiated CFs based on GIS-based net primary production data to account for land use as a natural resource in LCA. Levasseur et al. [82] introduce the concept of dynamic LCA, where the temporal profiles of emission are considered, and a dynamic characterization model is used to obtain time-dependent CFs.

b. Life Cycle Costing (LCC)

An economic analysis used in combination with a LCA and with equivalent system boundaries is LCC, a method used to calculate the total costs and revenues of a product, process or an activity over its lifespan, such as purchase price and all associated costs (delivery, installation, insurance, etc.), operating costs, including energy, fuel and water use, spares and maintenance, and end-of-life costs (such as decommissioning or disposal) or residual value (i.e., revenue from sale of product). One aspect that can be challenging is that LCC attempts to capture all costs across the life cycle, and some costs are borne by different actors with very different perspectives of the costs and potentially conflicting goals. An LCC may also be conducted to inform decision making on the cost borne by a particular actor present in the system. When performing LCC and LCA together, it is very important to avoid double counting: as explained in [83,84], LCC can be distinguished into conventional, environmental, and societal. While conventional LCC only accounts for the financial costs (i.e., internal budget costs and transfers, i.e., taxes, fees, and pecuniary externalities), environmental LCC consists of a conventional LCC analysis complemented with a parallel (classic) LCA analysis where environmental impacts are separately accounted for and reported. In the environmental LCC, the transfers should be included either in the LCC or LCA part, and externalities are not accounted for (except for those external costs that are expected to be internalized because of e.g., legislation, polluter pays principles). This provides a snapshot of economic alongside environmental burdens associated with a specific scenario, albeit the two aspects are reported separately. Lastly, societal LCA merges conventional LCC and (environmental) LCA results into one single result where internal budget costs are summed to external costs (i.e., the environmental impacts from the LCA are monetized as well as any other known externalities; transfers are excluded) using the so-called shadow prices. Economic life-cycle inventory faces many of the same data access and quality issues faced in LCA. Notably, robust data on shadow prices are lacking and only exist for a limited number of environmental emissions [83]. For this reason, we retain only environmental LCC (ELCC) in our proposed framework. Procedures for interpretation, communication, and review of the ELCC results are analogous to those for LCA.

c. Social Life Cycle Assessment (SLCA)

Social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle on human well-being, can be assessed by SLCA (least mature field of LCSA), which can complement LCA and ELCC. Although SLCA follows the ISO 14040 framework, some aspects differ, are more common or are amplified at each phase of the study. The UNEP Guidelines for Social Life Cycle Assessment of Products proposes a methodology to develop life cycle inventories. A life cycle inventory is elaborated for indicators (e.g., number of jobs created) linked to impact categories (e.g., local employment) which are related to five main stakeholder groups (e.g., [i] worker; [ii] consumer; [iii] local community; [iv] society and [v] value chain actors). While, an LCA and ELCC will mainly focus on collecting information on (mostly) physical quantities and monetary flows related to the product and its production/use and disposal, a SLCA will collect additional information on organization related aspects along the chain [85]. The importance of understanding social characteristics of supply chains have been increasingly recognized and lately many developments in the field allow a better quantification of these aspects, e.g., through the development of databases such as PSILCA [86] containing social information [87].

Methods to Prioritize

The following methods help to prioritize the results of certain impacts, e.g., between different impact categories or within a particular impact category. These methods assist in the comparison between scenarios because they deal with issues of weighting and normalizing individual results. This comes from the need to synthetize the results of the assessment to facilitate comparisons and communication to stakeholders/decision makers [88].

- *Analytic Hierarchy Process (AHP)*

The Analytic Hierarchy Process (AHP) is an effective tool for dealing with complex decision making and may aid the decision maker to set priorities and make the best decision. By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of a decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision-making processes. The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made (Figure S4 in Supplementary Materials). It is important to note that, since some of the criteria could be contrasting, it is not true in general that the best option is the one which optimizes each single criterion, rather the one which achieves the most suitable trade-off among the different criteria (e.g., social, economic, environmental, technical pillars). The AHP generates a weight for each evaluation criterion according to the decision maker's pairwise comparisons of the criteria. The higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each scenario (alternative) according to the decision maker's pairwise comparisons of the scenarios based on that criterion. The higher the score, the better the performance of the alternative with respect to the considered criterion. Finally, the AHP combines the criteria weights and the scenario scores, thus determining a global score for each option, and a consequent ranking. The global score for a given alternative is a weighted sum of the scores it obtained with respect to all the criteria.

- *Constraint Optimization (CO)*

Constraint optimization methods consider several system constraints such as the service or demands to be fulfilled (e.g., waste to be treated per year or energy-carriers to be generated, etc.), the technological capacities available or projected depending on the scope, and the legislative barriers/bans that are imposed on the system, and later derive optimal solutions on the basis of targeted objectives, for example minimizing global warming and costs, maximizing job opportunities, etc. In this context, advanced multi-objective formulations enable to find the pareto-optimal solution across the considered targeted objectives simultaneously (Figure S4 in Supplementary Materials). Different state-of-the-art modelling techniques exist for this, some of which permit to avoid weighting of the objectives, for example by defining upper and lower bounds for allowable/acceptable impacts and then deriving the optimum in this space as illustrated in [89]. This can be further advanced with other approaches for "structuring" the results such as AHP, to prioritize specific impact categories/objectives. CO can be used during scenario development, to consider possible constraints, and to analyze a scenario for feasibility and practical implementability and can also be used to identify efficient trade-offs in place of traditional weighting.

Policy Making Methods (Polmak)

Understanding the policy making and implementation process is important to potentially integrate research results [90]. Policy-making is a five stage process; agenda setting (based on a public problem or issue), policy formulation (policy makers formulate legislative, regulatory, or programmatic strategies to address the problem), policy adoption (from policy proposals to adopt a particular solution in the form of laws or bureaucratic rules), policy implementation (establishment of procedures, writing guidance documents, and issue grants-in-aid to other government bodies) and policy evaluation (analysis whether or not the policy addresses the original problem), Figure S5 in Supplementary Materials. Evaluation may reveal a need for revisions in policy, a need for changes in implementation, or even a whole new policy. It may also reveal new problems in need of policy solutions [91]. During policy development, stakeholder engagement is a meaningful part of formulating and implementing legislation because the stakeholders are those for whom such policy is designed to provide benefits, and/or on whom it imposes constraints.

Stakeholder Involvement Methods (SI)

Once the stakeholders are identified (cfr. stakeholder analysis), stakeholder involvement and active participation is crucial in each of the steps previously described: scenario analysis and development (e.g., by identifying innovative technologies), impact assessment modelling (e.g., during impact category and indicator selection), prioritization steps (e.g., by expressing their preference regarding weighting factors among different disciplines) and policy making (e.g., by clarifying their current issues and needs in society). Several participatory methods are commonly used, including questionnaire and telephone surveys, community workshops, public meetings and public comments opportunities [92].

Structuring Methods

Methods or tools to organize sophisticated empirical scientific research, help stakeholders to articulate and structure challenges and support transdisciplinary knowledge at a level appropriate for policy and decision making [93]. The Driving forces—Pressures—States—Impacts—Responses (DPSIR) Framework is the latest version of indicator frameworks developed by the Organization for Economic Co-operation and Development (OECD) [94]. This framework reveals a chain of causal links starting with "driving forces" (economic sectors, human activities) through "pressures" (emissions, waste) to "states" (physical, chemical and biological) and "impacts" on e.g., ecosystems, human health and functions, eventually leading to political "responses" (prioritization, target setting, indicators), Figure S6 in Supplementary Materials. Describing the causal chain from driving forces to impacts and responses is a complex task, and tends to be broken down into sub-tasks, e.g., by considering the pressure-state relationship separately. This framework can easily be applied to the waste/secondary resource sector as illustrated/done in [95] or [96]. Although this is developed mainly to address environmental sustainability, it can as well be a basis for the calculation of social, economic and technical aspects [97]. The DPSIR framework forms the basis of the holistic sustainability framework for urban waste management, as it enables a structure for indicators, methods, criteria and objectives, also including the responses on policy and society level.

3.3. Sustainability Framework

The proposed sustainability framework for urban waste management in European cities, which evaluates multi-geoscale, multisize and multidisciplinary impacts, has the final aim of supporting policy and decision making. Table 3 provides a clear overview of the main purpose of each of the selected methods within the framework. The DPSIR framework had been chosen to provide the overall structure of the conceptual framework, the latter being iterative. The responses may initiate new driving forces, which are different among individuals, companies, nations, etc. and they can be either primary (e.g., the need for food, low unemployment level) or secondary (e.g., the need for entertainment, faster mobility, etc.). Waste generation is for example extremely dependent on driving forces such as urban population growth, socio-economic development, and changes in consumption patterns. Driving forces lead to human activities such as transportation or food production, i.e., results of meeting a demand. These activities lead to pressures, which influence the state and consequentially causes impacts on society and environment, which may evoke new responses.

A starting point of this framework is a quantitative description of the current situation, a snapshot in time and space: the analysis of the WM system as it is today, based on (a) targeted waste stream(s) which is (are) generated in the focus area. This scenario is the basis for performing any sustainability impact assessment or further scenario development. This "base case" scenario needs to be analyzed in terms of physical and non-physical flows, the foreground and background processes and stakeholders, next to spatial, cultural and demographic characteristics. However, as the goal is "to perform better" in terms of overall sustainability, the key question is: what are the current bottlenecks, and which are the most promising eco-innovative scenarios? Therefore, a first step is to develop feasible alternative scenarios, based on circular economy principles, and accordingly analyze them in the same way as the basis scenario of the current waste management system. To do so, a set of scenario analysis and development methods was proposed, to be used complementary to each other providing the most comprehensive information. Each of these scenarios generates different pressures (e.g., excessive use of natural resources, increased prices because of low availabilities, difficult labor conditions). Because of the pressures of the different scenarios, the "state" or quality of the natural environment, the economic performance and/or human health and well-being is affected. In other words, changes in the state may have "impacts" such as on the functioning of ecosystems, their life supporting abilities, and ultimately on human health and on the economic and social performance of society [97].

Table 3. Overview of the selected methods, and description of their main function in the overall framework.

Type of Methods	Method	Main Function in Framework
Scenario analysis and development	MEFA	Quantifies and visualizes material and energy flows within the different scenarios.
	VSM	Adds information flows (value) to the different scenarios.
	SA	Identifies the stakeholders that are influenced by/able to influence decisions regarding waste management.
	UIS	Identifies opportunities to exchange material/energy/waste between urban and industrial areas and supports the development of circular economy scenarios.
	GSA	Shapes the scenarios from a spatial point of view and provides information to develop spatially-differentiated CFs for impact assessment.
	ForeS	Enables the development of scenarios that are snapshots of the future.
Impact assessment	LCA	Calculates environmental impacts, based on a life cycle perspective.
	ELCC	Calculates economic impacts, based on a life cycle perspective.
	SLCA	Calculates social impacts, based on a life cycle perspective.
Prioritizing	AHP	Helps in prioritizing among different scenarios based on selected criteria.
	CO	Useful to analyze conflicting objectives and to systematically identify efficient trade-offs.
Policy making	Polmak	Provides a better understanding of the policy making process.
Stakeholder involvement	SI	Multi-stakeholder involvement, i.e., integrating their ideas, knowledge, preferences, concerns, etc., is crucial in every step of the framework.
Structuring	DPSIR	Provides the overall structure of the framework.

When the ultimate goal is to improve the sustainability of the waste management system, at least the three pillars of sustainability should be addressed (Economy, Society and Environment); however, also the technical domain is extremely valuable as it identifies in an accessible way to discover when and to what extent a scenario reaches the policy targets set (e.g., target for recycling 65% of municipal waste by 2030 or a ban on landfilling of separately collected waste). These 4 pillars are considered the level 1 criteria according to the AHP approach. Level 2 criteria (sub criteria) on the other hand are the separate indicators, such as acidification, odor nuisance, job creation, child labor, capital investments, etc. In this respect, LCA, ELCC, SLCA and RA are methods that can be used in a combined way to cover the pillars and subcategories, to assess different types of impacts (multidisciplinary, multi-geoscale and multisize) in a (semi-) quantitative way, for each of the developed scenarios.

These methods are used to generate results along the cause-effect chain, which are then aggregated and eventually weighted to identify the best scenarios. The weighting is strongly affected by the decision maker's interest. The weighted sum of the scores of each (sub)criteria is the global score for one scenario, that way all scenarios with the same system boundary can be compared, i.e., based on pair-wise comparisons among the criteria, a ranking order of preference could be established (cfr. AHP method). However, as mentioned before, it may happen that not all scenarios are feasible to be implemented in practice, due to some technical, legislative, or other, constraints. Therefore, the CO method may be used to explicitly reflect the system- and process-specific constraints imposed upon the optimal solutions, to analyze possible conflicting objectives and to systematically identify trade-offs across multiple objectives [89,98]. The responses by society or policy makers are then the result of an undesired impact or the transition towards the most sustainable option. Responses can affect any part of the chain between driving forces and impacts, cfr. iterative model [97]. An example of a response related to urban waste management is the development of a policy to improve the separate waste collection system, to avoid food losses along the chain, enforcement of landfill taxes, development of an advanced waste treatment technology, concrete measures to promote re-use and stimulate industrial symbiosis—turning one industry's by-product into another industry's raw material, economic incentives for producers to put greener products on the market and support recovery and recycling schemes (e.g., for packaging, batteries, electric and electronic equipment, vehicles).

A major challenge in meeting sustainability goals is to strengthen cross-sectoral and trans-boundary developments in the field, where stakeholder participation, coordination, and commitment beyond narrow self-interest is required [99]. As can be seen from Figure 6, it is recommended to involve stakeholders in every step, from scenario development to policy making. The paradigm is that the community is at the center of what foremost needs to be protected, the community as it exists today though also considering the needs of future generations. The stakeholders, including the community, should be empowered to influence and share control over development initiatives and political decisions. The respective stakeholders must be involved in identifying and shaping eco-innovative solutions to ongoing waste management problems, to select and weight LCSA impact categories and interpret broad environmental issues interlinked with economic and social aspects, and support decision making for long lasting development solutions within the community's capacities [34].

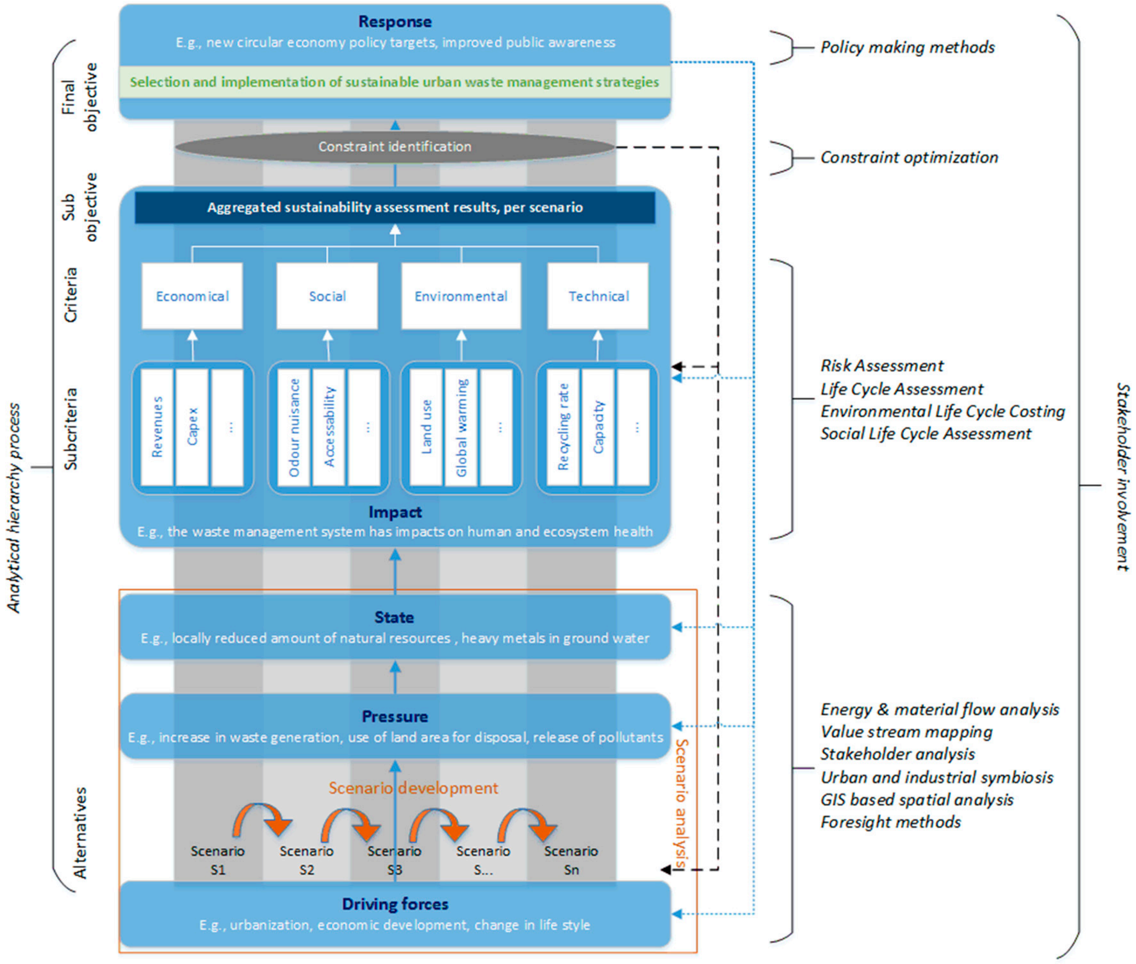

Figure 6. A holistic sustainability framework for waste management in European cities.

4. Conclusions

Sustainable development and resource efficiency ranks high on the European political agenda, visible through recent commitments such as the Raw Material Initiative on critical raw materials and the EU Circular Economy action plan [100,101]. The waste management sector is accordingly expected to reduce its adverse socio-economic and environmental impacts. However, this is challenging as multiple aspects are involved (economics, environment, social issues, geographic boundaries, linkages with other sectors, etc.). As a contribution to improve the assessment of the waste management sector's performance, this study proposes a conceptual framework based on a review of existing approaches and what the authors believe to be necessary advancements.

The framework consists of several methods which application is useful to provide informed and scientific sound evidence for decision- and/or policy-making in the field of waste management, to identify preferable WM scenarios for different cities or municipalities and to complement existing waste management insights. The concept of Life Cycle Thinking (LCT) is introduced to assess the performance of waste management in terms of impact by considering the whole supply chain, from raw material extraction and conversion, manufacture and distribution, use and/or consumption, to treatment and disposal. Key is to avoid burden shifting, among geographical regions, unit processes, or impact categories/sustainability pillars. However, as the LCT-based tools such as LCA were mainly developed to quantify regional/global impacts, also risk assessment is identified as an important method to measure local impacts. Quantifying the latter is extremely important for local government to determine and execute measures in the context of circular economy. Their authority is restricted to a city's administrative boundaries, i.e., it is important to have a clear vision on the possibilities within their authorized region, to reduce local impacts, and improve inter-municipal collaboration, while for national government agencies it is important to reach the targets set by the European Commission (EC).

Furthermore, the framework highlights the importance of spatial and temporal differentiation, constraints identification, as well as the value/quality of flows. This is particularly important in respect to secondary goods produced from waste. Indeed, knowing their quality is essential as this determines the actual market substitution effect on virgin products, thus the overall displacement (circularity) effect. On top, the involvement of stakeholders from scenario development, to impact assessment and policy making is recognized.

After careful evaluation of the available frameworks, it appeared that none of them was comprehensive enough to cover the objectives of this study. This does not necessarily disqualify their use, but, rather highlights their limitations. Overall, the framework proposed here is expected to provide guidance and structure on the use of methods to perform a holistic sustainability assessment of UWM and assists in European policy-making. This framework is ought to be easily transferable to other sectors (instead of waste management).

5. Discussions and Recommendations for Future Developments

Apart from the advantages that the development of a comprehensive sustainability framework may bring to the WM sector, it also implies an increased level of complexity, consequently demanding much time and resources (e.g., employees, software, knowledge, etc.). Somehow, a trade-off needs to be found between time and resource spending and the expected outcome of the research, with respect to an efficient allocation of means. However, the recommendations for further development as described below may reduce extensive resource and time usage.

5.1. Data Availability and Quality

To develop and analyze specific urban waste management scenarios, a significant amount of data is required, e.g., the source (households, small businesses, industrial plants, etc.), the amount of waste generated, the composition and value of waste and secondary goods, the direct and indirect emissions to water, soil and air, the geographical location of unit processes, the actors involved, the costs and revenues, etc. Other than for screening sustainability studies, there is a preference for collecting primary scenario-specific data in a bottom-up manner for detailed case studies (i.e., spatial and temporal differentiated inventory data, ideally measured, at both a unit-process and organization-level) rather than collecting aggregated top-down information and usage of average default values from secondary data sources such as estimations based on models, prior measurements, and published data [102]. This data is characterized not only by quantitative, but also by qualitative and semi-quantitative information. However, scenario development and analysis, as well as in impact assessment, clear guidelines on integrating GIS and forecasting supported tools is missing, which hampers a fast and efficient implementation and development of spatially/temporally-differentiated characterization, normalization or weighting factors, or site-specific data collection [103,104]. However, it must be said that there are many recent attempts to improve spatial/temporal differentiation in the field. For example, datasets with supply chain information such as ecoinvent v3.3 have made an important effort to differentiate the products supply chain flows and processes into the different geographic markets (consisting then of a mixture of countries). By using these, it is possible to have a geographic information on the impact occurrence (i.e., where). Other datasets such as the social hotspot database, GABI database, Agri-footprint, etc. do not yet contain this specific information. Yet, the emissions of waste management facilities may be very local, e.g., noise and smell. These are typically not included in current datasets for intrinsic difficulties in achieving good and reliable qualitative data. However, this data could be provided with dedicated studies/projects on urban waste management, e.g., by projects funded under WASTE-6b-2015—Eco-innovative strategies program.

Apart from data availability, also the quality of data is important as it affects the quality of decision support in the end. The level of data quality can be quantified in an uncertainty analysis. According to [105], there are 4 types of uncertainty: parameter or data uncertainty, model uncertainty, scenario uncertainty and uncertainty due to simplification. There are many kinds of approaches to deal with uncertainty; the scientific approach (e.g., laboratory tests to measure the Lethal Concentrations (LC50) to be used for the characterization model), the constructivist approach (stakeholder involvement), the legal approach (relying on policy documents such as ISO or United States Environmental Protection Agency), the statistical approach (e.g., Monte Carlo analysis or fuzzy set theory). However, although concerns about the quality of data for sustainability assessment have been raised for many years, the assessment of this quality is still not a standard feature, and systematic and comprehensive uncertainty analysis is still lacking in most case studies and databases [106].

5.2. Life Cycle Sustainability Assessment as A Tool for Policy Making

LCSA has received increasing attention over the past years mainly due to its comprehensiveness, while at the same time, its exact meaning, content and objectives are not always sufficiently transparent [107]. While using (environmental) LCA to measure the environmental dimension of sustainability is widespread, similar approaches for the economic (LCC) and the social (SLCA) dimensions of sustainability have still limited application worldwide. ISO guidelines specify the framework for LCA that consists out of 4 phases, and which is applicable to (e)LCC and SLCA, i.e., although the tools have different aims, a common goal and scope is needed when undertaking a combined LCSA. Therefore, an elaborated functional unit is needed, describing both technical and societal characteristics, and the LCSA system boundary must contain all unit processes relevant for at least one of the tools. However, no clear guidelines are available on the system boundary selection strategy or the justification of potentially excluded life cycle stages. The same goes for the endpoint and midpoint impact category selection. For an LCSA study, it is recommended that all impact categories that are relevant across the life cycle of a product/service are selected. In the case of waste management, impact categories such as odor nuisance, noise, etc. are very relevant, but these are not mentioned in the general perspectives provided by each of the three tools. The relevancy of impact categories could be addressed by stakeholder involvement. However, it the end, it is still up to the practitioner to finally decide on the impact category selection approach, which often results in non-comparable results among case studies [108]. Another aspect is the selection of robust, reliable and relevant indicators to assess the impacts related to the previously selected categories. This choice is not straightforward, as continuously new developments are published in the field of impact indicators (e.g., [109] for smell and [110] for marine surface area resources). Overall, LCSA is an abstract framework, with a multi-dimensional perspective and based on multi-criteria decision analysis, which needs to be made more operational.

Sustainability assessment studies of (urban) waste management studies also need to deal with handling of multi-functionality, for example when having multiple output-products from a technology. In this case, a choice must be made between different approaches among which system expansion and subdivision should be prioritized conforming with recent recommendations at e/u level [69]. Yet, many published LCA studies have applied a mix of allocation rules, combining revenue allocation, physical allocation, and system expansion within the same system, which obscures the system boundary identification and the main aim of the study [111]. The mingling between different types of allocation approaches may happen within the foreground system, the background system, or among both, as some databases with background information may be built with allocation principles or cut-offs rules that do not provide both allocation options. Consequential and attributional approaches have their own limitations and strengths, as thoroughly discussed in e.g., [112,113], which stimulates a debate on the most appropriate method, based on their accuracy, uncertainty, and how they inform policy decisions. On top, it should be noted that a waste-LCA often does not assign any burden of upstream processes to the waste generated, also referred to as the zero-burden assumption. However, also this is highly debated recently, because it becomes questionable when comparing the sustainability of products obtained from the valorization of waste with products originating from virgin raw materials. Several approaches exist to allocate part of the burden from consumer goods' production to the products from waste [114,115], such as the adapted 50:50 approach where the consumer goods and the recycled material each bear 50% of the environmental burden of the virgin raw material processing and recycling process [116]. Yet, regardless of the ongoing discussions, no consensus has been achieved.

Overall, LCSA can provide decision-makers with comprehensive data on the environmental, social and economic impacts of products, services and processes during the entire life cycle. It is intended to be a systematic, holistic, and objective method as it follows guidelines such as ISO 14040 (International Standard Organization 1997), CEN/TC 350 (CEN/TC 350 Sustainability of construction works 2012), the EeBGuide InfoHub [117], the ILCD handbook [71], the Handbook for Product Social Impact Assessment [118], etc. On this basis, it is desirable that literature studies are compatible and comparable with each other; however, they often consist of highly varying results, even when assessing similar products or services. This is due to the inherent differences in the approaches, the subjective and objective choices and assumptions a practitioner can make during each stage of an assessment, and the availability of data. This causes confusion for policy-makers, as it does not offer straightforward, solid background information without an in-depth understanding of the premises of a certain study and a good methodological knowledge. It is, therefore, recommended to provide clear and transparent reporting about methodological choices and explanations of results policy-makers with can make well-informed decisions [119].

5.3. Goal and Scope of the Conceptual Framework

The conceptual framework proposed in this study is comprehensive in the sense that it covers multiple aspects involved in the assessment of the sustainability of urban waste (secondary resource) management systems. As this is an important contribution in the transition towards a more circular economy, it is not the only step that is needed. Measures should also be taken more upstream, to prevent or reduce waste from being generated, e.g., through applying eco-design rules, which may extend the lifetime of a product, improve the ability to disassemble it, or reduce virgin resource needs by integrating recycled material in the manufactured products. The holistic sustainability framework as presented here could be applied to the more upstream processes (of manufacturing, mining, etc.) as well, with some slight modifications in datasets/system boundaries, as the overall selection of methods would stay the same. It could be useful to inform policy-makers even more about the best (combined) strategies to follow.

The framework as shown in Figure 6 might be adaptable for case studies other than waste management. However, the research has focused on collecting literature and data relating to this sector, and the framework should therefore be only considered suitable for this. Albeit the framework identified the main methods needed to perform a full sustainability analysis, it nevertheless did not propose a specific set of indicators to be used. There is no consensus regarding the choice of indicators (although the PEF recommends some methods), and it is highly dependent on the objectives of the study and the specific scenarios examined. A validation of this framework is desirable by applying it to a real-life case study, which is the intention of the authors in a later stage.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/7/2184/s1. Figure S1: Simplified schematic representation of MEFA, flows, stocks and boundaries. In this figure, goods represent material goods with a positive economic value only (excluding waste and emissions). Inflows, outflows and stocks are connected to geographic boundaries (left), inputs and outputs to system boundaries (right); Figure S2: Representation of industrial and urban symbiosis within a city [1]; Figure S3: Simplified schematic representation of flows and boundaries considered within the following assessment methods; (A) risk assessment (RA) focusing on emissions causing local impacts, (B) process-based LCA containing both emissions-based and resource-based indicators to assess mainly global impacts. In this figure, goods represent material goods with a positive economic value only (excluding waste and emissions); Figure S4: Simplified schematic representation of the concept of (A) the Analytical Hierarchy Process (AHP) which makes use of a hierarchy of criteria and alternatives [2] and (B) the pareto-optimization method; Figure S5: The policy making cycle [3]; Figure S6: Simplified schematic representation of the concept DPSIR: Driving forces—Pressures—States—Impacts—Responses Framework (DPSIR) which helps to structure indicators in the context of a causal chain [4].

Author Contributions: S.E.T., D.T., A.W. and J.D. all contributed to conception, design and interpretation of the proposed framework. All authors participated in drafting the article and critically revising the content. The authors gave their final approval of this version (and any revised form) to be submitted.

Funding: This research was funded by the REPAiR project (ID 688920) under H2020-EU.3.5.4.—Enabling the transition towards a green economy and society through eco-innovation, WASTE-6b-2015—Eco-innovative strategies.

Acknowledgments: The authors thank Sophie Sfez (Ghent University, department of green chemistry and technology) for her valuable contribution and comments at the first stage of this paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Hamilton, H.; Peverill, M.S.; Müller, D.; Brattebø, H. Assessment of Food Waste Prevention and Recycling Strategies Using a Multilayer Systems Approach. *Environ. Sci. Technol.* **2015**, *49*, 13937–13945. [CrossRef] [PubMed]
2. Yuan, H.; Huang, Z.; Xu, P. A framework for eco-efficiency of C&D waste management. *Procedia Environ. Sci.* **2016**, *31*, 855–859. [CrossRef]
3. Ellen MacArthur Foundation. Cities in the Circular Economy: An Initial Exploration, 2017. Available online: https://www.ellenmacarthurfoundation.org/publications/cities-in-the-circular-economy-an-initial-exploration (accessed on 18 January 2018).
4. De Wit, M.; Hoogzaad, J.; Ramkumar, S.; Friedl, H.; Douma, A. *The Circularity Gap Report: An Analysis of the Circular State of the Global Economy*; Circle Economy: Amsterdam, The Netherlands, 2018.
5. Eurostat. Available online: http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics (accessed on 10 December 2017).
6. Ekvall, T.; Assefa, G.; Bjorklund, A.; Eriksson, O.; Finnveden, G. What life-cycle assessment does and does not do in assessments of waste management. *Waste Manag.* **2007**, *27*, 989–996. [CrossRef] [PubMed]
7. Rockström, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F.S.; Lambin, E.; Lenton, T.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A safe operating space for humanity. *Nature* **2009**, *461*, 472–475. [CrossRef] [PubMed]
8. European Commission (EC). *Directive 2008/98/EC on Waste of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives—Official Journal of the European Union L 312/3*; European Commission (EC): Brussels, Belgium, 2008.
9. Ellen MacArthur Foundation; Granta. Circular Indicators: An Approach to Measuring Circularity. Available online: https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Methodology_May2015.pdf (accessed on 12 January 2018).
10. Huysman, S.; Debaveye, S.; Schaubroeck, T.; De Meester, S.; Ardente, F.; Mathieux, F.; Dewulf, J. The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resour. Conserv. Recycl.* **2015**, *101*, 53–60. [CrossRef]
11. European Environment Agency (EEA). *The European Environment—State and Outlook 2015: Synthesis Report*; European Environment Agency: Copenhagen, Denmark, 2015.
12. European Commission (EC). *Being Wise with Waste: The EU's Approach to Waste Management*; European Commission: Brussels, Belgium, 2010.

13. Weiland, U. *Land and Landscape Management in Europe—Common Report 2011*; Land and Landscape Management in Europe—Joint Master Programme (JMP) Sustainable Development; University of Leipzig: Leipzig, Germany, 2011.
14. Kasanko, M.; Barredo, J.I.; Lavalle, C.; McCormick, N.; Demicheli, L.; Sagris, V.; Brezger, A. Are European cities becoming dispersed? A comparative analysis of 15 European urban areas. *Landsc. Urban Plan.* **2006**, *77*, 111–130. [CrossRef]
15. Stanisavljevic, N.; Brunner, P.H. Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. *Waste Manag. Res.* **2014**, *32*, 733–744. [CrossRef] [PubMed]
16. Shmelev, S.E.; Powell, J.R. Ecological–economic modelling for strategic regional waste management systems. *Ecol. Econ.* **2006**, *59*, 115–130. [CrossRef]
17. Balaman, Y.; Wright, D.; Scott, J.; Matopoulos, A. Network design and technology management for waste to energy production: An integrated optimization framework under the principles of circular economy. *Energy* **2018**, *143*, 911–933. [CrossRef]
18. Chen, P.; Liu, K.; Ma, H. Resource and waste-stream modelling and visualization as decision support tools for sustainable materials management. *J. Clean. Prod.* **2017**, *150*, 16–25. [CrossRef]
19. Chong, Y.T.; Teo, K.M.; Tang, L.C. A Lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability. *Renew. Sustain. Energy Rev.* **2016**, *56*, 797–809. [CrossRef]
20. Corder, G.D.; McLellan, B.C.; Green, S.R. Delivering solutions for resource conservation and recycling into project management systems through SUSOP. *Miner. Eng.* **2012**, *29*, 47–57. [CrossRef]
21. Cristobal, J.; Limleamthong, P.; Manfredi, S.; Guillen-Gosalbez, G. Methodology for combined use of data envelopment analysis and life cycle assessment applied to food waste management. *J. Clean. Prod.* **2016**, *135*, 158–168. [CrossRef]
22. Habibi, F.; Asadi, E.; Sadjadi, S.J.; Barzinpour, F. A multi-objective robust optimization model for site-selection and capacity allocation of municipal solid waste facilities: A case study in Tehran. *J. Clean. Prod.* **2017**, *166*, 816–834. [CrossRef]
23. Iacovidou, I.; Millward-Hopkins, J.; Busch, J.; Purnell, P.; Velis, C.; Hahladakis, J.; Zwirner, O.; Brown, A. A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste. *J. Clean. Prod.* **2017**, *168*, 1279–1288. [CrossRef]
24. Inghels, D.; Dullaert, W.; Bloemhof, J. A model for improving sustainable green waste recovery. *Resour. Conserv. Recycl.* **2016**, *110*, 61–73. [CrossRef]
25. Khalili, N.; Duecker, S. Application of multi-criteria decision analysis in design of sustainable environmental management system framework. *J. Clean. Prod.* **2013**, *47*, 188–198. [CrossRef]
26. Liu, G.; Yang, Z.; Chen, B.; Zhang, L. Modelling a thermodynamic-based comparative framework for urban sustainability: Incorporating economic and ecological losses into emergy analysis. *Ecol. Model.* **2013**, *252*, 280–287. [CrossRef]
27. Lupo, T.; Cusumano, M. Towards more equity concerning quality of Urban Waste Management services in the context of cities. *J. Clean. Prod.* **2018**, *171*, 1324–1341. [CrossRef]
28. Mostafa, S.; Dumrak, J. Waste elimination for manufacturing sustainability. *Procedia Manuf.* **2015**, *2*, 11–16. [CrossRef]
29. Nixon, J.D.; Dey, P.K.; Ghosh, S.K.; Davies, P.A. Evaluation of options for energy recovery from municipal solid waste in India using the hierarchical analytical network process. *Energy* **2013**, *59*, 215–223. [CrossRef]
30. Ohnishi, S.; Dong, H.; Geng, Y.; Fujii, M.; Fujita, T. A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan. *Ecol. Indic.* **2017**, *73*, 513–524. [CrossRef]
31. Papargyropoulou, E.; Lozano, R.; Steinberger, J.; Wright, N.; Ujang, Z. The food waste hierarchy as a framework for the management of food surplus and food waste. *J. Clean. Prod.* **2014**, *76*, 106–115. [CrossRef]
32. Scheel, C. Beyond sustainability. Transforming industrial zero-valued residues into increasing economic returns. *J. Clean. Prod.* **2016**, *131*, 376–386. [CrossRef]
33. Shekdar, A. Sustainable solid waste management: An integrated approach for Asian countries. *Waste Manag.* **2009**, *29*, 1438–1448. [CrossRef] [PubMed]
34. Souza, R.G.; Rosenhead, J.; Salhofer, S.P.; Valle, R.A.B.; Lins, M.P.E. Definition of sustainability impact categories based on stakeholder perspectives. *J. Clean. Prod.* **2015**, *105*, 41–51. [CrossRef]
35. Steingrímsson, J.G.; Seliger, G. Conceptual framework for near-to-site waste cycle design. *Procedia CIRP* **2014**, *15*, 272–277. [CrossRef]

36. Wilson, D.; Rodic, L.; Cowing, M.; Velis, C.; Whiteman, A.; Scheinberg, A.; Vilches, R.; Masterson, D.; Stretz, J.; Oelz, B. 'Wasteaware' benchmark indicators for integrated sustainable waste management in cities. *Waste Manag.* **2015**, *35*, 329–342. [CrossRef] [PubMed]
37. Lazarevic, D.; Buclet, N.; Brandt, N. The application of life cycle thinking in the context of European waste policy. *J. Clean. Prod.* **2012**, *29–30*, 199–207. [CrossRef]
38. Cimpan, C.; Rothmann, M.; Hamelin, L.; Wenzel, H. Towards increased recycling of household waste: Documenting cascading effects and material efficiency of commingled recyclables and biowaste collection. *J. Environ. Manag.* **2015**, *157*, 69–83. [CrossRef] [PubMed]
39. Grasland, C.; Europe in the World. Contribution of ESPON to EU Policies, Brussels. Available online: https://www.espon.eu/sites/default/files/attachments/espon_ws_06052009_grasland_europe_in_the_world.pdf (accessed on 10 November 2017).
40. Hazen, E.; Suryan, R.; Santora, J.; Bograd, S.; Watanuki, Y.; Wilson, R. Scales and mechanisms of marine hotspot formation. *Mar. Ecol. Prog. Ser.* **2013**, *487*, 177–183. [CrossRef]
41. European Commission (EC). *The World Summit on Sustainable Development People, Planet, Prosperity*; European Commission (EC): Brussels, Belgium, 2012.
42. Yuan, C.; Wang, E.; Zhaj, Q.; Yang, F. Temporal discounting in life cycle assessment: A critical review and theoretical framework. *Environ. Impact Assess.* **2015**, *51*, 23–31. [CrossRef]
43. Emmott, N.; Bär, S.; Kraemer, A. Policy review: IPPC and the Sevilla process. *Eur. Environ.* **2000**, *10*, 204–207. [CrossRef]
44. Shortall, R.; Davidsdottir, B.; Axelsson, G. Development of a sustainability framework for geothermal energy projects. *Energy Sustain. Dev.* **2015**, *27*, 28–45. [CrossRef]
45. Burdett, L.; Cooksey, E.; Christie, I.; Wehrmmey, W.; Chenoweth, J.; Clift, R. *Environment Agency Scenarios 2030*; Science Report SC050002/SR1; Environment Agency: Bristol, UK, 2006.
46. Czaplicka-Kolarz, K.; Korol, J.; Ludwik-Pardała, M.; Ponikiewska, K. Material and Energy Flow Analysis (MEFA) of the unconventional method of electricity production coal gasification. *J. Sustain. Min.* **2014**, *13*, 41–47. [CrossRef]
47. Arena, U.; Di Gregorio, F. A waste management planning based on substance flow analysis. *Resour. Conserv. Recycl.* **2014**, *85*, 54–66. [CrossRef]
48. Eckelman, M.J.; Chertow, M.R. Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii. *J. Ind. Ecol.* **2009**, *13*, 758–774. [CrossRef]
49. Zhang, Y. Urban metabolism: A review of research methodologies. *Environ. Pollut.* **2013**, *178*, 463–473. [CrossRef] [PubMed]
50. Reed, M.; Graves, A.; Dandy, N.; Posthumus, H.; Hubacek, K.; Morris, J.; Prell, C.; Quinn, C.; Stringer, L. Who's in and why? A typology of stakeholder analysis methods for natural resource management. *J. Environ. Manag.* **2009**, *90*, 1933–1949. [CrossRef] [PubMed]
51. Sun, L.; Li, H.; Dong, L.; Fang, K.; Ren, J.; Geng, Y.; Fuiji, M.; Zhang, W.; Zhang, N.; Liu, Z. Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China. *Resour. Conserv. Recycl.* **2016**, *119*, 78–88. [CrossRef]
52. Vanderhaegen, M.; Muro, E. Contribution of a European spatial data infrastructure to the effectiveness of EIA and SEA studies. *Environ. Impact Assess.* **2005**, *25*, 123–142. [CrossRef]
53. Wandl, A.; Nadin, V.; Zonneveld, W.A.M.; Rooij, R.M. Beyond urban-rural classifications: Characterising and mapping territories-in-between across Europe. *Landsc. Urban Plan.* **2014**, *130*, 50–63. [CrossRef]
54. Dyson, B.; Chang, N. Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modelling. *Waste Manag.* **2005**, *25*, 669–679. [CrossRef] [PubMed]
55. Katsamaki, A.; Willems, S.; Diamadopoulos, E. Time series analysis of municipal solid waste generation rates. *J. Environ. Eng.* **1998**, *124*, 178–183. [CrossRef]
56. Navarro-Esbrı, J.; Diamadopoulos, E.; Ginestar, D. Time series analysis and forecasting techniques for municipal solid waste management. *Resour. Conserv. Recycl.* **2002**, *35*, 201–214. [CrossRef]
57. European Commission (EC). *Final Report. Monitoring Foresight Activities in Europe and the Rest of the World*; Publications Office of the European Union: Luxembourg, 2009.
58. Hauschild, M.; Rosenbaum, R.; Olsen, S. *Life Cycle Assessment. Theory and Practice*; Springer International Publishing AG: Cham, Switzerland, 2018; p. 1215. ISBN 978-3-319-56474-6.

59. Allesch, A.; Brunner, P. Assessment methods for solid waste management: A literature review. *Waste Manag. Res.* **2014**, *32*, 461–473. [CrossRef] [PubMed]
60. Morrissey, A.J.; Browne, J. Waste management models and their application to sustainable waste management. *Waste Manag.* **2004**, *24*, 297–308. [CrossRef] [PubMed]
61. Finnveden, G.; Moberg, A. Environmental systems analysis tools—An overview. *J. Clean. Prod.* **2005**, *13*, 1165–1173. [CrossRef]
62. Rapti-Caputo, D.; Sdao, F.; Masi, S. Pollution risk assessment based on hydrogeological data and management of solid waste landfills. *Eng. Geol.* **2006**, *85*, 122–131. [CrossRef]
63. Petts, J. *Handbook of Environmental Impact Assessment: Volume 2: Impact and Limitations*; Blackwell Science Ltd.: Oxford, UK, 1999; p. 450. ISBN 0-632-04771-2.
64. Benetto, E.; Tiruta-Barna, L.; Perrodin, Y. Combining lifecycle and risk assessments of mineral waste reuse scenarios for decision making support. *Environ. Impact Assess.* **2007**, *27*, 266–285. [CrossRef]
65. Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89–95. [CrossRef]
66. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Noms, G.; Rydberg, T.; Schmidt, W.P.; Suh, S.; Weidema, B.; Pennington, D. Life Cycle Assessment: Part 1: Framework, Goals and Scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef] [PubMed]
67. International Organization for Standardization. *ISO 14040—Environmental Management—Life Cycle Assessment—Goal and Scope—Definition and Inventory Analysis*; International Organization for Standardization: Geneva, Switzerland, 2006; p. 20.
68. International Organization for Standardization. *ISO 14044—Environmental Management—Life Cycle Assessment—Requirements and Guideline*; International Organization for Standardization: Geneva, Switzerland, 2006; p. 46.
69. European Commission (EC). Analysis of Existing Environmental Footprint Methodologies for Products and Organizations: Recommendations, Rationale, and Alignment, 2012. Available online: http://ec.europa.eu/environment/eussd/pdf/Deliverable.pdf (accessed on 16 November 2017).
70. Guineé, J.B.; Gorée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; de Koning, A.; van Oers, L.; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; et al. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. *Int. J. Life Cycle Assess.* **2002**, *7*, 311–313. [CrossRef]
71. European Commission (EC). International Reference Life Cycle Data System (ILCD) Handbook—General Guide for Life Cycle Assessment. Available online: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC48157/ilcd_handbook-general_guide_for_lca-detailed_guidance_12march2010_isbn_fin.pdf (accessed on 6 October 2017).
72. Weidema, B.; Ekvall, T.; Heijungs, R. Guidelines for Application of Deepened and Broadened LCA; Deliverable D18 of Work Package 5 of the CALCAS Project. Available online: http://www.leidenuniv.nl/cml/ssp/publications/calcas_report_d18.pdf (accessed on 26 June 2018).
73. Gentil, E.; Damgaard, A.; Hauschild, M.; Finnveden, G.; Eriksson, O.; Thorneloe, S.; Kaplan, P.O.; Barlaz, M.; Muller, O.; Matsui, Y.; et al. Models for waste life cycle assessment: Review of technical assumptions. *Waste Manag.* **2010**, *30*, 2636–2648. [CrossRef] [PubMed]
74. Brander, M.; Tipper, R.; Hutchinson, C.; Davis, G. *Consequential and Attributional Approaches to LCA: A Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels*; Ecometrica Press: London, UK, 2009; Available online: http://www.ecometrica.com/assets//approachesto_LCA3_technical.pdf (accessed on 12 January 2018).
75. Laurent, A.; Bakas, I.; Clavreul, J.; Bernstad, A.; Niero, M.; Gentil, E.; Hauschild, M.; Christensen, T. Review of LCA studies of solid waste management systems—Part I: Lessons learned and perspectives. *Waste Manag.* **2014**, *34*, 573–588. [CrossRef] [PubMed]
76. Laurent, A.; Clavreul, J.; Bernstad, A.; Bakas, I.; Niero, M.; Gentil, E.; Christensen, T.; Hauschild, M. Review of LCA studies of solid waste management systems—Part II: Methodological guidance for a better practice. *Waste Manag.* **2014**, *34*, 589–606. [CrossRef] [PubMed]
77. Astrup, T.F.; Tonini, D.; Turconi, R.; Boldrin, A. Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations. *Waste Manag.* **2015**, *37*, 104–115. [CrossRef] [PubMed]
78. Clavreul, J.; Guyonnet, D.; Christensen, D. Quantifying uncertainty in LCA-modelling of waste management systems. *Waste Manag.* **2012**, *32*, 2482–2495. [CrossRef] [PubMed]

79. Bisinella, A.B.; Ahmadi, A.; Tiruta-Barna, L.; Spérandio, M. Feasibility of rigorous multi-objective optimization of wastewater management and treatment plants. *Chem. Eng. Res. Des.* **2016**, *115*, 394–406. [CrossRef]
80. Kobayashi, Y.; Peters, G.; Khan, S. Towards More Holistic Environmental Impact Assessment: Hybridisation of Life Cycle Assessment and Quantitative Risk Assessment. *Procedia CIRP* **2015**, *29*, 378–383. [CrossRef]
81. Taelman, S.E.; Schaubroeck, T.; De Meester, S.; Boone, L.; Dewulf, J. Accounting for land use in life cycle assessment: The value of NPP as a proxy indicator to assess land use impacts on ecosystems. *Sci. Total Environ.* **2016**, *550*, 143–156. [CrossRef] [PubMed]
82. Levasseur, A.; Lesage, P.; Margni, M.; Deschenes, L.; Samson, R. Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environ. Sci. Technol.* **2010**, *44*, 3169–3174. [CrossRef] [PubMed]
83. Martinez-Sanchez, V.; Kromann, M.; Astrup, T. Life cycle costing of waste management systems: Overview, calculation principles and case studies. *Waste Manag.* **2015**, *36*, 343–355. [CrossRef] [PubMed]
84. Hunkeler, D.; Lichtenvort, K.; Rebitzer, G. *Environmental Life Cycle Costing*; CRC Press: Boca Raton, FL, USA, 2008; p. 232. ISBN 9781420054705.
85. Benoît, C.; Mazijn, B. *Guidelines for Social Life Cycle Assessment of Products: A Social and Socio-Economic LCA Code of Practice*; United Nations Environment Programme: Nairobi, Kenya, 2009.
86. Ciroth, A.; Eisfeldt, F. *PSILCA—A Product Social Impact Life Cycle Assessment Database, Database Version 1.0*; Documentation. Version 1.1; Greendelta: Berlin, Germany, 2016.
87. Moreno, R.; Lévová, T.; Bourgault, G.; Wernet, G. *Documentation of Changes Implemented in Ecoinvent Data 3.1*; Ecoinvent: Zurich, Switzerland, 2014.
88. Hummel, M.; Bridges, J.; IJzerman, M. Group Decision Making with the Analytic Hierarchy Process in Benefit-Risk Assessment: A Tutorial. *Patient* **2014**, *7*, 129–140. [CrossRef] [PubMed]
89. Vadenbo, C.; Tonini, D.; Astrup, T.F. Environmental Multi-objective Optimization for the Use of Biomass Resources for Energy. *Environ. Sci. Technol.* **2017**, *51*, 3575–3583. [CrossRef] [PubMed]
90. Hanney, S.; Conzalez-Block, M.; Buxton, M.; Kogan, M. The utilisation of health research in policy-making: Concepts, examples and methods of assessment. *Health Res. Policy Syst.* **2003**, *1*, 1–28. [CrossRef]
91. Brownson, R.; Chriqui, J.; Stamatakis, K. Understanding Evidence-Based Public Health Policy. *Am. J. Public Health* **2009**, *99*, 1576–1583. [CrossRef] [PubMed]
92. Contreras, F.; Hanaki, K.; Aramaki, T.; Connors, S. Application of analytical hierarchy process to analyze stakeholders preferences for municipal solid waste management plans, Boston, USA. *Resour. Conserv. Recycl.* **2008**, *52*, 979–991. [CrossRef]
93. Lewison, R.; Rudd, M.; Al-Hayek, W.; Baldwin, C.; Beger, M.; Lieske, S.; Jones, C.; Satumanatpan, S.; Junchompoo, C.; Hines, E. How the DPSIR framework can be used for structuring problems and facilitating empirical research in coastal systems. *Environ. Sci. Policy* **2016**, *56*, 110–119. [CrossRef]
94. European Environment Agency (EEA). *Environmental Indicators: Typology and Overview*; Technical Report No 25; Environment Directorate-General: Copenhagen, Denmark, 1999.
95. Schneider, P.; Anh, L.H.; Wagner, J.; Reichenbach, J.; Hebner, A. Solid Waste Management in Ho Chi Minh City, Vietnam: Moving towards a Circular Economy? *Sustainability* **2017**, *9*, 286. [CrossRef]
96. Greyl, L.; Vegni, S.; Natalicchio, M.; Cure, S.; Ferretti, J. The Waste Crisis in Campania, Italy. Available online: http://www.ceecec.net/case-studies/waste-crisis-in-campania-italy/ (accessed on 12 November 2017).
97. Kristensen, P. The DPSIR Framework. In Proceedings of the Workshop on a Comprehensive/Detailed Assessment of the Vulnerability of Water Resources to Environmental Change in Africa Using River Basin Approach, UNEP Headquarters, Nairobi, Kenya, 27–29 September 2004.
98. Vadenbo, C.; Hellweg, S.; Guillén-Gosálbez, G. Multi-objective optimization of waste and resource management in industrial networks—Part I: Model description. *Resour. Conserv. Recycl.* **2014**, *89*, 52–63. [CrossRef]
99. Thabrew, L.; Wiek, A.; Ries, R. Environmental decision making in multi-stakeholder contexts: Applicability of life cycle thinking in development planning and implementation. *J. Clean. Prod.* **2009**, *17*, 67–76. [CrossRef]
100. European Commission (EC). *The Raw Materials Initiative—Meeting our Critical Needs for Growth and Jobs in Europe, COM/2008/699*; European Commission (EC): Brussels, Belgium, 2008.
101. European Commission (EC). *Closing the Loop—An EU Action Plan for the Circular Economy, COM/2015/0614*; European Commission (EC): Brussels, Belgium, 2015.

102. Manfredi, S.; Pant, R. *Supporting Environmentally Sound Decisions for Waste Management*; A Technical Guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) for Waste Experts and LCA Practitioners; European Union: Luxembourg, 2011.
103. Zhang, Y.; Zheng, H.; Fath, B.; Liu, H.; Yang, Z.; Liu, G.; Su, M. Ecological network analysis of an urban metabolic system based on input–output tables: Model development and case study for Beijing. *Sci. Total Environ.* **2014**, *468–469*, 642–653. [CrossRef] [PubMed]
104. Roy, M.; Curry, R.; Ellis, G. Spatial allocation of material flow analysis in residential developments: A case study of Kildare County, Ireland. *J. Environ. Plan. Manag.* **2014**, *58*, 1–21. [CrossRef]
105. Rosenbaum, R. Chapter 40. Overview of Existing LCIA Methods—Annex to chapter 10. In *Life Cycle Assessment: Theory and Practice*; Hauschild, M., Rosenbaum, R., Olsen, S., Eds.; Springer International Publishing: Cham, Switzerland, 2018; ISBN 978-3-319-56475-3.
106. Heijungs, R.; Huijbregts, M. A Review of Approaches to Treat Uncertainty in LCA. In Proceedings of the 2nd International Congress on Environmental Modelling and Software, Osnabrück, Germany, 14–17 June 2004.
107. Guinée, J.B. Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges. In *Taking Stock of Industrial Ecology*; Clift, R., Druckman, A., Eds.; Springer International Publishing: Cham, Switzerland, 2016; ISBN 978-3-319-20571-7.
108. Valdivia, S.; Ugaya, C.M.L.; Sonnemann, G.; Hildenbrand, J. *Towards a Live Cycle Sustainability Assessment: Making Informed Choices on Products*; United Nations Environment Programme: Paris, France, 2011.
109. Marchand, M.; Aissani, L.; Mallard, P.; Béline, F.; Réveret, J.P. Odour and Life Cycle Assessment (LCA) in Waste Management: A Local Assessment Proposal. *Waste Biomass Valoriz.* **2013**, *4*, 607–617. [CrossRef]
110. Taelman, S.E.; De Meester, S.; Schaubroeck, T.; Sakshaug, E.; Alvarenga, R.; Dewulf, J. Accounting for the occupation of the marine environment as a natural resource in life cycle assessment: An exergy based approach. *Resour. Conserv. Recycl.* **2014**, *91*, 1–10. [CrossRef]
111. Weidema, B. In search of a consistent solution to allocation of joint production. *J. Ind. Ecol.* **2017**, *22*, 252–262. [CrossRef]
112. Weidema, B.; Pizzol, M.; Schmidt, J.; Thoma, G. Attributional or consequential Life Cycle Assessment: A matter of social responsibility. *J. Clean. Prod.* **2018**, *174*, 305–314. [CrossRef]
113. Martin, E.; Chester, M.; Vergara, S. Attributional and Consequential Life-cycle Assessment in Biofuels: A Review of Recent Literature in the Context of System Boundaries. *Curr. Sustain. Renew. Energy Rep.* **2015**, *2*, 82–89. [CrossRef]
114. Pradel, M.; Aissani, L.; Villot, J.; Baudez, J.C.; Laforest, V. From waste to added value product: Towards a paradigm shift in life cycle assessment applied to wastewater sludge—A review. *J. Clean. Prod.* **2016**, *131*, 60–75. [CrossRef]
115. Weidema, B.; Bauer, C.; Hischier, R.; Mutel, C.; Nemecek, T.; Reinhard, J.; Vadenbo, C.O.; Wernet, G. *Overview and Methodology Data Quality Guideline for the Ecoinvent Database Version 3*; Ecoinvent Report 1(v3); The Ecoinvent Centre: St. Gallen, Switzerland, 2013.
116. Allacker, K.; Mathieux, F.; Pennington, D.; Pant, R. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *Int. J. Life Cycle Assess.* **2017**, *22*, 1441–1458. [CrossRef]
117. Lasvaux, S.; Gantner, J.; Wittstock, B.; Bazzana, M.; Schiopu, N.; Saunders, T.; Gazulla, C.; Mundy, J.A.; Sjöström, C.; Fullana-i-Palmer, P.; et al. Achieving consistency in life cycle assessment practice within the European construction sector: The role of the EeBGuide InfoHub. *Int. J. Life Cycle Assess.* **2014**, *19*, 1783–1793. [CrossRef]
118. Fontes, J. *Handbook for Product Social Impact Assessment, version 3.0*; PRé Sustainability: Amersfoort, The Netherlands, 2016.
119. Säynäjoki, A.; Heinonen, J.; Junnila, S.; Horvath, A. Can life-cycle assessment produce reliable policy guidelines in the building sector? *Environ. Res. Lett.* **2017**, *12*, 013001. [CrossRef]