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An operational framework for sustainability assessment including local to global impacts: Focus on waste management systems

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ABSTRACT

Assessing the sustainability of waste management systems (WMSs) is key to reduce the impacts incurred by human activities. The article presents the development of an operational sustainability framework for the assessment of WMSs involving stakeholders and experts from different fields. The operational framework presented achieves comprehensiveness by including multidisciplinary impacts (environmental, social, and economic impacts), accounting for spatial differentiation regarding the occurrence and magnitude of the impacts (local to global) and complementing well-established methods in life cycle assessment (LCA) with local impact assessment methods. In this respect, the assessment of social local impacts (e.g., Odour, Landscape Disamenities), which has so far received little attention in the literature, has been included. The procedure for the definition of the operational framework is described in detail, including the selection of the impact categories and associated indicators. Finally, an aggregation method was defined considering the perception of stakeholders, allowing for aggregating the impact in five areas of protection (Prosperity, Human Well-Being, Human Health, Ecosystem Health and Natural Resources).

1. Introduction

Assessing the sustainability of waste management systems (WMSs) requires comprehensively addressing the three pillars, i.e. society, environment, and economy. A sustainability framework shall include a set of impact categories, each described by one or more indicators, belonging to different areas of protection (AoP, e.g., Human Health, Ecosystem Health) that may be further grouped under the three pillars of sustainability (Gaasbeek and Meijer, 2013). Life cycle methodologies are widely used for the calculation of indicators for the impact categories, for example life cycle assessment (LCA) or costing (LCC) for environmental and economic impacts. Social and socio-economic aspects are typically assessed using social LCA (SLCA), which has no related standards, although guidelines exist for the selection of relevant stakeholders and indicators (UNEP, 2011) and, in general, for conducting a full assessment (UNEP-SETAC, 2009). In defining the framework, stakeholder involvement is considered key for the selection of impact categories (Souza et al., 2015). The application of these methodologies to WMSs can contribute significantly to improve the social, economic and environmental performance of cities. However, while WMSs have been widely assessed with LCA (see review from Astrup et al., 2015; Laurent et al., 2014a,b) and, to a lesser extent, with LCC (see review from De Menna et al., 2018) the definition and application of a comprehensive sustainability assessment framework for the evaluation of WMSs is still an ongoing work. Such a framework would be a useful tool for a range of professionals involved in WMSs (e.g., urban planners, administration). Notably, the most recent attempt to holistically address sustainability is the project PROSUITE, aiming to develop a tool to assess the sustainability of new technologies, including a comprehensive framework with 29 impact categories and 5 AoPs: Human Health, Prosperity, Ecosystem Health, Human Well-Being, and Natural Resources (Gaasbeek and Meijer, 2013). However, the resulting framework focuses on new technologies and includes little information on the methodology to calculate the indicators. Likewise, other attempts have a narrow focus on very specific waste types/treatments, such as waste-to-energy (Chong et al., 2016), mineral processing (Corder et al., 2012), green waste (Inghels et al., 2016) or industrial waste (Scheel, 2016). As a result, some areas are not well-covered in literature, such as the comprehensive assessment of WMs in cities and/or urban environments, with some exceptions such as (Liu

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et al., 2013), which considered waste treatment in cities although it doesn't include a comprehensive set of impacts (e.g., environmental impacts focus in few emissions). den Boer et al. (2007) present a sustainability framework for WMSs, but a very general perspective is adopted without specific recommendations on the impact indicators. Similarly, other proposals focus on the general framework without detailing choices and calculations of the indicators (Corder et al., 2012; Iacovidou et al., 2017; Inghels et al., 2016). Chong et al. (2016) propose a rather comprehensive sustainability framework including a set of environmental, economic and social indicators, but their selection is only based on a literature review without stakeholders' involvement. As opposed to this, Souza et al. (2015) selected a set of sustainability indicators using a methodology that included the consultation of stakeholders alongside other methods (e.g., causal maps). However, the article has a general approach with no available background information regarding the calculation of the indicators.

An aspect deserving special attention when developing a sustainability framework is the inclusion of local impacts affecting the social dimension of sustainability, e.g., noise, odour (micro-impacts, see Taelman et al., 2018), as these can significantly affect the surrounding population (Woon and Lo, 2016). The quantification of these impacts can be very useful to improve WM and its perception at local level. Another remarkable pending issue is the consideration of temporal and spatial variability in the calculation of the impacts, for which specific research is required to define adapted characterisation factors and inventory data. This is important to improve the reliability of the impacts (Yuan et al., 2015) and is a field under development (e.g., Helmes et al., 2012).

Finally, once indicators are selected, aggregation shall be performed in function of the communication goal. Aggregation refers to the process of integrating sustainability indicators into a single composite index (or a final ranking; Gan et al., 2017). Typically, this implies normalisation for indicators (e.g., Global Warming, Eutrophication) to be expressed on a common scale, and eventually also weighting to reflect the relative importance of each of the three pillars with respect to their contribution to the overall sustainability of the system. Aggregation is essential to provide a synthesis of the multi-dimensional impact of a system, draw conclusions on ranking between alternatives, and enhance the communication of the results. Only a few studies propose aggregation techniques in sustainability frameworks for WMSs. This is the case of Chong et al. (2016) where the overall sustainability is assumed to be dictated by the least performing indicator, following previous formulations (Pollesch and Dale, 2015). The study is focused on the waste-to-energy treatment (not the whole WMS), and the selection of the indicators is purely based on literature research and the author's reasoning.

Considering all the above, the EU project "Resource Management in Peri-Urban Areas" (REPAiR; ID: 688920) aims to address the sustainability assessment of WMSs to improve the decision-making in this field. *The project deals with the sustainability of different types of waste, focusing in each case study on some particular flows (e.g., organic waste, construction and demolition) in the endeavour to promote local sustainable circular economy solutions.* Within this project, the study from Taelman et al. (2018) presents an overview of the studies that attempted to develop frameworks for a comprehensive sustainability assessment of WMSs. Following this research line, our study aims to narrow this general approach towards an operational framework that can be applied to case studies, defining the specific impacts to be considered and the methods for the analysis. The development of the operational sustainability framework includes the selection of the impact categories alongside suitable indicators and the final aggregation techniques, in which the stakeholders' participation is key. The specific goals of the study are: i) to identify a set of impact categories and associated indicators to assess the sustainability of WMSs in cities through a coherent methodology involving stakeholders/experts from different fields; ii) to address both global and local impacts, particularly focusing on social micro-impacts by defining adequate impact categories and indicators; iii) to define an aggregation method to synthetize and express sustainability at AoPs level (e.g., Prosperity, Human Health).

2. Methodology

2.1. Selection of the impact categories

The point of departure for developing the operational sustainability framework is Taelman et al. (2018), where different types of impact categories were identified (multidisciplinary, multi-geoscale and multisize impacts). Accordingly, different selection approaches were considered for the selection of the impact categories and indicators included in the operational sustainability framework (*Selection Process A* in Fig. 1). *Multidisciplinary impacts* represent environmental, social and economic impact categories (three pillars of sustainability), and the AoPs were defined within this general classification. The concept of *multi-geoscale* impacts reflects the geographical spread of these impacts and its consideration avoids possible burden shifts to other geographic locations. Moreover, the magnitude or extent of the impacts has been defined considering *multisize impacts*, which can range from micro (local; e.g., noise, smell and other disamenities due to waste management) to macro (global; e.g., climate change), depending on the affected area. In this context, the impacts from WM are differentiated according to their geographical location, magnitude and origin.

The selection approach A1 (Fig. 1) was followed to identify and select multidisciplinary impact categories. This approach entails a participatory process that was conducted with experts and stakeholders considering multidisciplinary impacts, i.e. selecting the most appropriate environmental, social and economic impact categories which deemed to be relevant for the sustainability assessment of WMSs. The starting point was a preliminary set of 48 impact categories that had been identified as eligible from literature alongside additional ones adapted from the PROSUITE FP7 project (see the full list in Appendix A). This list was presented to a sample of stakeholders involved in the project, seeking an even contribution from the different case studies in the project (6 European cities: Naples, Ghent, Amsterdam, Lódz, Pécs, Hamburg), their background (scientific community, local or regional authorities, WM companies) and academic expertise based on the areas of work of the partners in the project (geography, environmental sciences, social sciences). The final distribution of the respondents (54 in total) can be found in Appendix B. The respondents scored each category based on their perceived relevance between 1 (not relevant) and 4 (very relevant). The application of a specific psychometric rating scale for a questionnaire shall be done in accordance with the specific needs. Although the Likert scale (from 1 to 5) is a very common one used in literature, there is extensive literature discussing about which type of rating scale is more appropriate (Kuhlmann et al., 2017; Voutilainen et al., 2016). In this study, a 1 to 4 scale was considered more suitable because it forces respondents to pronounce their preference (there is no neutral option).

The results from the scoring exercise were used to rank the impact categories. Furthermore, these midpoint categories were categorized into the 5 AoP as proposed by PROSUITE and a threshold value of 2.6 was considered to select the categories included in the framework (which retained the impact categories scoring 65% or higher based on relevancy as indicated by the representative sample). Additionally, a limitation of a maximum of 10

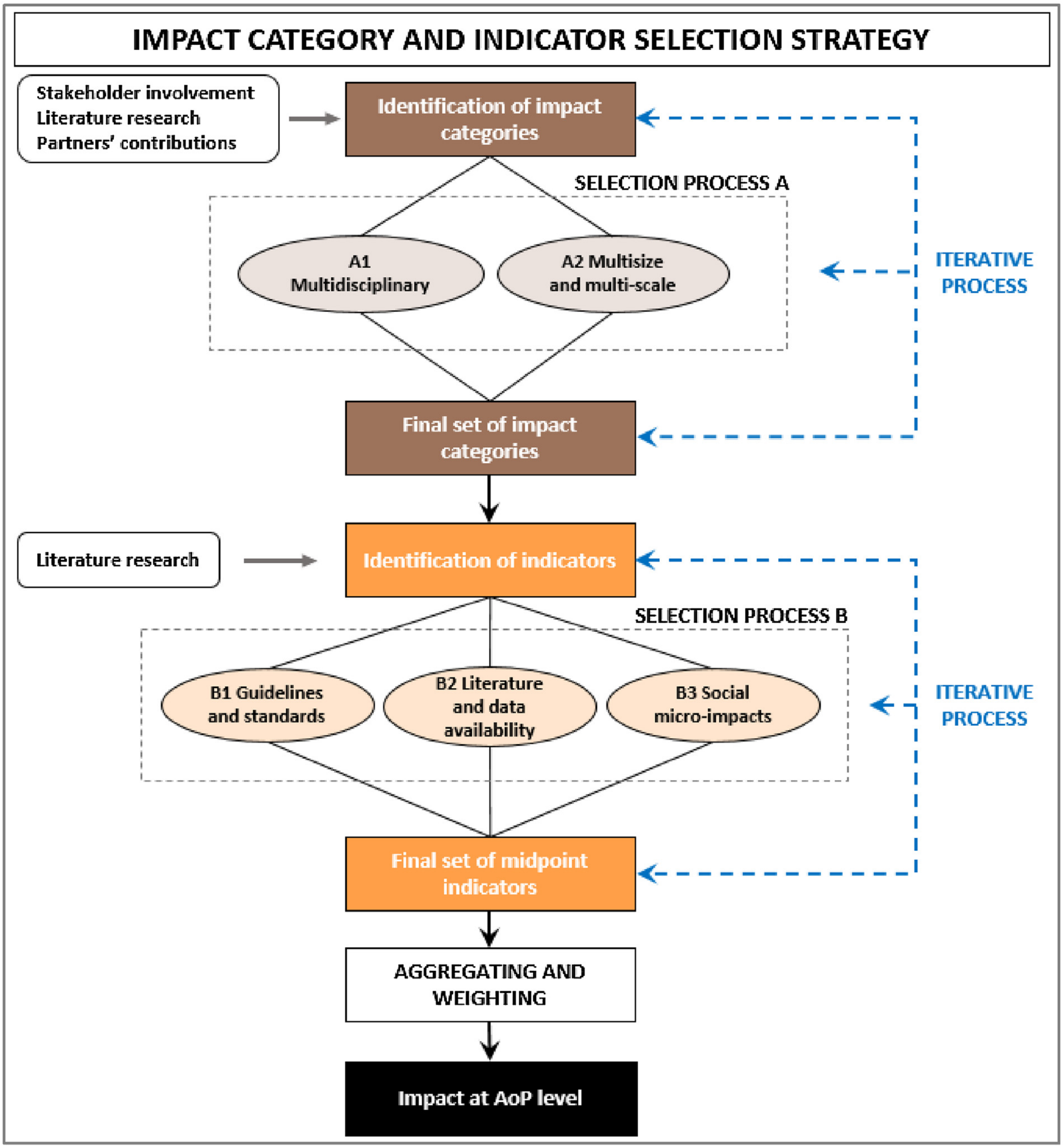

Fig. 1. Procedure for the identification and selection of impact categories and indicators, towards the final operational sustainability framework.

categories per AoP was set to balance the number of categories among the different AoPs, which excluded some additional ones in the AoP Human Well-Being. After the selection of a preliminary set of impact categories, an expert panel debate (including non-consortium members) was held in the REPAiR project to further discuss the selection. The expert panel suggested a set of modifications such as merging categories or including categories initially excluded but considered important.

In parallel, the selection approach A2 (Fig. 1) was considered for the multi-geoscale and multisize impact categories. In this stage, the authors analysed the different impacts from a theoretical point of view to decide which multi-geoscale and multisize impacts could be identified. It should be highlighted that the theoretical conception of the framework may differ from the practical application proposed due to, e.g., the limitations derived from the lack of databases and methods to support spatial differentiation.

2.2. Selection of the indicator for each impact category

After selecting the impact categories, the most appropriate midpoint indicator[1] was defined for each category (Process B in Fig. 1). As shown in Fig. 1, three approaches were considered for this selection, depending on the type of impact category. For some categories such as those categorized under the AoP Human Health, AoP Ecosystem Health and AoP Natural Resources (linked to traditional LCA), the indicators to be used were selected based on the most up-to-date guidelines and standards (B1 in Fig. 1). For other indicators, such as economic ones, this was not possible and their

[1] A midpoint indicator shows the potential impact of a single environmental, social or economic category at a point in the cause-effect chain (environmental mechanism) that is before the endpoint (the final consequence of the impact).

selection was done in accordance with literature and data availability (B2 in Fig. 1). The availability of indicators for the evaluation of social micro-impacts is limited because little research has been done so far in this field. To select the most appropriate indicator (B3 in Fig. 1), a literature search was conducted for each impact category to identify potentially suitable indicators. To select the most appropriate indicator amid alternatives, a valuation was conducted scoring from 1 to 4 the following criteria (see details in Appendix C):

- Feasibility: regarding practical implementation and use (e.g., in LCA software tools, connection with background databases)
- Relevance: how relevant is the indicator to assess the impact of interest?
- Easiness to interpret: degree of clarity to express the impacts of the category for policy makers and other stakeholders
- Achievability: Degree of effort required for the implementation (e.g., in terms of data needs and time window)

In this case, the scoring was done by the authors, since the selection of the most appropriate indicator is not purely a perception-based process but requires expertise regarding life cycle methods and impact assessment. To be eligible, an indicator has to score at least 2 out of 4 in all criteria, and 3 or more out of 4 in at least two criteria. The average score was considered for each eligible indicator, and the one with the highest score was selected as the most appropriate indicator available for a selected impact category. Each criterion was considered to have the same weight. The results of the scoring and the final selection of indicators are presented in Section 3.3.3.

2.3. Aggregation

The final aggregation was performed by positioning the framework on the strong sustainability ground. Strong sustainability imposes that no aggregation of indicators across the three pillars is allowed during the assessment (Mori and Christodoulou, 2012), whereas weak sustainability allows for unlimited substitutability between dimensions (i.e. compensation of the indicators across the pillars). Choosing a suitable aggregation technique required reviewing the literature regarding normalisation, weighting and aggregation techniques. Normalisation/weighting sets were recently proposed by Sala et al. (2018) in the context of Product Environmental Footprint for 15 environmental indicators and by Laurent et al. (2014b) (PROSUITE project) for a number of environmental and socio-economic indicators. However, the application of these (or other) normalisation/weighting sets was not considered appropriate for this framework. The main drawback is the limited coverage offered, i.e. for a significant number of indicators included in this framework, normalisation and weighting sets are not available. We instead propose an *ad hoc* aggregation approach that applies a multi-criteria decision analysis (MCDA) technique to derive a relative ranking of the scenarios assessed for each of the five AoPs considered. Acknowledging the number of different alternative MCDA methods, we choose to implement the method ELECTRE II (Elimination and Choice Translating Reality; Figueira et al., 2005, 2010; Lima and Salazar Soares, 2011). ELECTRE II is part of the ELECTRE family of outranking methods for decision-making. The choice is supported by the following reasons: i) the method was originally developed to solve the problem of ranking alternatives from best to worst, which aligns with the objectives of the framework, i.e. to support decision-making between alternatives; ii) the tool is freeware and the maths is transparently retrieved; iii) the level of complexity (compared to ELECTRE III or similar) is deemed sufficient to achieve the aggregation objectives. The aggregation steps are described herein. Notice that aggregation is performed on each individual AoP separately, i.e. 5 rankings of the alternatives (scenarios) assessed are obtained.

2.3.1. Normalisation

First, per each individual AoP, a min-max normalisation (also called rescaling; see Appendix D, Eqs. D.1–D.2) is performed on the characterised impact results. Rescaling, compared with other techniques such as vector-based normalisation, provides the advantage to obtain strictly positive normalised values in the range (0, 1). This is important considering that some LCA midpoint indicators, after characterisation, may result in negative values when assessing WMS, due to the commonly applied zero-burden assumption and the accounted credits for co-products/co-services generated (e.g., Zhao et al. (2009). Rescaling is applied according with Eq. (1), where nr_{ij} is the normalised value, given a number of indicators I_j ($j = 1, m$) and of alternatives A_i (i=$1, n$) assessed:

$$For\, j = 1,\ m$$

$$nr_{ij} = \frac{r_{ij} - \min_i(r_{ij})}{\max_i(r_{ij}) - \min_i(r_{ij})}\ \forall i,\ i = 1, n \quad (1)$$

2.3.2. MCDA: deriving the concordance and discordance matrix

The concordance matrix C is constructed based on the pairwise comparison of each indicator *I* between two alternatives A_x and A_y, scoring with 1 for each criterion (indicator) for which alternative A_x is better than alternative A_y. The concordance index *c* of a pair of alternatives (A_x, A_y) is the sum of the scores obtained from this comparison (Lima and Soares, 2011); see Eqs. D.3–D.4. It should be noted that weights may be applied at this stage (ω_j; Eq. D.3). In the context of this study, weights were derived from a survey submitted to the project stakeholders (see Appendix E; Table E.1). In this respect, the excel-model provided (Supplementary material A) also allows for no weighting, i.e. all the categories within a selected AoP are assumed equally important. The discordance matrix D is constructed based on the differences between the values of the indicators of two alternatives A_x and A_y. The discordance index *d* for a pair of alternatives *(Ax, Ay)* is the maximum value obtained from all the differences (across normalised and weighted indicators results) between A_x and A_y (Lima and Salazar Soares, 2011); see Eqs. D.5–D.6.

2.3.3. MCDA: correction of concordance and discordance matrix with a threshold

Thresholds may be used to further correct concordance and discordance matrix. As stressed in Lima and Salazar Soares (2011), these thresholds are not unique and should in principle be defined by the decision maker. In this study, we propose the implementation of concordance and discordance thresholds following the formulation given in Hartati et al. (2011); see Eqs. D.7–D.8. The matrix C and D are now “corrected” by discarding the concordance indexes that are below the concordance threshold *ct* and the discordance indexes that are above the discordance threshold *dt*. Two corrected matrices C’ and D’ are then obtained; see Eqs. D.9–D.10.

2.3.4. MCDA: aggregating matrixes and deriving the ranking of the alternatives

Once the corrected matrices C’ and D’ are obtained, they can be aggregated. The aggregated matrix E is obtained as the product between the xy^{th} concordance and discordance index (Eq. D.11; $e_{xy} = c_{xy} \cdot d_{xy}$). The aggregated score associated with an alternative A_x can then be derived (Eq. D12; $\Sigma_x e_{xy}$ with $y = 1,n$) and the set of alternatives $A_{1,n}$ can finally be ranked, per each AoP, based on the score obtained.

3. Results

This section presents the operational sustainability framework developed in the study, including the basic elements for the methodological approach adopted (3.1), the results of the selection process for the impact categories (3.2) and the indicators (3.3), the aggregation and final framework (3.4).

3.1. Functional unit, system boundaries and data requirements

The system boundaries for the assessment include all the processes and actors involved in the life cycle, which are divided in two systems (Fig. 2). First, the foreground system includes upstream processes and WM activities that are mainly located in the focus area (area of analysis, where the generation of waste occurs) and the surrounding region but that may also take place elsewhere, as might be the case for waste fractions that are exported and treated somewhere else (Taelman et al., 2018). Second, the background system includes processes from the supply chain that are usually outside the focus area, but could as well be located in the focus area, as might be the case for energy and materials supply required for treating the waste. In case eco-innovative solutions include changes upstream of the cycle (e.g., packaging reduction, other manufacturing that ensures a longer lifetime of products), the foreground system shall be extended to include these upstream processes. In this context, the functional unit considered for the assessment of WM is the treatment of (A) waste generated by (B) in the focus area during one year, being (A) the type of waste (e.g., glass, plastic waste), and (B) the waste generator (e.g., households, SMEs, governmental institutions) (Taelman et al., 2018).

The application of the operational framework will require different types of data, depending on the indicators selected. Provided that the aim is assessing the consequences/changes incurred in the system by selected actions (eco-innovative solutions), a consequential approach is recommended systematically applying system expansion using marginal market data to account for the substitution of technologies and products (Ekvall and Weidema, 2004; Weidema et al., 1999) (cfr. avoided products in Fig. 2). However, an attributional approach might also be used when finding marginal suppliers is too complex or involves high uncertainty. For the collection of the foreground data, a bottom-up approach with primary data collection is preferred (by contacting the stakeholders, spreading surveys amongst inhabitants, etc.), although secondary data (top-down) such as literature or databases are likely needed to compensate for data gaps. Secondary data should be used for the background system, for instance from databases (e.g., ecoinvent, ELCD, Gabi).

3.2. Impact categories

The results from the scoring of impact categories by stakeholders and experts can be found in Appendix E. After the expert panel discussion, different changes were applied. Regarding the AoP Human Well-Being, Urban Space Consumption was merged with Access to Green Spaces because both address a very related impact. For the same reason, Public Acceptance was merged with Not in my Backyard Syndrome. Moreover, the category Total Employment was included because it was considered as an important element. The impact categories Total Employment and Social Costs were preliminary linked to both the AoPs Prosperity and Human Well-Being, and Water Depletion was linked to the AoP Human Health and Ecosystem Health. Finally, the impact category Environmental Health was split up into four impact categories (Global Warming, Ozone Depletion, Ionising Radiation, Tropospheric Ozone Formation), in accordance with Gaasbeek and Meijer (2013). The resulting set of impact categories after these changes is shown in Appendix F. Moreover, further inclusion/exclusion of certain impact categories in the final framework was done on the basis of the indicator selection, as explained in Section 3.2.1.

3.2.1. Environmental and socio-environmental impact categories

Regarding the environmental impact categories, the preliminary selection after the expert panel debate is shown in Appendix F. However, the final selection acknowledges some important limitations and facts. First, Biodiversity was removed from the framework as a midpoint impact category for two reasons. On one hand, traditional LCA methods model Biodiversity often in the context of species loss/gains as an endpoint impact category, correlating to the AoP Ecosystem Health (Souza et al., 2015). However, there are no characterisation factors available to calculate an indicator at midpoint level for Biodiversity, since it is *per se* an endpoint. Furthermore, the aggregation technique chosen (ELECTRE) does not request that the AoP Ecosystem Health is expressed in Biodiversity loss or improvements, so from this perspective there was no need to retain Biodiversity as an impact category at endpoint level. On the other hand, Biodiversity might be expressed (at midpoint level) in terms of genetic resource variability (Taelman et al., 2016), which links to the AoP Natural Resources, but in practice this impact is only assessed through land use change modelling. Therefore, no indicator for biodiversity at midpoint level was further considered. Moreover, the impact categories Water depletion and Land use were not linked to the AoP Natural Resources in the final framework and were instead linked to the AoP Human Health, as suggested in recent studies (Huijbregts et al., 2017; Sonderegger et al., 2017; Taelman et al., 2016).

3.2.2. Economic impact categories

The economic categories preliminarily selected were Capital Productivity, Labour Productivity, Resource Productivity and Revenues and Taxes (see Appendix F). These categories may be *per se* adequate to describe a WM system, each of these categories have different units and some cannot be adjusted to the functional unit (e.g., Capital Productivity is expressed in €/hour, which cannot be linked to an amount of waste). For this reason, an alternative approach was considered. While an economic life cycle perspective was considered as the most comprehensive analysis to account for the overall cost of WM, LCC was deemed not to be appropriate in this case. There are two main reasons for this: i) while important advances have been achieved recently (among other, Martinez-Sanchez et al., 2016, 2015), the methodology is not yet standardized, leading to a variety of diverse and incoherent applications in the recent literature, particularly in respect to societal LCC, as stressed in De Menna et al. (2018). In addition, ii) there is a lack of available data regarding the costs of background processes, i.e. the supply chain of WMS. Recently, some databases such as ecoinvent v3.0 and later versions have attempted to include economic data but important components such as labour costs are not yet considered. Moreover, this economic information is provided in a simplified and aggregated manner and currently cannot be accessed using traditional LCA software such as Simapro, OpenLCA or Gabi (GreenDelta, 2018; PRé Consultants, 2018; thinkstep, 2018). Acknowledging these limitations, and the fact that the social impacts are to some extent accounted as local impacts, the category Social Costs (see Appendix E) was discarded from the framework and the indicators Capital Expenditure (CAPEX), Operational Expenditure (OPEX) and End-of-Life Expenditure (OELEX), as proposed in (Gaasbeek and Meijer, 2013), were introduced. In addition, the impact category Revenues was included, as it accounts for business income allowing the calculation of the net costs/gains of an operational process. These impact categories focus on accounting the costs of the foreground system, excluding the background system. Including these categories also

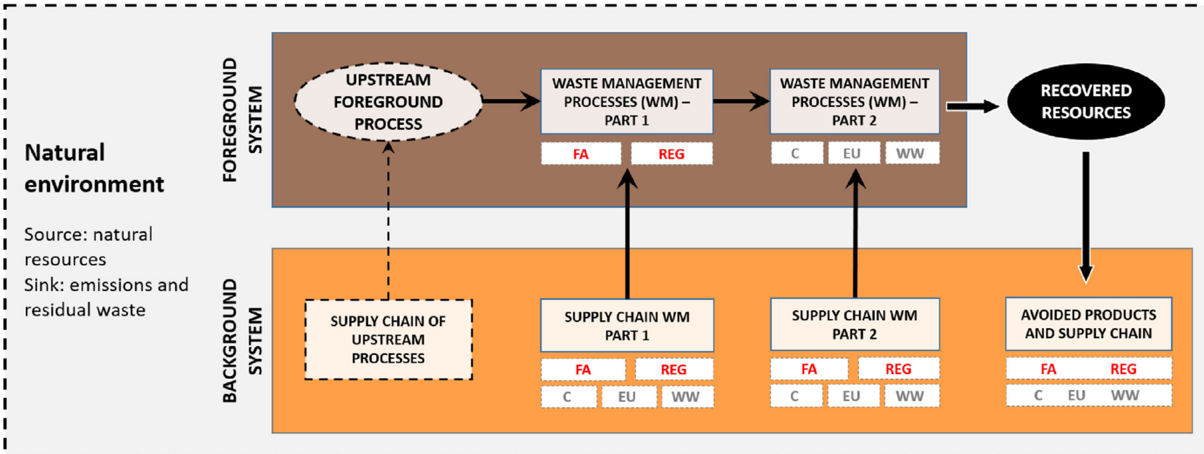

Fig. 2. Foreground and background system boundaries of the metabolism under study. Waste management processes include all activities related to WM (e.g. collection, transport, landfilling, etc.). *FA = Focus area, REG = Region, C = Country, EU = European Union, WW = Worldwide, WM = Waste management.*

allows, when assessing innovative solutions/changes for the *status quo*, to investigate the effects of economy of scale, where potential cost advantages arise with increase of scale. Finally, owing to the lack of reliable datasets, the assessment of Occupational Health was also narrowed to the impact associated with the foreground system. Accordingly, the category was moved from the AoP Human Health, as originally proposed in the PROSUITE project, to Human Well-Being because it is a micro-impact affecting workers of the WM system.

3.3. Indicators

Once the set of impact categories was defined, an appropriate indicator had to be identified to represent the impact in each category. The stakeholders were not involved in this process because selecting an appropriate indicator is rather a technical issue that does not involve perception as much as the selection of impact categories does.

3.3.1. Guidelines and standards

The selection of the indicators for the categories affecting the AoPs Natural Resources, Ecosystem Health and Human Health was based on available guidelines and well established LCIA methods. For instance, the ILCD handbook evaluates and recommends impact categories and methods to be used in LCA, but this guideline dates back to 2008. Several impact categories and indicators have experienced a notable development over the past years and the EU recommendations were subject to updates as it is a fast evolving research field. In the context of the Product Environmental Footprint (PEF), latest revised in 2018, an update is provided regarding recommendations of the European Commission in terms of methods to assess the impact categories as discussed in ILCD (European Commission, 2018). On top of this, also recent and accurate methods are provided by the LCIA method ReCiPe, which is one of the most highly valued methods included in the major LCA software and databases (Huijbregts et al., 2017).

The recommendations from the PEF were followed, always considering the latest version of the method proposed. However, there were three exceptions for which the latest version of ReCiPe was used instead of the one proposed by PEF. These exceptions concern the categories of Land Use and Particulate Matter, because the methods proposed were not compatible with the software and databases considered in the framework, and the category of Fossil Depletion, for which PEF recommended a superseded method. A summary of the indicators selected for the impact categories can be found in Table 1. For more details regarding the selection of these indicators and the references considered, please see Appendix G.

3.3.2. Literature and data availability

Regarding the categories affecting the AoP Prosperity, the indicators selected only account for the economic costs of the foreground system due to the lack of accurate background data as earlier mentioned in Section 3.2.2. Guidance from literature was considered when defining the costs in each impact category. Table 2 outlines the impact categories considered for the AoP Prosperity in the framework.

3.3.3. Social micro-impacts

The definition of indicators for social micro-impacts was demanding because little research has been done on these. As explained in Section 2.3, the main indicators found in literature along with some new proposals from the experts were considered and evaluated to identify the most appropriate indicator for each category. The results of this evaluation can be found in Appendix H (Table H.1), along with the final indicator selected and the description of the different indicators proposed. Table 3 presents a summary of the final set of indicators selected for the assessment of the social impact categories. As for the economic AoP, also in this case all the indicators focus on the foreground system, since the social impacts considered affect only the focus area.

3.4. Aggregation and final operational sustainability framework

The aggregation proposed in this framework allows obtaining five relative rankings of the WM scenarios assessed, i.e. one per each of the five AoPs considered. Maintaining separate rankings per AoP is justified by the initial choice of positioning the assessment on the ground of strong sustainability, i.e. avoiding aggregation and eventual compensation between indicators belonging to different AoPs. This also avoids *ex-ante* any potential compensation across the three pillars of sustainability. With the aim of providing a ready-to-use tool for the project REPAiR, we developed a Microsoft Excel-model spreadsheet, which is provided as Supplementary material (Supplementary material A, excel model) to this article. The model implements the mathematical method for MCDA detailed in Appendix D alongside the non-compensatory function from Díaz-Balteiro and Romero (2004), which may also be used in alternative to the MCDA for aggregating the results or in the context of potential sensitivity analyses. With the formula of Díaz-Balteiro and Romero (2004), a scenario is as sustainable as its least sus-

Table 1
Impact categories and associated indicators for the AoPs ecosystem health, natural resources and human health.

Impact category	Indicator	Impact size	Units	Reference
Fossil Depletion	Fossil Resource Scarcity	Macro	kg oil eq./FU (foreground and background sytems)	ReCiPe method (Jungbluth and Frischknecht, 2010)
Eutrophication	Freshwater Eutrophication	Meso	kg of P eq./FU (foreground and background sytems)	ReCiPe method (Helmes et al., 2012)
	Marine Eutrophication	Meso	kg of N eq./FU (foreground and background sytems)	ReCiPe method (Helmes et al., 2012)
Ecotoxicity	Aquatic Ecotoxicity	Meso	CTU_e/FU (including foreground and background systems)	USEtox model (Rosenbaum et al., 2008)
Land Use	Occupation and Time-Integrated Transformation	Macro	$m^2 \times$ yr/FU (foreground and background sytems)	ReCiPe method (Curran et al., 2014; de Baan et al., 2013)
Human Toxicity	Human Toxicity, Cancer	Macro	CTU_h/FU (including foreground and background systems)	USEtox model (Rosenbaum et al., 2008)
	Human Toxicity, Non-Cancer	Macro	CTU_h/FU (including foreground and background systems)	USEtox model (Rosenbaum et al., 2008)
Ozone Depletion	Stratospheric Ozone Depletion	Macro	kg CFC-11 eq./FU (foreground and background sytems)	ReCiPe method (WMO, 2011)
Tropospheric Ozone Formation	Ozone Formation, Human Health	Meso	kg NO_x eq. to air/FU (foreground and background sytems)	ReCiPe method (van Zelm et al., 2016)
Particulate Matter	Fine Particulate Matter Formation	Meso	kg $PM_{2.5}$ eq. to air/FU (foreground and background sytems)	ReCiPe method (van Zelm et al., 2016)
Ionising Radiation	Ionising Radiation Increase	Meso	kBq Co-60 eq. to air/FU (foreground and background sytems)	ReCiPe method (Frischknecht et al., 2000)
Global Warming	Climate Change	Macro	kg of CO_2 eq/FU (foreground and background sysyems)	IPCC (Joos et al., 2013; Myhre et al., 2013)
Water Use	Water Consumption	Meso	m^3 water-eq consumed/FU (foreground and background systems)	AWARE method (Boulay et al., 2018)

CFC = chlorofluorocarbon, DCB = Dichlorobenzene, FU = Functional unit, PM = particulate matter, CTU_h = Comparative toxic units.

Table 2
Impact categories and associated indicators for the AoP Prosperity.

Impact category/indicator	Description	Details
Capital Expenditure (CAPEX)	Measures the total costs to acquire, maintain/upgrade (so to extend the useful life) the physical assets of a WM system. E.g., land, buildings, equipment	*Impact size: Micro, Units: €/FU (foreground system), Reference: PROSUITE project* (Gaasbeek and Meijer, 2013)
Operational Expenditure (OPEX)	Considers all the costs during the normal operation of the WM system. E.g., energy, labour, insurance, repair and maintenance	
End of Life Expenditure (OELEX)	Considers the costs to properly finish operations and dismantle facilities of the WM system. E.g., landfilling wastes	
Revenues	From the standpoint of the entrepreneur, the revenues of sales of products.	

FU = Functional unit, WM = Waste management.

tainable aspect, i.e. the sustainability performance is limited and ultimately determined by the least performing indicator. Such formulation has also been recently discussed in Pollesch and Dale (2015).

The final operational sustainability framework consists of three distinct layers (Fig. 3). Firstly, the inventory layer consists in accounting all the elements in the system that will have a social, economic or environmental impact. As shown in Fig. 3, the system under study includes WM processes such as collection, transport and treatment, but also the production of secondary materials. In addition, processes upstream of waste generation such as the production phase can be included when deemed relevant to investigate the potential impact of circular economy initiatives. On top, also the supply chain processes (and their respective impact) are considered relevant and are included in the analysis. The application of the framework involves collecting different types of data, covering social, economic and environmental aspects and different spatial scales and time horizons, which is a time-consuming effort. A preliminary table summarizing the basic data needs of the foreground system is provided to ease data collection (Appendix J).

The second and the third layers of the operational sustainability framework are the results of the life cycle impact assessment, namely the midpoint (results at midpoint level) and the aggregation layer (normalisation and multi-criteria analysis). The framework is comprehensive in the sense that, apart from including transdisciplinary impacts, also spatial differentiation of the occurrence of impacts and the magnitude of impacts (local to global), was taken into account. It combines both traditional environmental LCA methods which assess the global impacts for society with rather local impact assessment methods such as local economy indicators or nuisance impact categories, e.g., odour and landscape disamenities. A detailed description of all impact categories and indicators in the operational framework can be found in Appendix I.

4. Discussion and conclusions

4.1. Comprehensiveness and advances

This study presents a comprehensive operational framework for the assessment of WMSs encompassing the three pillars of sustainability (social, environmental, economics). The framework targets the waste management systems of a selected geographic area, including activities such as collection, transport and treatment, but also recovery and production of secondary materials. Processes upstream of waste generation, such as the production phase, may be included when deemed relevant to investigate the potential impact of circular economy initiatives. The supply chain processes that support the WMS are included in the analysis allowing for a holistic life cycle perspective (see system boundary layer in Fig. 3). Comprehensiveness is achieved by i) including multidisciplinary impacts, ii) accounting for spatial differentiation with

Table 3
Impact categories and associated indicators for the AoP Human Well-Being assessing social micro-impacts.

Impact category	Indicator	Description	Unit	Reference
Effectiveness in Achieving Behaviour Change	Change in (MSW) Selective Collection Behaviour	The selective collection of waste (capture rate) can show the change of households' behaviour.	% (amount selectively collected key waste flow X per actor per year/total amount of key waste flow X generated per actor per year)	(Inoue and Alfaro-Barrantes, 2015; Markle, 2014; Miliute-Plepiene et al., 2016; Park, 2018; Wilson et al., 2015)
Public Acceptance/NIMBY Syndrome	Cost-Effectiveness for Residents Resulting from Waste Segregation	The acceptance is estimated using the percentage of sorting and the financial costs.	%/FU	REPAiR team proposition; see Appendix H and Appendix I (Box I.12)
Stakeholders' Involvement	Stakeholders' Engagement in a Project Activity	The proportion of stakeholders attending an activity (compared to the total invited) can indicate their engagement.	% (stakeholders engaged/stakeholders invited)	(Brody, 2003)
Urban Space Consumption/Access to Green Spaces	Urban Space Consumption of the Waste Collection and Treatment System	Considers the space used for WMS (including facilities) against the total area of the region.	m^2/m^2 (area occupied by public waste collection points and treatment facilities per FU/total land area of the region)	(den Boer et al., 2007)
Odour	Odour Footprint	Quantifies the impact of odour considering the persistence of odorants and using CFs.	kg H_2S eq./FU (only foreground system, processes in focus area and region)	(Peters et al., 2014)
Landscape Disamenities	Variation of Property Value as a Result of WM Infrastructure/Operations	Quantification of the disamenities in monetary terms using hedonic prices for housing.	€/FU (only foreground system, processes in focus area and region)	(European Commission, 2014)
Private Space Consumption	Private Space Consumption of the WM System	Considers the area used inside private houses for waste storage against the living space.	m^2/m^2 (waste storage space inside housing per FU/average available living space per actor in the focus area)	(den Boer et al., 2007)
Accessibility Of WM System	Percentage Of Doorways Within an Interval of Distances Between the Door and the Waste Collection Points	Considers ranges of distance to access waste collection points (door-to-door collection is 0 m).	% (of doorways for each distance range in the focus area)	(Carlos et al., 2016; Gallardo et al., 2010; Rada et al., 2013)
Occupational Health	Fatal and Non-Fatal Accidents at Workplace	Risks related to work and linked to the workers' health.	Number of fatal and non-fatal accidents/FU	(Ciroth and Eisfeldt, 2016)

FU = Functional unit, WM = Waste management, MSW = Municipal solid waste, CF = Characterisation factor, NIMBY = Not in my back yard.

respect to occurrence and magnitude of the impacts (local versus global) and iii) combining established environmental LCA methods assessing global impacts with local impact assessment methods such as economic indicators or nuisance impact categories (e.g., odour and landscape disamenities). One of the particular gaps in literature that the framework intends to address is the inclusion of a comprehensive set of local impact categories, which was covered in a very limited way in previous studies (Corder et al., 2012; Inghels et al., 2016). Overall, the set of impact categories and indicators presented for the assessment of the micro-impacts are a first attempt to assess comprehensively these impacts. This is done with the aim to strengthen evaluations at local/regional level and help decision-making processes with improved information on the local impacts that may affect the population in the surroundings of the WMS and are thereof considered important by local stakeholders as much as global issues (e.g., global warming). However, future research should further test and improve these indicators, focusing on the main challenges for their application. Regarding the indicator Change in (MSW) Selective Collection Behaviour (category Effectiveness in achieving behaviour change), the main challenge lies in the measurement of the effect of an action, since there are other factors affecting this behaviour (e.g., ethical, social pressure). Moreover, this relation can vary from one country to another depending on the development of the system. Similarly, the indicator Variation of Property Value As a Result of Waste Management Infrastructure/Operations (category Landscape disamenities) may be subject to further improvements in respect to disaggregating the individual contributions to the disamenities, such as noise, visual impact or smell, now fully aggregated. For other indicators, no information that could be applied to the specific context of waste management was found in literature. This is the case for Public Acceptance/NIMBY Syndrome and Stakeholders Involvement. In these cases, new indicators for the assessment were proposed. Another criticality for the sustainability assessment is the data availability. The application of the indicators proposed in the framework will have to be adapted to the specific data availability of the system under assessment. For instance, the categories assessing economic impacts in the framework were limited to the foreground system due to the lack of reliable background data for the assessment of the whole life cycle. In future, improved background costing data may for example justify a full life cycle costing.

The approach applied for aggregation, avoiding any compensation of the impact across AoPs and thus across pillars, positions the framework on a strong sustainability ground. In place of a final single composite index, a relative ranking (one per each of the five AoPs considered) derived with MCDA technique is proposed. This allows for a relative comparison of the WMS scenarios assessed, highlighting best/worst solutions in each AoP and facilitating synthesis and communication of the results in the endeavour of best supporting an informed decision-making process. Most of the sustainability frameworks mentioned earlier do not include or suggest specific aggregation approaches (e.g., Scheel, 2016; Souza et al., 2015; Corder et al., 2012; den Boer et al., 2007; Liu et al., 2013). Others, such as Chong et al. (2016), follow the principle that the sustainability of a system is determined by its least performing indicator (normalised), suggesting the application of the non-compensatory formula by Díaz-Balteiro and Romero (2004). This formulation is also thoroughly discussed by Pollesch and Dale (2015), where, however, the focus is on the general aggregation theory rather than its specific application to sustainability frameworks. While we also implemented this formula to be potentially used as sensitivity analysis (see Supplementary material A; excel model), a major drawback of this approach is that the information regarding non-extreme indicators is inevitably lost as only the value of the

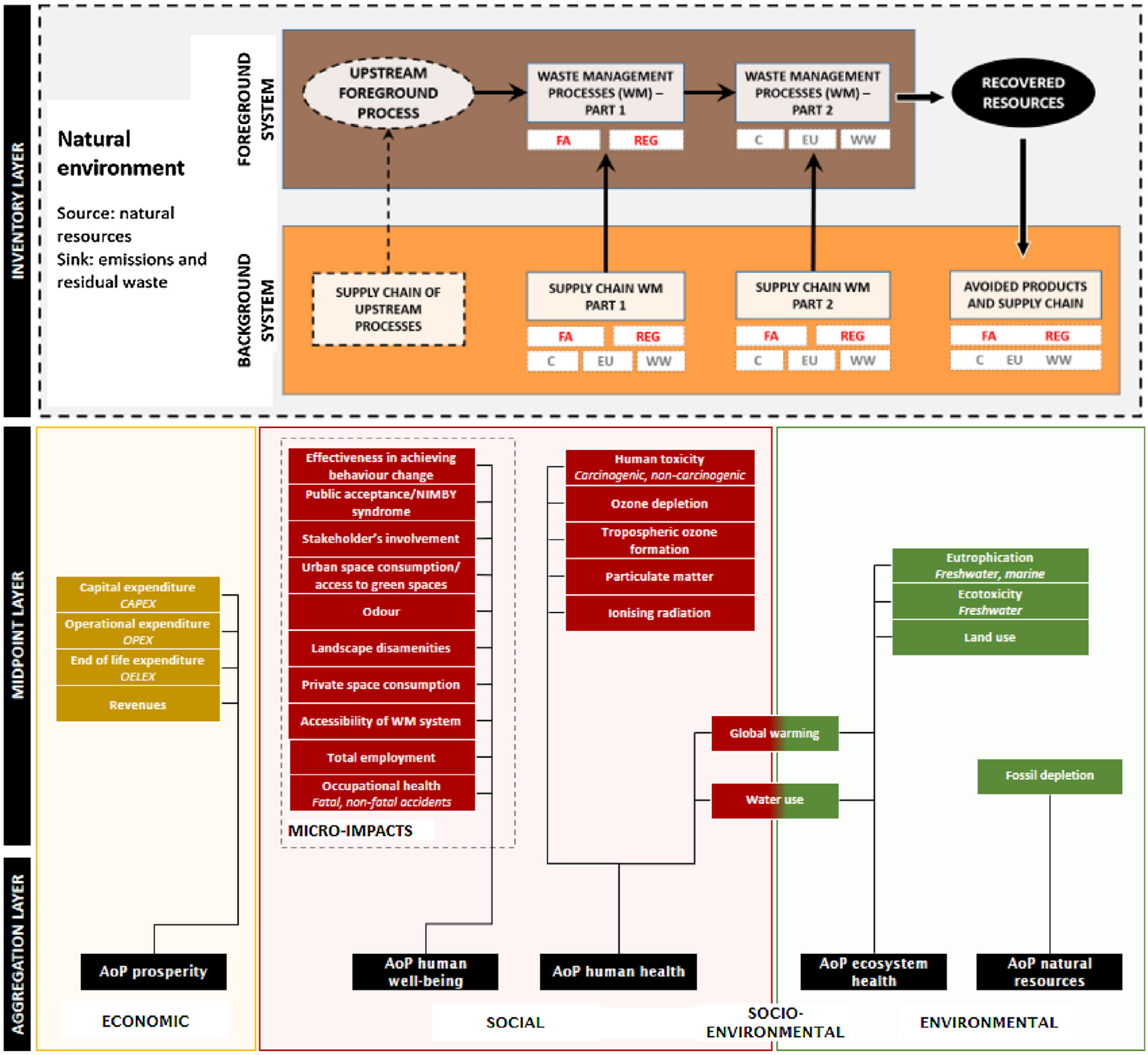

Fig. 3. Diagram of the final operational sustainability framework. Waste management processes include all activities related to WM (e.g. collection, transport, landfilling, etc.). *FA = Focus area, REG = Region, C = Country, EU = European Union, WW = Worldwide, WM = Waste management.*

least performing indicator is retained, as discussed elsewhere (Gan et al., 2017).

4.2. Learnings and perspectives

In spite of the advances presented, a clear learning drawn from our exercise is that more research is required to further develop the indicators for micro-impact categories. These categories require further research focused on the development of appropriate indicators for their application. Data availability represents another critical aspect. We anticipate this to be an issue when addressing local impacts (e.g. disamenities) and costs. In this respect, focusing on foreground cost was suggested as a means to overcome the issue of still incomplete lifecycle datasets on costing. Regarding the practical application of the framework, it should be borne in mind that selected indicators may require further (mathematical) elaboration to align/allocate the results to the studied FU. This is anticipated for some of the indicators under the AoP Human Well-Being, e.g., according to European Commission (2014) the indicator 'disamenities' should be quantified as property value loss following installation of a treatment plant. To align the impact to the FU (e.g., management of the waste generated in a year in a given area) a critical evaluation of suitable allocation strategies is needed, for instance considering the lifetime of the facility or the annual capacity, which will depend on the data available for the case study.

Research is currently being conducted to apply the operational sustainability framework presented to various European cities as case studies. This will provide further insights on the environmental, social and economic impacts of WMSs and circular economy initiatives as well as on the potential strengths and weaknesses of the proposed framework.

4.3. Target audience and users

The operational sustainability framework is intended to be used for the assessment of the WMS as it is today compared to alternative eco-innovative solutions, i.e. specific actions to improve the current performance. These may entail the implementation of new materials or processes, comprise suggestions to adjust legislation or identify spatial design developments. Participation of local/regional stakeholders is key to identify such solutions. While the application of the operational sustainability framework certainly requires the involvement of sustainability specialists, the results are ultimately addressed to local stakeholders to support informed decision-making processes. In this respect, the aggregation effort is truly meant to facilitate synthesis and communication of the assessment results by ultimately ranking the alternatives assessed from best to worst. While this may incur detail loss, further information can be drawn looking at midpoint results, where impact contributions (hotpots) can be identified. All in all, the ambition is to shed new light on participatory and science-based decision-making by involving local stakeholders in the entire process, i.e. from the initial definition of the framework and associated impact categories, through the alternative solutions to be assessed, up to the final interpretation and communication of specific case study results.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.rcrx.2019.100005.

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