REPAiR

REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism

D4.4 Definitive framework for sustainability assessment

Version Final

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Acronyms and Abbreviations

AoP	Area of Protection
AP	Avoided Products
BS	Background System
C	Country
CAPEX	Capital Expenditures
CBS	Cost Breakdown Structure
CF	Characterisation Factor
CFC	Chlorofluorocarbons
cLCC	Conventional Life Cycle Costing
CML	Centre of Environmental Science of Leiden University
DALY	Disability-Adjusted Life Year
DCB	1,4-Dichlorobenzene
EC	European Commission
eLCC	Environmental Life Cycle Costing
ELCD	European Life Cycle Database
EU	European Union
FA	Focus Area
fLCC	Financial Life Cycle Costing
FS	Foreground System
FU	Functional Unit
GDSE	Geodesign Decision Support Environment
GIS	Geographic Information System
ICT	Information and Communication Technology
ILCD	International reference Life Cycle Data system
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kBq	kilo Becquerel
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment

LCT	Life Cycle Thinking
MSW	Municipal Solid Waste
NMVOC	Non-Methane Volatile Organic Compounds
NOx	Nitrite/nitrate
NPV	Net Present Value
ODP	Ozone Depletion Potential
OELEX	End of Life Expenditures
OPEX	Operational Expenditures
OSF	Open Science Framework
OTV	Odour Threshold Value
P	Phosphorus
PEF	Product Environmental Footprint
PM	Particulate Matter
PSILCA	Product Social Impact Life Cycle Assessment
REG	Region
SC	Supply Chain
sLLC	Social Life Cycle Costing
SME	Small and medium-sized enterprise
WM	Waste Management
WMO	World Meteorological Organization
WMS	Waste Management System
WP	Work Package
WW	Worldwide

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Publishable Summary

This document is the deliverable 4.4 of work package 4 of the REPAiR project, which is the first public deliverable in this work package. The document presents the development of the comprehensive sustainability framework for the assessment of the present urban metabolism in the case study areas (cfr. WP3) and the eco-innovative solutions and strategies (cfr. WP5). The main innovation of this framework is the evaluation in a multidisciplinary and spatially-differentiated way, to be able to better grasp the possibilities of the less investigated peri-urban areas.

Firstly, the basic elements of the approach adopted in the framework are defined, particularly the functional unit, the system boundaries and the data needs for its implementation. When defining the impact categories and indicators in the framework, the impacts were considered at three levels: transdisciplinary (social, economic, environmental), multi-scale (geographical location) and multi-size (magnitude). Moreover, different categories and indicators will require different methodologies, from Life Cycle Assessment (LCA) to local system analysis of certain indicators. Consequently, different types of data and software will be required.

For the midpoint impact categories in the framework, a selection process was conducted involving stakeholders and experts from different areas of expertise. In a first stage, the preference of a sample of 52 respondents that was representative for the different case studies and areas of expertise was considered. The respondents rated a list of impact categories, gathered from a literature review, according to their personal opinion on relevancy for the project. In a second stage, the resulting preliminary set of categories was modified to limit the categories to a manageable number and considering also limitations regarding data availability and intrinsic methodological complexity. These categories were classified according to five areas of protection (AoPs) at the endpoint level (human well-being, human health, prosperity, ecosystem health and natural resources). However, D4.4 only defines the framework (in detail) until the midpoint level, and will not elaborate on the aggregation of the impacts into endpoint indicators (this will be addressed in D4.5).

After the selection of the final set of impact categories, a proper indicator was defined for each category. For those categories applying LCA, this was a more straightforward process, since these indicators are well established and commonly applied. However, this was not the case for the categories belonging to the AoP prosperity or AoP human well-being, which required specific research. Different approaches were used for obtaining a comprehensive view and understanding of the impact categories selected. In the case of the AoP human well-being, selection criteria were developed to rate the different indicators and to select the most adequate one (e.g., the odour footprint indicator was selected for odour). For the impact categories selected under the umbrella of prosperity, a thorough literature

research was done to understand possible limitations of indicators, and to finally select the most appropriate method to be applied in REPAiR. It must be highlighted that both the selection of impact categories and indicators was an iterative process, and changes were implemented when new information or limitations were acknowledged. Moreover, the application of some indicators was limited to the foreground system due to the lack of data availability. This was the case for the categories within the AoP prosperity, for which proper background data has not been developed.

The document also provides the necessary practical guidelines and methods for the application of the framework, in order to ease the assessment in the case study areas by the partners.

1. Introduction

Waste management (WM) is a crucial service in European cities due to the high amount of waste generated. A European citizen generates on average 483 kg of municipal waste per capita (Eurostat, 2016), which must be managed following adequate standards. During the last decades, there has been a constant improvement of the sustainability of WM because of an increasing concern from population, industries and authorities. The recent interest in circular economy strategies in Europe resulted in a set of measures from the European Commission called the Circular Economy package (EC, 2015), which also entail improvements in waste management. Key is to move from the perception of 'waste as a problem' to 'waste as a resource'. The EU waste hierarchy should be put into practice, by e.g. focussing of waste prevention strategies or collecting high quality waste streams for re-use, remanufacturing and/or recycling. It requires engagement from industry, government and citizens to develop strategies to reduce environmental burden as well as creating e.g. jobs for a growing green economy (Hollins et al., 2017; EC, 2015).

In this context, there is extensive literature assessing the environmental impacts of waste from a life cycle perspective (Al-Salem et al., 2009; Astrup et al., 2015; Laurent et al., 2014), but there are few attempts for a comprehensive sustainability assessment of WM systems considering environmental, social and economic impacts. Moreover, only few studies focused on the local socio-economic impacts of WM (e.g., odour, space occupation), however, considered as relevant by many stakeholders (Woon and Lo, 2016).

The REPAiR project aims to develop a life cycle-based sustainability framework that fills this gap. The assessment includes impacts at multi-scale (different geographical levels), multi-size (micro to macro) and transdisciplinary (social, economic, environmental) level. It also intends to advance in the analysis of local and regional impacts from WM (e.g., disamenities) by applying life cycle tools, which were focused until now mainly on global impacts.

This report is the first publicly available deliverable of work package 4 (WP4), which focuses on the analysis of the sustainability of waste management. Previous deliverables in WP4 (D4.1, D4.2 and D4.3) were confidential and focused on data availability, preliminary sustainability framework and local socio-economic impacts respectively. In D4.4, an overview of key information stated in previous confidential deliverables is presented to allow a better understanding of the overall methodology followed, and the multi-objective framework for sustainability assessment is finalized and discussed.

2. Deliverable 4.4: goals and strategy

The core objective of this deliverable is to present the holistic framework developed in REPAiR for the sustainability assessment of European waste management systems (WMSs) until the midpoint impact category (Figure 1). The ultimate goal is then to apply this framework to both the current WM situation and eco-innovative solutions in each of the case study areas, to analyse the overall sustainability (upcoming Deliverables D4.6 and D4.7).

The specific objectives of D4.4 are the following:

- To present relevant information for the understanding of the sustainability assessment developed in REPAiR.
- To discuss the Areas of Protection (AoP) that will be considered in the sustainability assessment.
- To define the impact categories and respective indicators that will be used to analyse local, regional and global impacts.
- To include the environmental, social and economic dimensions of sustainability in the approach of the assessment.
- To define the methodology to consider the impacts at multi-scale (different geographical levels) and multi-size (micro to macro) level.

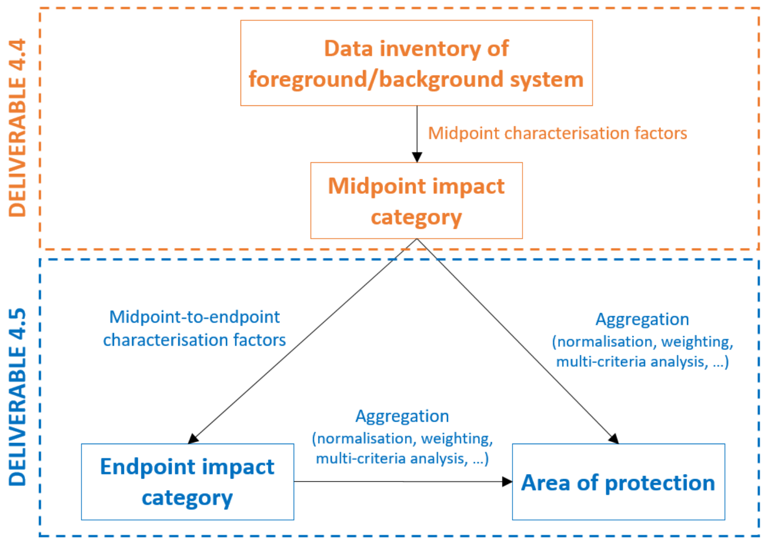

Figure 1. Generic impact pathway for the life cycle-based impact assessment, from data inventory to impact assessment at the level of area of protection. Orange: stages covered in this deliverable.

3. System boundaries for impact assessment

3.1 Processes and actors

The functional unit (FU) considered for the assessment is '*the treatment of (A) waste as it is generated by (B) in the focus area during one year*', of which (A) represents the type of waste (e.g., food waste), and (B) the waste generator(s) in the focus area (FA) (e.g., households, SMEs, companies with more than 100 employees). The types of waste considered in the different case study areas of REPAiR are discussed in D3.1, D3.3 and D3.4 to D3.8 (upcoming).

The assessment includes at least all the processes and actors required for the functioning of the WMS.

The foreground system includes the core WMS and the main processes, such as waste collection, transportation, separation, treatment and manufacture of secondary products. Figure 2 illustrates the processes included in the foreground system: WM processes that take place in the FA or region (Figure 2, PART 1) and WM processes that take place outside the region (Figure 2, PART 2), and possibly include upstream processes. The latter are included when eco-innovative solutions address issues affecting upstream phases of the waste (e.g., at the product production level, such as avoiding packaging). In that case, the foreground system must be extended. Thus, each of the case study areas in REPAiR needs to develop process flow charts for each of the key waste flows under study, starting from the generation of waste in the FA.

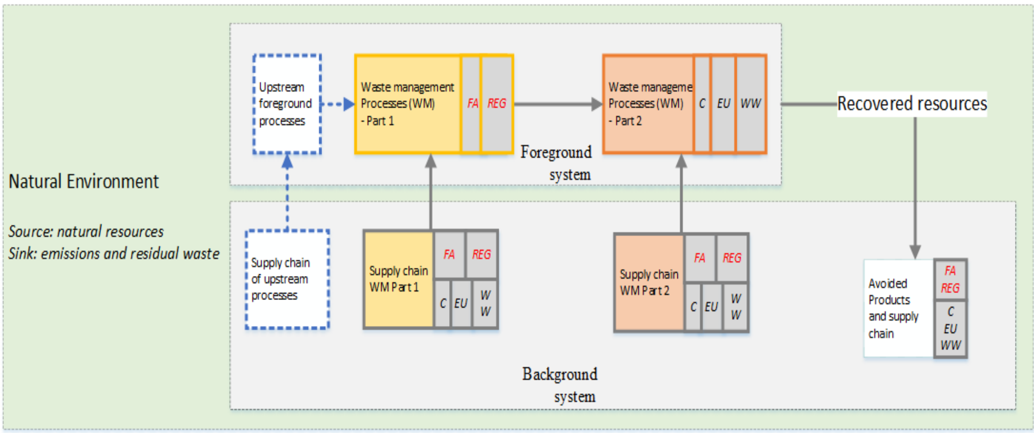

Figure 2. System boundaries (life cycle perspective) as considered in the REPAiR project. Applicable to all case study areas. Abbreviations: FA= focus area, REG = region, C = Country, EU = Europe, WW = worldwide, WM = waste management.

However, Life Cycle Thinking (LCT) is introduced to go beyond the traditional focus of the WM processes as such, and includes the entire life cycle of the service, which begins with the extraction of natural resources from the environment. In this sense, it is necessary to include in the assessment the background system, which takes into account all the processes that are required to support the foreground system (e.g., energy and materials), as visualised in Figure 2. In particular, the background system includes the supply chain processes to support PART 1, PART 2, and in case relevant, the upstream processes.

Because the foreground system will generate secondary products from the waste (recovered resources), the background system will include induced effects from alternative production of resources recovered from waste generated (e.g., electricity production from waste may substitute fossil-based electricity), that way accounting for the displacement of conventional products in the market.

All supply chain processes may be located either in the FA, in the region level, at country level, in Europe or beyond. The same goes for the production processes of the avoided products (cfr. D4.2), Figure 2.

3.2 Data needs (cfr. WP3)

The methodology chosen to be implemented in the project is the process-based *Life Cycle Assessment (LCA)*, which requires the quantification of the inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) for a given step in producing a product/service. This methodology is broadly accepted in scientific literature and has been standardized through the international standards ISO 14040 and 14044 (ISO, 2006a, 2006b). Also at the EU level, guidelines and recommendations to perform LCA are established, among all the ILCD handbook (EC, 2010), 'the product environmental footprint (PEF)' guide (Manfredi et al., 2012), the guide to interpret LCA results (Zampori et al., 2016), 'land-use related environmental indicators for LCA 'report (Vidal-Legaz et al., 2016), etc.

A *consequential* approach is recommended (ISO, 2006a, 2006b), by systematically applying *system expansion* using marginal market data to account for the substitution of technologies and products that occur because of the multi-functionality of the system assessed (based on fulfilling the FU). This approach is used to understand the environmental impacts related to those activities that are expected to change when producing, consuming, and disposing a product (or service in the case of waste management). For example, the research question can be the following: "how does the environmental impact change when product X (e.g., fossil-based electricity) is replaced by product Y (e.g., bio-based electricity)?" The environmental burden of product fossil-based electricity is then avoided and can be subtracted from the bio-based electricity environmental impact. However, fossil-based electricity includes multifunctional processes in its life cycle, and thus the resulting co-products and functions (e.g., fossil-based heat) are also avoided and need to be replaced by alternative products and functions. Likewise, the co-products and functions in the life cycle of bio-based electricity (e.g. bio-based heat) replace also other products and functions. Multifunctional processes can thus make consequential modeling complex and data demanding. Moreover, it is not always straightforward which products and functions are avoided. If finding the marginal suppliers is too complex or involves too many uncertainties, the attributional approach (using average market data) will be used. In the case of multifunctional processes (most likely applicable to WM activities), the environmental load of the inputs and outputs is divided among the co-products and functions. Following the ISO recommendations, it is preferred to subdivide the multifunctional process or, if this is not feasible, to determine a physical causality for allocation (mass, energy content, …). Economic revenue as allocation strategy is the least preferred strategy (Goedkoop et al., 2016).

For the analysis of the foreground system, the collection of data can be done bottom-up (preferred) or top-down. The bottom-up method entails the collection of primary data by first-hand experience or from (local) stakeholders, while top-down comprises the use of secondary data sources such as literature, reports, European databases, GIS-based maps, both for the assessment of the current situation and for eco-innovative solutions (cfr. WP5). Data inventory for the foreground system depends on the selected impact categories, amongst others: material and energy inputs, emissions, land use, products, by-products and waste flows, quality of waste flows, cost factors, revenues and social data. Secondary data (e.g., databases such as ecoinvent, PSILCA, NEEDS, ELCD, Agribalyse) will be used for the background.

Because the main focus of REPAIR is on the management of the waste and its transformation into valuable products, important efforts will be directed to collect specific data for end-of-pipe WM solutions and technologies both at local and regional levels. However, to achieve circularity in materials/energy markets, solutions may be found both in terms of optimal end-of-pipe systems and waste/energy prevention/reduction strategies. Therefore, as discussed in the previous subsection, upstream processes and flows might be considered when relevant for the development of eco-innovative solutions. In contrast to purely waste-oriented studies, where the zero burden approach can be applied (no environmental impact assumed for the incoming waste), this is not the case for upstream processes (prior of waste generation). The case study areas in REPAiR might consider both types of solutions and will gather the necessary additional primary and secondary data.

4. The sustainability framework: impact categories

4.1 Identification of impacts

The starting point for the development of the sustainability framework was the outcome of the PROSUITE (Prospective Sustainability Assessment of Technologies) EU-funded FP7 project. The project was funded by the European Commission between 2009 and 2013 and focused on the sustainability of new technologies. The sustainability assessment in PROSUITE presents 29 midpoint impact categories and five major Areas of Protection (AoP) or endpoint impact categories: prosperity, human health, human wellbeing, ecosystem health and natural resources. However, PROSUITE did not focus on waste management, nor circular economy, and excluded spatial differentiation. Therefore, further development has to be made according to the objectives of REPAiR.

One of the aims of the sustainability assessment methodology is to avoid possible burden shifting amongst processes, locations and types of impacts. In this sense, impacts could be grouped according to three different categories in REPAiR:

- *Transdisciplinary impacts*; nature of impact
- *Multi-scale impacts*; geographical location of impact
- *Multi-size impacts*; magnitude of impact

Transdisciplinary impacts represent environmental, social and economic (three pillars of sustainability) impact categories. Within this general classification, the five AoPs as defined in PROSUITE are included. Identification of relevant transdisciplinary midpoint impact categories was done on the basis of literature research and expertise of the WP4 team (which consisted of partners with different backgrounds).

Regarding multi-scale or spatialized impacts, their analysis can provide valuable insights on the location of the most impactful elements for decision makers, which can help to prioritize measures.

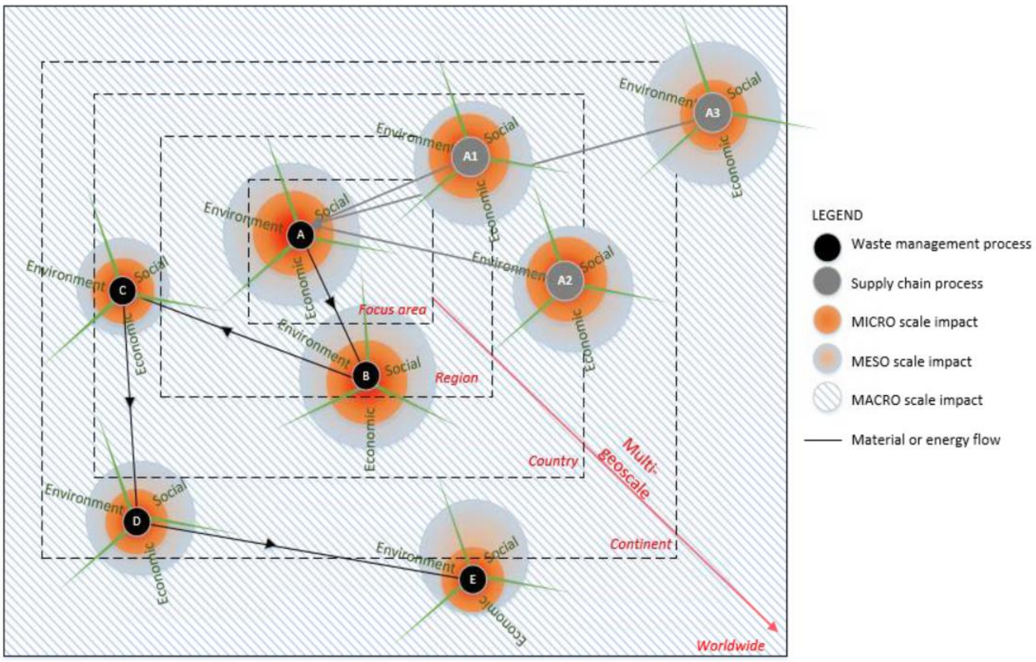

Figure 3. Hypothetical example to illustrate multi-scale and multi-size impacts. Location of foreground system processes (A – E) and background processes (A1-A3) represents the multi-scalability, according to the geographical boundary classification scheme, and visualization of micro/meso/macro (multi-size) level impacts caused by each process.

Multi-size impacts refer to the magnitude of the impact that will take place (e.g., global warming is a macro impact whereas odour nuisance is a micro impact, affecting the surroundings only) as shown in Figure 3 and Table 1.

*Table 1. The scale/magnitude of an impact caused by a particular process, length and area specifications per type of impact (micro/meso/macro)**

Scale	**Length**	**Area**	**Description**
Micro	1 m – 10 km	1 m^2 – 100 km^2	Local
Meso	10 km – 1,000 km	100 km^2 – 1,000,000 km^2	Regional/Continental
Macro	>1,000 km	>1,000,000 km^2	Global

**The length and surface area of each category is defined in function of the REPAiR project, Source: Deliverable 4.1*

The total impact per AoP is then calculated as the summation of the burdens associated with the (extended) WM (supply) chain minus the sum of the burdens of the avoided conventional products, cfr. eq. 1.

$$AoP_{impact} = (FS_{impact} + BS_{impact}) - AP_{impact} \quad \textit{(eq. 1)}$$

Where AoP_{impact} represents the total impact per AoP, FS_{impact} and BS_{impact} the impact caused by the foreground system and background system, respectively, and AP_{impact} the impact related to the avoided products (credits from system multifunctionality).

4.2 Selection of impacts

The selection approach depends on the type of impact: multi-scale and multi-size impacts are mainly selected based on restricted data-availability, while transdisciplinary impacts are selected based on the interest of the consortium members.

4.2.1 Multi-scale and multi-size impacts

Different types of impacts are not quantifiable (e.g. due to limited data availability, lack of spatialized LCA methods, etc.). Therefore, a trade-off between considering feasibility of implementation and fulfilling the objectives of REPAiR needs to be identified. Those impacts that will be assessed within the project are visualised in Table 2 (cfr. D4.2).

Table 2. Overview and identification of multi-size and multi-scale impacts following operations of the foreground system (PART 1, PART2, upstream) and background system (beyond the mere waste management system) and differentiation between multi-size impacts. Examples of the impacts selected are given in the last column. Upstream-related processes and impacts are not visualised in this table but follow the same selection as the (supply chain of) avoided products. Source: Deliverable 4.2, Sue Ellen Taelman (2017).

Type of process	*Location (multi-scale)*	*Impacts (multi-size)*	*Example of impact*
WM part 1	*FA + Region*	*Micro*	*Odour of waste collection in FA/R*
WM part 1	*FA + Region*	*Meso/macro*	*CO_2 emissions transport of waste in FA/R*
SC of WM part 1	*Country + Europe + WW*	*Meso/Macro*	*Increased employment in C/EU/WW because of export of waste/ by products*
WM part 2	*Country + Europe + WW*	*Meso/Macro*	*Resource use for electricity production taking place at C/EU/WW*
SC of WM part 2	*Country + Europe + WW*	*Meso/Macro*	*Emission leakages while digesting the exported waste*
Avoided products	*Country + Europe + WW*	*Meso/Macro*	*Emissions related to the production of the avoided product itself (e.g. chemical fertilizer)*
SC of avoided products	*Country + Europe + WW*	*Meso/Macro*	*Emissions produced by the supply processes of the avoided product (e.g. transportation of ingredients for the fertilizer)*

(*) WM= waste management, SC = supply chain, FA= focus area, R = region, C = country, EU = Europe, WW = worldwide.

4.2.2 Transdisciplinary impacts

Regarding the midpoint impact categories, a collaborative process was started in order to select the definitive set. A questionnaire with transdisciplinary midpoint impact categories was distributed among a representative sample of the consortium (equal representation of all case study areas and both local/regional government, WM companies and academic institutions were covered). The questionnaire respondents were asked to give a score [1-4] which indicated their personal interest (relevance) regarding a particular impact category. In total, 52 questionnaires were filled in. The impact categories were categorized per AoP. A cut-off methodology was thereafter applied as follows: 1) a threshold limit was set on 2.6/4 which retained the impact categories that scored 2.60 or more, and 2) a limitation of the amount of impact categories per AoP (max. 10) to balance the results. The final set included 28 impact categories selected through this representative sampling procedure. A final check was performed during an expert panel debate with multi-disciplinary experts in the field, both REPAiR and non-REPAiR members. The four main points raised by the expert panel were: 1) possibility of grouping certain social impact categories, 2) including again total employment as an important impact category which was first removed because of the cut-off method, 3) identification of midpoint impact categories that potentially have pathways towards multiple AoPs, and 4) identification of micro impacts due to specific foreground processes located in the FA and regional territory, and the meso to macro impact categories.

Special attention is needed regarding impact categories that have linkages with multiple AoPs, as there is a risk of double counting (multiple accounting of the same effect of one flow, an emission or resource, in different impact categories). Though, it is perfectly possible that multiple pathways will be investigated when there is no risk for double counting, depending on the indicators that will be selected and their respective cause-effect chain.

The final set of impact categories in addition to the comments raised by the expert panel can be observed in Figure 4. The next step is to identify the most relevant and feasible indicators to quantify each of the midpoint impact categories. D4.3 already focussed on micro impacts within the AoP human well-being and the most appropriate indicator was selected for each impact category taking into account available methods and literature. This deliverable will provide an overview of the results of D4.3, alongside a description of the remaining midpoint impact categories (global to regional impacts) by proposing the most suitable indicators to be used within the project.

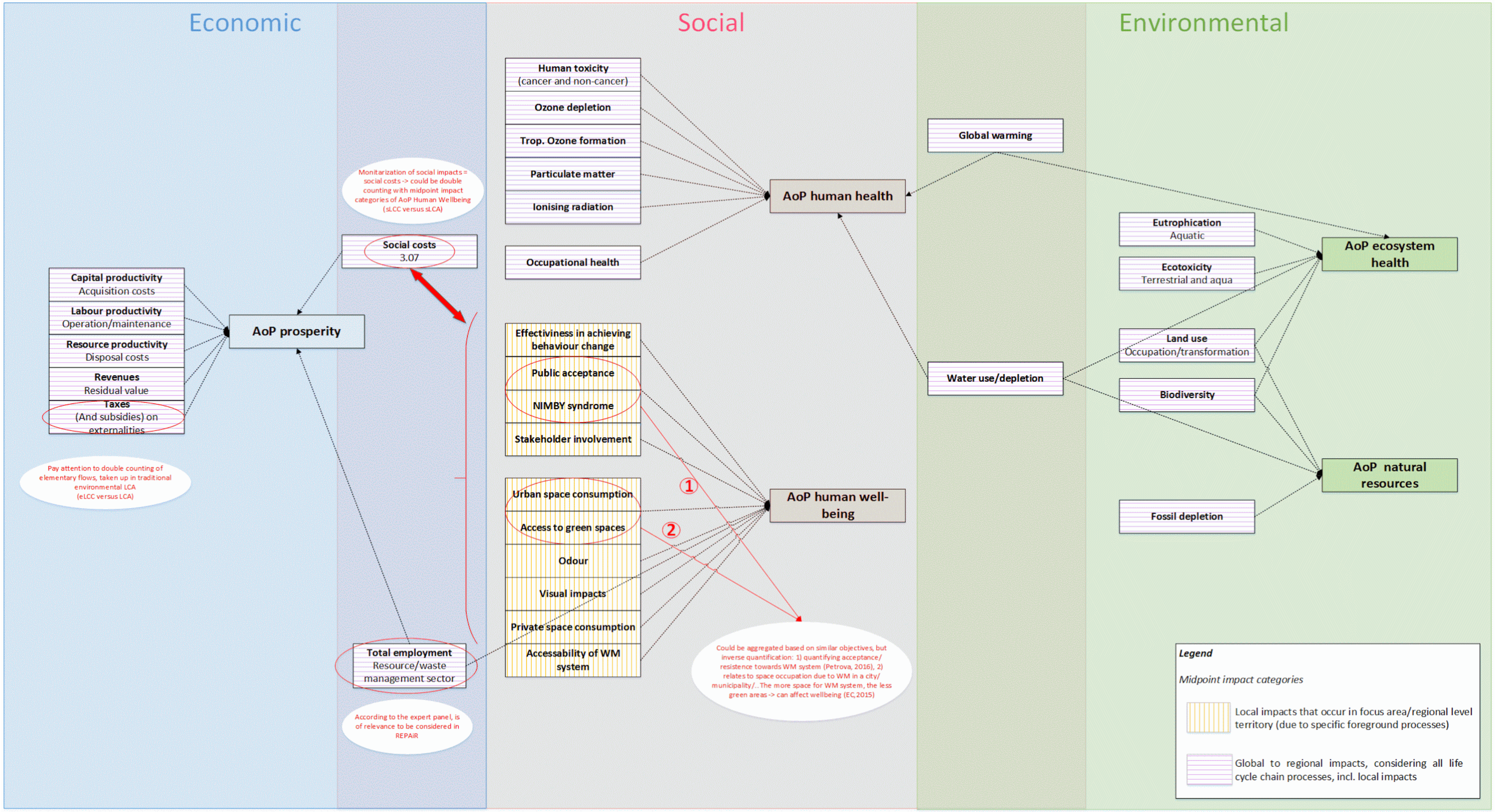

Figure 4. Impact categories selected for the sustainability assessment framework in REPAiR (cfr. D4.3).

4.3 Selection of indicators

This section describes the indicators selected for each impact category, classified per sustainability pillar and per AoP. Figure 5 shows the respective sections where the indicators of each of the midpoint impact categories are described. Information regarding data needs and characterisation factors (CF) to perform the sustainability assessment can be found in section 5 which concerns practical guidelines.

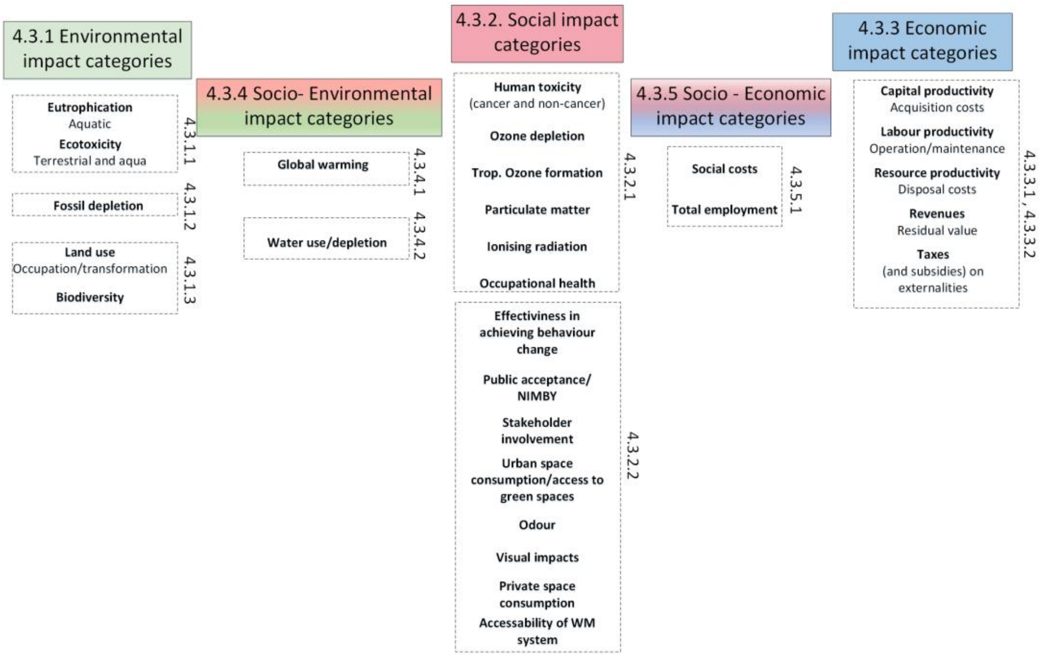

Figure 5. Structured overview of the different sections of the midpoint impact categories as described in this deliverable.

Within the ILCD Handbook, the following default midpoint impact categories were recommended for impact assessment in traditional LCA (including the AoP human health, ecosystem health and natural resources):

- Climate change
- (Stratospheric) Ozone depletion
- Human toxicity
- Respiratory inorganics
- Ionizing radiation
- (Ground-level) Photochemical ozone formation
- Acidification (land and water)
- Eutrophication (land and water)
- Ecotoxicity
- Land use
- Resource depletion (minerals, fossil and renewable energy resources, water)

However, ILCD analysis, evaluation and selection of recommended methods all refer to methods available by 2008, i.e. several impact categories 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 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 impact method ReCiPe, which is one of the most highly valued LCA methods included in the major LCA software and databases (Huijbregts et al., 2017). An evaluation of the proposed methods in each of these two recent reports is needed to align the selection with the objectives of the project (see table 3).

Table 3. Midpoint LCA related impacts categories and their indicators based on recent reports of (EC, 2018) and (Huijbregts et al. 2017). Green coloured references are the indicators retained to be used in the REPAiR project.

Impact categories	References		Preferred reference and comments
	PEF (1)	ReCiPe (2)	
Eutrophication	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	Helmes et al. 2012	EC (2018) recommends the EUTREND eutrophication model as used in the previous version of ReCiPe (i.e. ReCiPe 2008), so Helmes et al. (2012) as used in ReCiPe (2016) is more updated.
Ecotoxicity	USEtox model, (Rosenbaum et al, 2008)	Van Zelm et al. 2009	RECiPE (2016) included an updated version of the USEtox model (which is the recommendation of EC (2018). Therefore, Van Zelm et al. is the preferred reference.
Land use	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	De Baan et al. 2013; Curran et al. 2014	The method LANCA has only been adapted for Gabi databases and compatibility with other databases is uncertain. Inconsistencies may occur when merging databases and using different types of software tools. Therefore, De Baan et al. (2013)/Curran et al. (2014) is recommended to be used in the REPAiR project.
Fossil depletion	CML Guinée et al. (2002) and van Oers et al. (2002)	Jungbluth and Frischknecht 2010	The reference for the fossil depletion impact category from EC (2018) is obsolete and unused.
Global warming	Baseline model of 100 years of the IPCC (based on IPCC 2013)	IPCC 2013; Joos et al. 2013	Both use the same reference but EC (2018) is the most recent report.

Water use/depletion	Available WAter REmaining (AWARE) in UNEP, 2016*	Döll and Siebert potential 2002, Hoekstra and Mekonnen 2012	AWARE is a regionalised Life Cycle Impact Assessment (LCIA) method for water scarcity and is therefore the preferred reference.
Human toxicity	USEtox model (Rosenbaum et al., 2008)	Van Zelm et al. 2009	RECiPE included an updated version of the USEtox model (as recommended by EC, 2018). Therefore, Van Zelm et al. (2009) is retained in this case.
Ozone depletion	Steady-state ODPs as in (WMO 1999)	WMO 2011	The references are from the same organisation (WMO), but ReCiPe, 2016 is more updated.
Tropospheric ozone formation	LOTOS-EUROS (Van Zelm et al., 2008) as applied in ReCiPe 2008	Van Zelm et al. 2016	The reference for tropospheric ozone formation from EC (2018) is the one used in the previous version of ReCiPe, so Van Zelm et al. (2016) is more updated.
Particulate matter	PM model recommended by UNEP (UNEP 2016)	Van Zelm et al. 2016	The characterisation factors of the UNEP model are provided in a document and can be implemented in Simapro creating a new method. It differentiates between rural/urban and height of the stalk, which is good for analysing primary data from the case studies, but this distinction is not made in ecoinvent processes and thus cannot be applied automatically. Also an average might be considered for ecoinvent processes. Consequently, Van Zelm et al. (2016) is considered more practical and feasible to be used and is therefore is retained.
Ionising radiation	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al., 2000)	Frischknecht et al. 2000	Both use the same reference for ionising radiation but EC (2018) is the most recent report.

(1) Product Environmental Footprint (PEF). European Commission (2018). Product Environmental Footprint Category Rules Guidance. Version 6.3 - May 2018. Retrieved from http://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_guidance_v6.3.pdf

(2) Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., ... van Zelm, R. (2017). ReCiPe 2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y

(*) Recent report of AWARE : Boulay et al. 2018

Recently, two main trends can be found in the development of LCIA methods, namely i) enhancing consensus for the development of mutual models for the dispersion of pollutants in the environment, definition of human uptake pathways, endpoint metrics for human health damage in models and approaches (mainly led by UNEP SETAC Life Cycle Initiative and the European Platform for LCA), and ii) strengthening regionalization and spatial resolution in impact assessment models to reflect the variation of the impacts depending on the location. The latter can be done in two ways: (1) by using recipient archetypes, e.g., indoor/outdoor, urban/rural, and remote area classification for human recipients and different soil types for e.g., metal fate or (2) by using specific locations by means of GIS or continental/national boundaries, ecozones or regions, while the relevant resolution may vary between impact categories (Pettersen and Song, 2017).

However, because of data intensity, spatial differentiation is not (always) applied in each of the methods as also recommended/proposed by PEF and ReCiPe. Though, in case there are regionalised characterisation factors available (cfr. ReCiPe 2016, e.g., impact categories land occupation and water use), a problem arises regarding inconsistencies with the background LCA databases. For example, Ecoinvent v3.4 is not adapted yet in terms of site-specific flows and background data and therefore these spatially-differentiated CF's cannot be used, as explained in section 5.

4.3.1 Environmental impact categories

4.3.1.1 AoP: Ecosystem health

The midpoint impact categories that have solely a cause-effect chain with the AoP ecosystem health are eutrophication, ecotoxicity and land use (presented in Boxes 1 to 3).

Box 1. Impact category: Eutrophication

Indicator: ***Freshwater eutrophication***

Impact size: Meso

Description: The indicator measures the potential impact of certain substances (especially nitrogen and phosphorus-based compounds) to contribute to the eutrophication of aquatic ecosystems. The excess of these substances leads to the proliferation of plants or algae, which results in the depletion of the oxygen concentration.

Units: kg of P eq. / FU (including foreground and background systems)

Reference: Helmes et al. 2012

Box 2. Impact category: Ecotoxicity

Impact size: Meso

Description: This indicator measures the potential of chemicals emitted to air, soil and water to affect ecosystems, and is calculated considering the persistence of the chemicals as well as their toxicity (effect). The indicator will be calculated aggregating three ecotoxicity indicators that hold the same units: terrestrial ecotoxicity potential, freshwater ecotoxicity potential and marine ecotoxicity potential.

Indicator 1: ***Freshwater ecotoxicity***

Units: kg 1,4-DCB eq. / FU (including foreground and background systems) **Reference:** Van Zelm et al. 2009
Indicator 2: *Marine ecotoxicity* **Units**: kg 1,4-DCB eq. / FU (including foreground and background systems) **Reference:** Van Zelm et al. 2009
Indicator 3: *Terrestrial ecotoxicity* **Units**: kg 1,4-DCB eq. / FU (including foreground and background systems) **Reference:** Van Zelm et al. 2009

Box 3. Impact category: Land use

Indicator: *Occupation and time-integrated transformation* **Impact size**: Macro **Description**: The land use category quantifies the damage to ecosystems due to the occupation of a certain area, its transformation or a combination of both impacts. **Units**: m^2 × yr / FU (including foreground and background systems) **Reference:** De Baan et al. 2013; Curran et al. 2014

Land and water surface are finite and usually constant in total available amount. They cannot be consumed but only occupied, and they become available again for other uses after occupation. Therefore, they can be considered flow resources. The use of a flow resource may have (local) impacts on the temporary availability of, and therefore the competition (among humans and the environment) for, this resource. Moreover, potential impacts of land occupation/transformation have traditionally not been connected to the AoP Natural Resources, but instead to the AoP Ecosystem Health by several already existing methods assessing land use impacts through changes in biodiversity, soil quality, erosion, etc. (Sonderegger et al., 2017; Taelman et al., 2016). Therefore, the pathway land use - AoP natural resources has not been further investigated.

4.3.1.2 AoP: Natural resources

The impact category fossil depletion (Box 4) only affects the AoP natural resources.

Box 4. Impact category: Fossil depletion

Indicator: *Fossil resource scarcity* **Impact size**: Macro

Description: This indicator measures the cumulative amount of fossil fuels used, which affects the availability of this resource and leads to an increment on the extracting costs.
Units: kg oil eq. / FU (including foreground and background systems)
Reference: Jungbluth and Frischknecht 2010

4.3.1.3 AoPs: Ecosystem health, natural resources

Although the impact category of **biodiversity** was initially considered as a midpoint impact category belonging to the AoPs ecosystem health and natural resources based on the questionnaire results, traditional LCA methods model biodiversity as an endpoint impact category, correlating to the AoP ecosystem health, which quantifies the loss in species due to e.g., land use over time and space (Souza et al., 2015). No midpoint characterisation factors are available, so the coupling with the data inventory of the case study areas towards impact assessment at midpoint level is not straightforward. Following this reasoning, the category biodiversity as a midpoint category has been excluded from the LCSA. Figure 4 shows also a pathway towards the AoP natural resources, as biodiversity includes a variety of genetic resources (phylogenetic diversity), also explained by Weidema and Lindeijer (2001). However, changes in the amount of genetic resources are accounted for but only in a way to determine land use impacts (AoP ecosystem health), as described in Taelman et al. (2016). Therefore, the pathway biodiversity (genetic resources) - AoP natural resources is not further considered in the project.

The categories ‘Global warming’ and ‘Water use’ are addressed in the section of socio-environmental impacts (section 4.3.4) because they also affect the AoP human health.

4.3.2 Social impact categories

4.3.2.1 AoP: Human health

The AoP human health holds 6 impact categories (Box 5 to 11). The methodology for the calculation of the indicators of these impact categories is similar to environmental impact categories, since LCA is also applied (see section 4.2). The impact category ‘occupational health’ is not inherently part of traditional LCA impact assessment. It follows social LCA methods, as mentioned by Dreyer et al. (2006) and Ciroth and Eisfeldt (2016).

Box 5. Impact category: Human toxicity

Impact category: Human toxicity (aggregated)
Impact size: Macro

Description: This indicator measures the potential of chemicals emitted to air, soil and water to affect human health, and is calculated considering the persistence of the chemicals as well as their toxicity (effect).
Indicator 1: *Human carcinogenic toxicity* **Units**: kg 1,4-DCB eq. / FU (including foreground and background systems) **Reference:** Van Zelm et al. 2009
Indicator 2: *Human non-carcinogenic toxicity* **Units**: kg 1,4-DCB eq. / FU (including foreground and background systems) **Reference:** Van Zelm et al. 2009

Box 6. Impact category: Ozone depletion

Indicator: *Stratospheric ozone depletion*

Impact size: Macro

Description: This impact category quantifies the potential of certain emissions to reduce the thickness of the stratospheric ozone layer, which increases the fraction of solar UV-B radiation reaching the Earth's surface. This impact can harm both human and animal health, as well as ecosystems.

Units: kg CFC-11 eq. / FU (including foreground and background systems)

Reference: WMO, 2011

Box 7. Impact category: Tropospheric ozone formation

Indicator: *Ozone formation, human health*

Impact size: Meso

Description: This indicator measures the potential of formation of ozone in the troposphere because of photochemical reactions of NO_x and Non Methane Volatile Organic Compounds (NMVOCs). This process depends on the concentration of these components and the meteorological conditions, and can affect humans with respiratory distress.

Units: kg NOx eq. to air / FU (including foreground and background systems)

Reference: Van Zelm et al. 2016

Box 8. Impact category: Particulate matter

Indicator: *Fine Particulate matter formation*

Impact size: Meso

Description: This indicator measures the potential for emitting anthropogenic fine particulate matter (with a diameter of less than 2.5 μm), which are a mixture of organic and inorganic substances (e.g. SO_2, NH_3, NO_X). These emissions were linked to respiratory morbidity when inhaled.

Units: kg PM2.5 eq. to air / FU (including foreground and background systems)

Reference: Van Zelm et al. 2016

Box 9. Impact category: Ionising radiation

Indicator: *Ionising radiation increase*

Impact size: Meso

Description: This indicator measures the impact on human health of the release of radioactive material (radionuclides) to the environment. These radionuclides generate ionising radiation that can lead to damaged DNA-molecules.

Units: kBq Co-60 eq. to air / FU (including foreground and background systems)

Reference: Frischknecht et al. 2000

Box 10. Impact category: Occupational health

Indicator: *Fatal and non-fatal accidents at workplace*

Impact size: Micro

Description: Occupational health refers to the management of risks related to work and is directly linked to the worker's health.

Units: Number of fatal and non-fatal accidents / FU (only foreground system)

Reference: Ciroth and Eisfeldt, 2016

Following the framework of PROSUITE EU FP7 project, the impact category 'occupational health' was initially categorized as a midpoint impact category under the AoP human health (cfr. D4.2). However, up until today, there is not a broadly accepted standard or reference for social indicators, but a broad set of indicators is collected for and made available in the PSILCA database, to be able to cover many different viewpoints and applications, inspired by UNEP-SETAC (2009). The category 'occupational health' for the stakeholder category 'workers' is one of the subcategories included in the database. As this database is developed to support social LCA assessment, the impact category 'occupational health' is considered a midpoint category for the AoP human well-being, rather than the AoP human health (Ciroth and Eisfeldt, 2016; Eisfeldt, 2017).

The PSILCA database proposes different indicators to assess the category '*occupational health*' and obtain an overall picture of the level of safety risks: "Rate of non-fatal accidents", "Rate of fatal accidents", "DALYs due to indoor and outdoor air and water pollution", "Workers affected by natural disasters" and "Presence of sufficient safety measures”. In REPAiR, the indicators selected to address the category ‘*occupational health*’ are “fatal and non-fatal accidents at workplace” because the main principles governing the protection of workers’ health and safety are laid down in a 1989 framework Directive 89/391/EEC, the basic objective of which is to encourage improvements in occupational health and safety. One of the key aspects of improving occupational health is reducing the number of fatal (death of the victim within one year) and non-fatal (at least four full calendar days of absence from work and considerable harmful injuries) accidents.

In principle, the impact on occupational health caused by the background system can be included in the sustainability analysis when making the connection between the inventory of the foreground system and the PSILCA database. However, as it is inherent in the nature of social LCA, to some extent it has a subjective nature because it depends on cultural and even individual evaluations and conventions (Eisfeldt, 2017). Consequently, many uncertainties arise when using this background database due to inherent subjective modelling choices, low data quality, etc. For example, the risk assessment method in PSILCA includes the assignment of an ordinal level to the observed indicator values. These levels and the assessment are indicator-dependent. In most cases, 6 different levels are distinguished on a negative scale: no risk, very low risk, low risk, medium risk, high risk, and very high risk. However, for a few indicators such as ‘respect of indigenous rights’ and ‘social benefits’, an opportunity scale is proposed to reflect a positive social impact, expressed by high, medium or low opportunity. The assignment of risk levels to the indicator values is based on international conventions and standards, labour laws, expert opinions but also own experience and evaluation (Eisfeldt, 2017). Another example is the use of an activity variable (Norris 2006), necessary to describe the relevance of impacts caused by a process in a life cycle. This variable is supposed to reflect the share of a given activity associated with each unit process (UNEP-SETAC, 2009) and, therefore, quantifies the respective social indicators related to the product system. Two proposed activity variables are 1) worker hours, i.e. the time workers spend to produce a certain amount of product in the given process or sector (in principle only applicable to the stakeholder category ‘workers’) and 2) value added, i.e. the difference between the sum of the inputs and outputs of each industry or commodity, divided by the gross output, from Eora (2015) (Eisfeldt, 2017). Though, no consensus has been found on the use and application of activity variables.

Based on the above reasoning, it has been proposed to apply the indicators ‘fatal and non-fatal accidents at workplace’ for the foreground system only, under the AoP human well-being and to consider it as a local impact category, rather than a life cycle based one (box 10).

In all probability, this indicator must be allocated to the FU which represents one single key flow (e.g. food waste, key flow A). For example, if 1 fatal accident per year is reported for waste treatment company X located in the FA/region, this accident has to be allocated to the specific key flow, most likely on a physical unit basis (e.g. mass-based: company X processes yearly 500 ton of key flow A and 700 ton of key flow B, then the amount of accidents should be multiplied by the factor 500/1200). The selected allocation strategy has to be applied for all foreground system activities in the FA/region.

4.3.2.2 AoP: Human well-being

This AoP includes eight impact categories that focus on social impacts at local level (disamenities), which have received little attention until now in life cycle studies of WMSs. The partners in REPAiR conducted an extensive research to find indicators for the measurement of these impact categories. For each category, various indicators were presented and the most appropriate one weres selected through a valuation process (D4.3). Table 4 shows the list of indicators resulted from this process.

Table 4. Micro impact categories and respective indicators. Selection criteria applied: feasibility, relevance, easiness to interpret, achievability. In bold the indicators preliminary selected.

IMPACT CATEGORY	INDICATOR	FEASIBILITY	RELEVANCE	EASINESS TO INTERPRET	ACHIEVABILITY	Average
A "Effectiveness in achieving behaviour change"	**A1: : Change in (MSW) Selective collection behaviour**	2	2	4	3	**2,75**
	A2: Composit indicator about waste/environmental conscious actions	2	3	3	2	2,50
	A3: Company related behaviour	2	1	4	3	~~2,50~~
B "Public acceptance/NIMBY syndrome"	**B1: Cost-effectiveness for residents resulting from waste segregation**	2	2	4	3	**2,75**
	B2: Societal awareness	2	3	2	2	2,25
	B3:"NIMBYst" profile indicator	2	3	2	2	2,25
	B4: Spatial conflicts intensity indicators	1	2	3	1	~~1,75~~
	B5: Municipal budget waste management expenditure indicator	2	1	4	3	~~2,5~~
C "Stakeholder involvement"	C1: Voter turnout	2	1	3	4	~~2,50~~
	C2: Stakeholder engagement for developing regulations	1	2	2	3	~~2,00~~
	C3: Stakeholders' satisfaction with the process of participation	2	3	3	1	~~2,25~~
	C4: The Social capital	1	2	2	2	~~1,75~~
	C5: Stakeholders' engagement in the project activities (workshops, monitoring and planning processes, etc.)	2	2	4	2	**2,50**
	C6: The effectiveness of the public participation exercise	2	2	2	2	2,00
D "Urban space consumption/access to green spaces"	D1: Distance to and coverage of urban green spaces and wasted landscapes	3	4	3	2	3,00
	D2: Urban space consumption of the waste treatment system (operational infrastructure of waste)	2	4	4	4	**3,50**
	D3: Spatial efficiency of the waste treatment system (operational infrastructure of waste)	2	2	3	3	2,50
	D4: Landscape fragmentation	2	2	3	3	2,50
E "Odour"	**E1: Odour footprint**	4	3	4	2	**3,25**
	E2: Odour impacts in LCA	2	3	4	1	~~2,50~~
	E3: Variation of property value as a result of a project - odour	3	3	4	2	3,00
F "Landscape Disamenities, cfr. Visual impacts"	**F1: Variation of property value as a result of a project - landscape**	3	3	4	2	**3,00**
	F2: Willingness To Pay (WTP)	2	3	4	1	~~2,5~~
G "Private space consumption"	**G1: Private space consumption of the waste treatment system**	2	4	4	2	**3,00**
	G2: Share of high-quality land in built-up areas (private properties built by housing and/or outbuildings)	1	2	3	3	~~2,25~~
	G3: Spatial capacity of private areas for waste management	1	2	3	3	~~2,25~~

	G4: Mean share of area designated for waste storage on privately-owned property in the total area of property	2	2	3	2	2,25
H "Accessibility of WM system"	H1: Time-use for waste sorting	2	3	3	2	2,50
	H2: Willingness to pay for others handling the sorting	2	3	3	2	2,50
	H3: Percentage of doorways attending to the distance of waste collection points	2	3	4	2	**2,75**

The assessment of these impact categories is limited to the foreground system (see section 3.1) because they refer to micro-impacts that are only relevant at local or regional scale.

Box 11. Impact category: Effectiveness in achieving behaviour change

Indicator: ***Change in municipal solid waste (MSW) selective collection behaviour***

Impact size: Micro

Description: The selective collection of waste streams in a territory can show the change of households' behaviour which is reflected in the amount of MSW recycling. This change can be triggered by improvements in recycling performance, pro-environmental manufacture of products and demographic characteristics of individuals.

Units: % (amount selectively collected key waste flow X per actor per year/ total amount of key waste flow X generated per actor per year)

Reference: Inoue and Alfaro-Barrantes, 2015; Markle, 2014; Miliute-Plepiene et al., 2016; Park, 2018; Wilson et al., 2015

The impact category *"Effectiveness in achieving behaviour change"* is presented in Box 11. The indicator proposed is the change in selective collection behaviour. This is a simple and easily applicable indicator based on the fact that the recycling rate can indicate the impact on behaviour change of the current situation and the eco-innovative solutions.

The required data are the percentages of selectively collected waste (for each type of key flow to be analysed in the study area) to the total amount of key flow generated by an actor (the concerned parties, e.g., households, organisations, SMEs, …) per year. These data can be obtained from public databases or from specific surveys conducted within the case study areas.

However, there are some points of attention that will need to be addressed. Firstly, there are plenty of influencing factors of pro-environmental behaviour and its change (e.g., moral, personal traits, social pressure), which may hamper the assessment of the effect of eco-innovative solutions in particular. Literature and research works found a correlation of 0.2-0.7 (with an average of 0.42) between these factors, but the difficulty lies in the measurement of the effect of one certain eco-innovative solution. Secondly, separation of waste is not equally linked/linearly correlated to environmental behaviour in all the countries, depending on the degree of development of the system. Finally, the spatial differentiation is only possible when data regarding selective collection is available at small geographical scales (e.g., neighbourhoods, cities).

Besides the so-called separation rate, another important aspect can be the amount of municipal solid waste created by households (or other actors) and its change. Its increases or decreases can also reflect to the 'waste behaviour' of a certain society.

Box 12. Impact category: Public acceptance/NIMBY syndrome

Indicator: ***Cost-effectiveness and acceptance towards waste sorting*** [(1)]

Impact size: Micro

Description: Resulting from local regulations, general costs appear for residents to collect waste. These costs derive from the potential to reuse or valorise waste, but also derive from the specific management model implemented in a given area. Usually, local authorities impose varied rates, financial profits or punishment to encourage to sort waste. The public acceptance indicator is presented as an equation that contains two factors: the potential financial profits or costs for actors enforced by local authorities to stimulate them to sort the waste and effective sorting efficiency of certain types of waste. The indicator takes into account possible differences (in costs or sorting behaviour) among several locations within the focus area.

Units: %/FU (foreground system, focus area only)

Reference: REPAiR team proposition

[(1)] The indicator as proposed in box 12 is selected to represent the merged impact category public acceptance/NIMBY syndrome, as a result of the selection and evaluation approach presented in D4.3. However, it must be pointed out that this indicator is mainly suitable to address impacts on 'public acceptance', and not representing the impact related to 'NIMBY syndrome'.

Regarding the '*public acceptance/NIMBY syndrome*' category, the indicator selected is expressing the sorting behaviour of certain key waste flows generated by a specific actor in different spatial subunits of the focus area (e.g., neighbourhoods), see Box 12.

Assessment of public acceptance (Y, in %) for sorting the key waste flow under study (Eq. 2):

$$Y = \frac{\sum_{i=1}^{n} Cs_i}{\sum_{i=1}^{n} Cu_i} \; x \; \frac{\sum_{i=1}^{n} Xs_i}{\sum_{i=1}^{n} (Xu_i \; x \; Wsu_i)} \; x \; 100\% \qquad (Eq. \; 2)$$

where:
i – index of spatial subunit
n – total number of spatial subunits in the focus area
Cs_i – total yearly fee for sorting the key waste flow per kg in spatial subunit i [€/kg];
Cu_i – total yearly fee for mixed waste per kg in spatial subunit i [€/kg];
Wsu_i – weighted fraction of key flow (unsorted) in mixed waste in spatial subunit i [kg/kg];
Xs_i – total weight of key waste flow sorted (yearly average) per actor in spatial subunit i [kg/year];
Xu_i – total weight of mixed waste (yearly average) per actor in spatial subunit i [kg/year].

As can be observed, the data required include the costs for actors in the focus area to collect their waste. Linked to the FU of the system under study, focus in on the costs of sorting the key waste flows as considered in the different case study areas compared to the cost of mixed waste (economic incentives). Total financial cost can result directly from a fee to be paid for waste collection or can contain also other financial effects, such as a fee of penalty for non-sorted waste when it is required by law multiplied by the probability of such penalty enforcement or any financial encouragements, tax reductions, etc. These data can be obtained from local sources such as regulations, laws and reports.

This indicator measures the relation between sorting of waste by e.g., households and the economic incentives (fees). The decision to initiate waste sorting may come from different factors (e.g., economic, cultural, legislative), but since waste collection costs are decreasing, non-economic factors are becoming more important reinforcing residents' acceptance. The smaller financial encouragement and the higher sorting efficiency, the higher public acceptance is perceived. For example, in case the difference in fees is high, people may separate based only on economic advantages, instead of public acceptance. In the case of waste sorting by households required by law, potential risk of penalty can be calculated and taken into consideration as external financial incentive.

The applicability of the indicator is limited to eco-innovative solutions that influence sorting behaviour (because of e.g., other economic incentives, awareness campaigns, etc.) but when eco-innovative solutions deal with changes in the upstream processes (before waste collection) of downstream (treatment), the public acceptance cannot be measured. On top, spatial differentiation is only possible when data regarding selective collection and fees is available on small geographical scales (e.g., neighbourhoods, cities). Finally, this indicator only is useful when the key flow is not (fully) sorted and partially (totally) ends up in mixed waste in the focus area during sorting/collection.

Box 13. Impact category: Stakeholders' involvement

Indicator: ***Stakeholders' participation in the project activities*** (workshops, monitoring and planning processes, etc.)

Impact size: Micro

Description: The proportion or the number of stakeholders that actually participated compared to the total invited stakeholders per project activity is considered as an indicator to measure the involvement of stakeholders during the project processes.

Units: % (stakeholders participated/ stakeholders invited) per FU (foreground system only)

Reference: Brody, 2003

For the impact category of '*stakeholders' involvement*', the indicator stakeholders' involvement (participation rate) in the project activities was considered (Box 13). The data required for this indicator might be obtained from the list of stakeholders invited/present at different REPAiR events as well as from planning processes activities (e.g., participation on planning consultation). If a list of potentially interested stakeholders is available, the percentage of total involved stakeholders can be calculated (available in WP5). Thus, it is only applicable to project activities with stakeholder involvement taking place in the case study areas.

It must be noticed that this indicator does not give details about the type of stakeholders involved (stakeholders within and without consortium are equally considered) and does not consider external factors (e.g., reasons of 'no-show'). Moreover, it is difficult to link the indicator to the base case or the eco-innovative solutions because project activities should refer to specific case study areas (stakeholders at consortium meetings are not useful) and to different scenarios (current versus eco-innovative solutions), since LCSA results are site- and scenario-specific. Workshops organised to understand the base case situation, are representative for the calculation of stakeholders' participation for the reference situation (for each type of key flow discussed). A similar approach can be used for the eco-innovative solutions workshops.

Box 14. Impact category: Urban space consumption/access to green spaces

Indicator: ***Urban space consumption of the waste collection and treatment system*** (operational infrastructure of waste)[(1)]

Impact size: Micro

Description: The indicator considers all the urban space used by the Waste Management System (WMS) (along its different phases and facilities) against the total surface area of the region.

Units: m^2/m^2 (area occupied by public waste collection points and treatment facilities per FU / total land area of the region)

Reference: den Boer et al., 2007[(2)]

[(1)] The indicator as proposed in box 14 is selected to represent the merged impact category urban space consumption/access to green spaces, as a result of the selection and evaluation approach presented in D4.3. However, it must be pointed out that this indicator is mainly suitable to address impacts on 'urban space consumption', and not representing the impact related to 'access to green spaces'.

[(2)] The indicator urban space consumption as represented in den Boer et al. (2007) focuses only on public space collection points in cities. However, to align better with the objectives of the REPAiR project, it is proposed to broaden the indicator's scope towards all waste treatment facilities at regional level.

Regarding the impact category of '*urban space consumption/access to green spaces*', the indicator selected for its assessment is the urban space consumption of the waste treatment system (Box 14). This indicator requires the collection of data on land occupation of the existing and future WMS and the total territorial area of the region (private and public space). Although it is not defined in the reference paper, space consumption is clearly localisable and the sensitivity of different demographic groups can be related to the indicator by spatially relating them to an area.

To align with the FU which focuses on one key waste flow, a suitable allocation strategy needs to be chosen (case-dependent). For example, one does not have to account for the full area occupied by a composting plant, but only for a part of it, as the plant most likely deals with multiple waste streams.

Box 15. Impact category: Odour

Indicator: *Odour footprint*

Impact size: Micro

Description: This indicator quantifies the impacts of odour considering the persistence of odorants. A number of 33 linear midpoint characterization factors based on hydrogen sulphide equivalents are provided. Calculation of CFs are based on the potential malodorous air generated by the compound released to the atmosphere considering dilution, chemical reactions (atmospheric lifetime) and olfactory threshold value (OTV) as key modelling parameters.

Units: kg H_2S eq. / FU (only foreground system, processes in focus area and region)

Reference: Peters et al., 2014

The indicator odour footprint was considered for the impact category '*odour*' (Box 15). The main advantage of this indicator is that it provides ready-to-use midpoint characterisation factors for use in LCA studies. Additionally, equations for calculating midpoint characterisation factors for other compounds of interest are reported. Data is required on odorant emissions (e.g., mass per unit of waste) occurring at facilities/processes located in the FA or region where degradation of organic matter takes place (e.g. composting plants), so ideally experimental measurements are required. If possible, technology-specific emission data should be used. If not available, data from literature studies and environmental declarations from similar existing plants may be used instead.

Wind/turbulent airflow is discarded because it is very site-specific. The "odour footprint" does not include local populations and exposure pathways since estimating the actual effect on local people is not really the aim of LCA, which instead should provide decision-makers with an *a priori* comparison of potential impacts of alternative scenarios.

Regarding the evaluation of eco-innovative solutions, the main drawback of this indicator is that most solutions will be developed in a hypothetical way, not applied in practice, which makes it difficult to estimate the effect on the release of odorous emissions.

Box 16. Impact category: Landscape disamenities

Indicator: ***Variation of property value as a result of waste management infrastructure/operations***

Impact size: Micro

Description: This indicator quantifies the disamenities in monetary terms, evaluating the effects of waste management facilities on property prices using hedonic prices, which is an indirect quantification of the preference.

Units: €/ FU (only foreground system, processes in FA and region)

Reference: European Commission, 2014

For the impact category of '*landscape disamenities*', the indicator variation of property value as a result of a project was considered (Box 16). This method allows including local disamenities-related impacts in the framework, quantifying externalities to estimate the induced cost of WM facilities on nearby properties (thus to society). Spatial differentiation is important (the closer the disamenities, the more it affects the house prices negatively), as well as temporal-differentiation (development stage of the facility). European Commission (2014) suggests to calculate the property value decrease as follows:

1. Establishment of a territorial scope, defining the affected area and a maximum distance beyond which the WM facilities do not affect market prices. In general, it is considered a maximum distance of 4-5 km around the facilities and, upon data availability, it is possible to take into account the variation in property prices at different distance ranges (0-1 km, 1-2 km, 2-3 km, 3-4 km, 4-5 km).
2. Specification of the surface (size as m^2) and the market values of the real estates taken into consideration by consulting the land register or specific databases.
3. Identification of the real estate price reduction, by comparing the market values of comparable real estates (for housing type, size, people living, etc.) that are located in areas not affected by the presence of WM facilities. In case no data is available regarding the market value of properties, and evaluation method such as willingness-to-pay could be a way out to estimate the real estate price changes.

The main data needed is the market price of the properties and the selling prices, as well as data about structural characteristics of the houses located nearby WM facilities (e.g. type of housing, people living, size, etc.). Additional data about waste is also required (e.g. typology, amount treated annually). This is necessary in order to later normalise the property value loss to an annual average, e.g. when the FU is expressed as waste treated per year.

With respect to data needs, it is necessary to verify the data availability and the possibility to obtain information on other characteristics of the real estates properties. If it is possible, a linear regression is applied as follows (Eq. 3, Casado et al., 2017):

$$P = \beta 0 + \beta 1 X_1 + \beta 2 X_2 + \dots \beta n X_n + \varepsilon \qquad \textit{(Eq. 3)}$$

In the above formula, *P* represents the dependent variable, i.e. the market price of a property, X_i is a set of independent variables (such as: type of house, age, etc.), *n* represents the total number of model parameters, β is the regression coefficient and finally ε is the error term.

In the study conducted by Nahman (2011), it emerges that at the greatest considered distance (between 3 and 4 km), the loss of value per property is equal to about 210 €, while at the smallest distance the loss is equal to about 1471 €. However, the results are very variable and depend strictly on the context under consideration.

In the case where it is not possible to obtain any information on the independent variables described above, the following simplified formula (Eq. 4) proposed by the European Commission (EC, 2014) can be applied:

$$B = \Sigma i\ Si * Vi * \Delta\% \qquad \textit{(Eq. 4)}$$

In this case, B represents the estimated increase/decrease in property values (€), i is the type of property, S is the total surface (m2), V is the observed value (€/m²) and finally Δ% represents the increase/decrease in price. For the latter, some default values (in the case data are not available) are suggested in EC (2014). The negative impact of a certain WM facility, in terms of disamenities, is considered to be a fixed amount that does not vary significantly with the amount of waste being disposed or treated at the site. However, in REPAiR, the results of landscape disamenities should be linked to the FU (waste treatment for 1 year). The negative impact of landscape disamenities should be represented as a cost per amount of waste processed, to be able to compare different scenarios (Nahman, 2011). As this indicator considers the landscape disamenity of the whole treatment plant (which can deal with multiple waste streams), each case study has to identify a suitable allocation strategy that will depend on data availability and other assessment-specific assumptions), to link the impact to the FU. For example, let us consider an incinerator that receives 100,000 t/year of mixed MSW during a lifetime of 25 years and that induces an average loss of value equal to 1500 €/property on 10000 properties (total loss=15 M€): the loss per tonne of waste sent to incineration (regardless of the quality/type of such waste, to simplify) would equal: 15 M€/(100,000 t/year * 25 year) = 6 €/t waste. Martinez et al. (2015), in the supporting information, reports a value of ca. 4 €/t waste landfilled, derived from estimations done by COWI A/S.

The main critic to this indicator is related to the aggregation of disamenities-related impacts, i.e. it is not possible to disaggregate the individual contributions of noise, smell, visual impacts, etc. Thus, there is only a global value including all disamenities (odour, visual impacts, etc.) and could be also caused by other activities besides the SM sector. Moreover, it requires gathering information regarding market building prices and distances to WM facilities, which implies that estimations on changes of property values should be conducted for the eco-innovative solutions (i.e. expected change compared to *status quo*). However, as this indicator was found the most appropriate one to calculate landscape disamenities in the REPAiR project, it is assumed that changes in property values reflect foremost visual impacts.

Box 17. Impact category: Private space consumption

Indicator: *Private space consumption of the waste management system*

Impact size: Micro

Description: This indicator measures the area used inside private houses and space occupied within privately-owned surface for waste temporary storage (litter bins, containers, etc.) and relates it to the total available living space.

Units: m^2/m^2 (waste storage space inside housing per FU / of average available living space per actor in the focus area)

Reference: den Boer et al., 2007

The private space consumption of the WMS indicator is selected for the impact category '*private space consumption*', as presented in Box 17. The waste collection system largely determines both the type of containers used to store the waste and their everyday managing.

The required data can be obtained from statements provided by the actors under study (e.g., households), the so-called declarations on the number of people living in the household and also from information on the number of containers/bins, which allows the estimation of the area occupied per container expressed in m^2. Additionally, a questionnaire would reveal the area occupied by the containers per total private space. The data obtained is of quantitative nature, which allows for establishing a register that assigns a specific waste collection service to the private space consumption of particular actors.

Gathering relevant data in individual case studies may be time-consuming, while determining the type of containers used is different depending on local laws might result a good alternative. Moreover, adequately located and easily accessible centralised recycling facilities allow to a great extent waste collection beyond privately-owned land, which is not included in this indicator. Estimations on increased/decreased space consumption for garbage storage during the eco-innovative solutions has to be made, which is not evident.

Similar to urban space consumption (box 14), allocation methods need to be applied in this context.

Box 18. Impact category: Accessibility of WM system

Indicator: ***Percentage of doorways attending to the distance of waste collection points***

Impact size: Micro

Description: This indicator estimates the percentage of households that need to walk defined ranges of distances (e.g., 0-50 m; 50-100 m; etc.) to access the nearest public waste collection points based on access routes. Due to different cases, the types of collection point varies, such as container parks, common dustbins and door-to-door collection. For the door-to-door collection, the distance is 0 m. Based on the waste generation tax and the number of waste collection points, the optimum location of these points using GIS can be evaluated and proposed. The necessity of door-to-door collection can be discussed based on the analysis results.

Units: % (of doorways for each distance range in the focus area) per key flow and per actor(s) as described in the FU

Reference: Carlos et al., 2016; Gallardo et al., 2010; Rada et al., 2013

The indicator selected for '*accessibility of WM system*' is the percentage of doorways attending to the distance of waste collection points (Box 18). The distribution of inhabitants in a town, the waste collecting modes, and the location of waste collection points are crucial factors to ensure the participation in waste separation. It is important that the location of waste collection points are as close as possible to the users, and this point should be addressed in eco-innovative solutions. The data required for the calculation of the indicator includes the number, type and location of the collection points in the specific area. By using GIS, data can be transformed into percentage of doorways attending to the distance to the collection points.

Three basic GIS files need to be prepared: 1) location of collection points (e.g., containers) for the relevant key waste flow, 2) walkable street network (exclude motorways, include if possible walking paths) and 3) location of doors (use address points or building centroids if not readily available). A second step includes the identification of the collection point for each door per key flow. Then, the distances (collection point-door) need to be calculated and categorized in the following *i* ranges: [0-50] m ;]50-100] m ;]100-200] m ;]200-300] m ;]300-400] m ;]400-500] m ;]500-600] m ;]600-700] m ;]700-800] m ; >800 m and the percentages X*i* per distance range need to be quantified. On top, a weighted average over the different ranges is taken, to provide a single score. There are 10 distance ranges in total, and the [0-50]m range is the most accessible one, while >800m range has the lowest accessibility. This is translated into 'weights' as visualised below.

Table 5. Weighting factors of the distance ranges considered in the impact category 'accessibility of the WM system'.

Distance ranges (i)	Scoring system	Weighted average (wa_i)
0-50	10	18% = 10/55
50-100	9	16% =9/55
100-200	8	15% =8/55
200-300	7	13% =7/55
300-400	6	11% =6/55
400-500	5	9% =5/55
500-600	4	7% =4/55
600-700	3	5% =3/55
700-800	2	4% =2/55
800	1	2% =1/55
	SUM =55	

The accessibility (A) to the WMS is then calculated according to Eq. 5:

$$A(\%) = \sum_{i=1}^{10} wa_i \; x \; X_i \qquad \textit{(Eq. 5)}$$

where wa_i represents the 'weights' of the distances ranges i (see table 5), and X_i, the % of distances door-to-collection points.

This indicator must only be applied for collection and storage activities in the FA. When eco-innovative solutions concern other collection strategies of certain key flows, new GIS maps have to be created.

The main drawback is the relatively high amount of data needed to link this impact to a specific case study area, dealing with a specific key waste flow (FU), i.e. only those collections points for the key flow and actor(s) as mentioned in the FU need to be considered. This indicator accounts for the distance a resident of the FA needs to walk to reach the nearest collection point, giving preference to low distances ranges.

4.3.3 Economic impact categories

This section focuses on economic impact categories, which affect the AoP prosperity. Although the purely economic impact categories selected in D4.2/D4.3 (capital productivity, labour productivity, resource productivity, revenues and taxes) are adequate to describe a WMS, each of these categories has different units that are hard to relate to the chosen FU of the case study areas. Thus, the results from these categories are difficult to integrate in the framework of the sustainability assessment. For this reason, alternative indicators were considered, in particular the use of life cycle costing in the project is evaluated in this section.

4.3.3.1 Review on the application of life cycle costing

The life cycle costing (LCC) methodology consists of aggregated costs related with the system along its life cycle. Unlike LCA, no standards have been published for LCC. Therefore, different guidelines can be found in literature with notable differences regarding both the definition of LCC and the methodology to be followed.

In accordance with Martinez-Sanchez et al. (2015), there are three main types of LCC. The financial or conventional one (fLCC/cLCC) typically accounts for the "own" economic costs of a company or a system. The environmental LCC (eLCC) is also a financial assessment presented along with an LCA, but in this case the system boundaries are expanded to be consistent with the LCA, including all the stakeholders affected. Finally, the societal LCC (sLCC) includes social and environmental externalities in the cost by assigning monetary values to the respective effects.

- Financial (or conventional) LCC (fLCC/cLCC)

The fLCC (also called conventional LCC, cLCC) was the first to be implemented and is the most widely used one. Although national standards have been defined for its application in some countries (Australian/New Zealand Standard™, 2014), there is not a generally accepted and implemented methodology. Most guidelines developing its application focus on construction assets, since these assets have a relatively long lifespan and thus including the whole life cycle in the analysis of the costs is relevant (New South Wales Treasury, 2006).

One of the main elements in the application of LCC is the definition of the cost breakdown structure (CBS), which is key for a consistent collection of data. The CBS states all the relevant costs that should be included for the analysis of the system including the whole life cycle (De Menna et al., 2018; Martinez-Sanchez et al., 2016). Having access to a previous CBS from a similar system can be helpful for its definition.

In order to be able to add and compare cash flows that are incurred at different times during the life cycle of a project/product/service, they have to be made time-equivalent. To account for the time value of money, discounting must be applied to all costs to convert them to the net present value (NPV), usually at the base year (Lavappa and Kneifel, 2016; Fuller, 2016). The discount rate represents the investor's minimum acceptable rate of return. Unlike for environmental costs, for which there is an ongoing scientific discussion on the issue, the discounting of economic costs based on inflation and interests is common practice to account for depreciation and widely accepted.

- Environmental LCC (eLCC)

The application of eLCC in previous literature shows a blurred definition and remarkable variations among studies, which makes it confusing. However, using the guidelines from Hunkeler et al. (2008) and the code of practice from Swarr et al. (2011) is common practice in recent studies (Asiedu and Gu, 1998).

In accordance with Hunkeler et al. (2008), eLCC should include both the analysis of the costs and the environmental impacts. Regarding the financial assessment within the eLCC, it extends the fLCC by internalising environmental externalities (e.g. carbon emissions through a carbon trading scheme) that are forecasted to be internalised in monetary terms in a period that is relevant for the analysis (Martinez-Sanchez et al., 2015). Although it is less common in previous literature, direct and indirect valuation methods can be used to quantify these environmental costs (Reddy et al., 2015).

The environmental impacts can be assessed using LCA, and its application should be consistent with the economic assessment of the eLCC. Thus, both should follow the structure presented in ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). The eLCC would include the following stages (UNEP-SETAC, 2011):

1. Definition of a goal, scope and FU
2. Inventory of the costs
3. Aggregation of the costs by cost categories
4. Interpretation

This integration of LCC and LCA has been done in different ways in literature. Some studies focused on the financial or the environmental part. For instance, in a study on beer production from Amienyo and Azapagic (2016), an extensive analysis of the environmental results is done whereas the costs are briefly presented in a graph. In contrast, in a study from Rivera and Azapagic (Schmidt Rivera et al., 2014) on production on ready and home-made meals, the costs of the system are extensively assessed comparing different scenarios and the environmental impacts are discussed in a qualitative graph (ranking options). Other studies only implement a partial LCA, focusing on global warming potential (Asselin-Balençon and Jolliet, 2014). These different approaches respond to the goals of the study, the specific context must be considered to develop the eLCC in a way that responds to the research questions of the study.

Focusing on waste management, a different methodology was adopted by Carlsson Reich (2005), who converted the environmental impacts in LCA to monetary units using different methods such as ecotaxes (Eldh and Johansson, 2006). These costs were merged with those from LCC to provide weighting and potentially a single indicator. However, this methodology might be considered a sort of societal LCC rather than an eLCC (De Menna et al., 2018). Similarly, Rigamonti et al. (2016) defined an indicator to assess the economic and environmental performance of different WMSs in Italy.

There are some specific points from the methodology that should be considered. In eLCC all the stakeholders must be considered, and the cost of the transfers between them should be included. The revenues are not “avoided costs”, but transactions between stakeholders (Martinez-Sanchez et al., 2015). If environmental or social impacts are to be merged with those of financial LCC, attention must be paid to avoid double counting of any environmental impacts that were already considered (directly or indirectly) in LCA. For instance, if there are costs that respond to taxes with environmental motivation, these should be excluded for the aggregation. Also, scarcity of resources should not be valued in this case, since it leads to double counting to some extent because it already constitutes a part of the financial costs, i.e. scarce resources are more expensive to buy (Carlsson Reich, 2005). The aggregation of the impacts in monetary units can be useful because it is a very familiar unit and a simple indicator. However, it might give the false impression of certainty (Gluch and Baumann, 2004) whereas the uncertainty can be high, especially if discount rates are applied.

According to some of the earliest studies (Carlsson Reich, 2005; Gluch and Baumann, 2004), the usefulness of the results from a eLCC may be compromised due to this uncertainty. The application of eLCC can partially deal with its uncertainty (only for known sources) applying scenario forecasting, sensitivity analysis or Monte Carlo simulation, among others (Gluch and Baumann, 2004). There is an interesting proposal from Ciroth (2009) who developed a pedigree matrix as an indicator to evaluate the quality of the data used in the LCI. It appears clear that, once the limitations are understood, its application may provide useful information about the complexity of the system and can contribute to identify and understand important environmental problems. Therefore, the recommendation is to perform fLCC combined with LCA (i.e eLCC).

- Societal LCC (sLCC)

In sLCC social and environmental externalities must be monetized and considered along with the rest of the economic costs.

Regarding the valuation of environmental and social impacts, Table 6 summarizes some of the methods that can be used. However, apart from foreground processes, also background ones are necessary for the calculation of the costs. These background processes need to be considered to make sure the full life cycle is assessed, but right now there is not a consistent database that provides these costs. The only database with life cycle background data that somehow includes cost factors is the Ecoinvent database, versions 3 and following. However, only ‘basic prices’ are included for reference products (neither for by-products, nor for waste streams), often calculated based on the prices of ingredients/inputs in a particular process, which only shows partially the costs. Labour costs, profit of the producer or expenses for waste treatment are not included. Therefore, this information is insufficient to be used in REPAiR, and not consistent with the foreground cost factors.

Table 6. Methods for the monetary valuation of environmental and social impacts.

Name of the method	Brief description
Market prices	This method consists of the estimation of what the consumer is willing to pay at the current level of supply. It can be used to calculate damage costs, loss of production and loss of capital. For instance, for the emissions depleting the tropospheric ozone layer, the impact of the decreased crop yield can be valuated with this method.
Revealed willingness to pay	This method is used when the goods whose cost is to be estimated are not marketed, and thus information on people's expenditures or related marketed goods must be used. Within this category would be the *hedonic pricing method*, which estimates the cost of environmental qualities through *surveys* to consumers. Another widely used method within this category is the travel cost studies, which uses the willingness to pay for visiting recreational sites differing in quality. Finally, also shadow prices are included here, which are based on what people are willing to give up in order to receive/make use of the value of a good or service.
Expressed/stated willingness to pay	This method estimates the price of an environmental good that is not marketed or related to any marketed goods. They consist of surveys that make people face artificial scenarios and price the goods. This category would include contingent valuation and choice modelling, which try to compensate the bias of the inconsistency between what people think, say and do.
Imputed willingness to pay	This method includes damage cost avoided, replacement cost and substitute cost method. These methods estimate the price of an environmental impact using the difference between a certain good and its substitute which allows avoiding the specific environmental impact.
Political willingness to pay	This method is similar to the willingness to pay methods, but at the political level. In this case, political decisions are used for the estimation of an environmental cost. For instance, if there is an explicit will to pay the cost or if there is a tax for a certain environmental impact.
Avoidance/prevention costs	This method consists of estimating what it would have cost to limit an environmental burden. For instance, to put a limit to the amount of a certain emission that can be released.

Source: Adapted from Ahlroth, 2014; Ahlroth et al., 2011; Singh, 2006

Focusing on waste management, sLCC has been applied using different approaches and methodologies. Martinez-Sanchez et al. (2015) considered as externalities certain emissions to air (CO_2, CH_4, N_2O, $PM_{2.5}$, NO_X, SO_2,SO_4, CO, Hg), and used national accounting prices (also called shadow prices) as costs, which approximately reflect the willingness to pay. Additionally, the budget costs were converted from factor prices (market prices excluding taxes) to accounting prices (including externalities) applying a net tax factor proposed by the government. Similarly, Massarutto et al. (2011) assessed a hypothetical neighbourhood considering certain emissions to air (PM_{10}, NO_X, SO_2, VOC, CO, HCl, As, Cd, Ni, Cr, VI, Hg, HF, Pb, dioxins), global warming and disamenities and leachates. In this case, all data was retrieved from EU projects and literature, except CO_2 eq. emissions (average price of national emission trading certificate).

Other authors have focused on fewer key emissions. Teerioja et al. (2012) compared two WMSs considering CO_2 eq., SO_2 and NOx. The selection of these emissions was done in congruence with its relative importance and with data availability. In this line, Dahlbo et al. (2007) focused on fossil fuels, accounting for the social costs of CO_2 eq. emissions released (expected prices from the EU trading scheme) and the scarcity price of non-renewable sources (using the marginal exploration costs as a proxy). In addition, LCA was also applied using three different methods. The results were represented using rankings, showing the values for each method and case and assigning a position.

Woon et al. (2016) adopted a more complete approach analysing two alternatives for WM (landfill and incineration). The externalities considered were the opportunity cost of land, using land sales comparison approach; the disamenities, using housing unit price reduction; and the emissions to air (PM_{10}, $PM_{2.5}$, NO_X) using the impact pathway analysis from a EU-funded project. The study uses an eco-efficiency indicator to integrate the economic results with the life cycle human health impacts, and states a separate portfolio. This study covers different perspectives and combines environmental and economic results in all representations.

Some studies applied additional analysis to assess how variations in key variables affect the results. Among the studies reviewed, the most common techniques are sensitivity analysis and breakeven analysis. Regarding discounting, in case it is applied low social discount rates should be used since the social perspective is being adopted in this case (for instance, 0.1%). This is not the case for many of the studies reviewed. For instance, the study from Teerioja et al. (2012) shows that the costs from externalities are almost irrelevant (1%), but the authors used a discount rate of 5%. Similarly, Woon et al. (2016) conclude that incineration is better than landfilling especially due to the revenues from energy recovery applying a discount rate of 4% for environmental externalities.

4.3.3.2 Impact categories selected

Regarding the social costs, the state of the art for the LCC methodology has been presented in this document. In this sense, two main drawbacks were identified for the use of LCC to measure social costs.

Firstly, LCC has been applied in many ways in recent articles lately (mainly because there is no standard available as compared to LCA), resulting in a notable inconsistency and lack of reliability. This is particularly true for sLCC, which is the least maturely developed one.

Secondly, but equally important, is the lack of easily available data regarding costs of background processes of WMSs. For example, the economic data included in Ecoinvent 3.0 and later versions was contemplated as a potential source, but it is incomplete because it excludes important components, like labour costs. Moreover, the costs are provided in a simplified and aggregated way (the total for a reference product of a specific process) and the data is not available in the latest Simapro, nor OpenLCA software versions (personal communication with Ecoinvent provider). Thus, economic data can be only accessed through a digital spreadsheet in an Excel file provided by ETH Domain and the Swiss Federal Offices that are the founders of Ecoinvent with the list of products and their costs, but it cannot directly be extracted from any software tool. This limits the application of LCC to a great extent, in fact, it narrows the method to a non-life cycle costing method, as the background system cannot be supported sufficiently.

Considering the above mentioned limitations, a possible approach for the assessment of the economic impacts of the different case studies is **focusing on the entire foreground system and its related costs**. This approach would make sense because the local economic impacts are of great interest for the decision-making. Moreover, it would be consistent with the overall perspective of the project, which highlights the integration of local impacts related to the WMS.

In this sense, an alternative approach might be adopting the proposal from PROSUITE for the assessment of micro-economic impacts, which includes the assessment of the indicators capital (CAPEX), operational (OPEX) and end-of-life (OELEX) expenditures (Boxes 19 to 21). These three indicators can aggregate the economic costs of the entire studied foreground system. Therefore, it is proposed to retain the CAPEX, OPEX, OELEX indicators (already including transfers, i.e. taxes and subsidies) in addition to revenues which can be presented separately, rather than capital, labour, and resource productivity as mentioned before. The impact categories of social costs and total employment are discussed in section 4.3.5.1.

Box 19. Impact category: Capital expenditure (CAPEX)

Indicator: *Capital expenditure*

Impact size: Micro

Description: Measures the total costs to acquire, maintain or upgrade the physical assets of a waste management system (e.g. land, buildings, equipment).

Units: € / FU (foreground system)

Reference: Gaasbeek and Meijer, 2013

Box 20. Impact category: Operational Expenditure (OPEX)

Indicator: *Operational expenditure*

Impact size: Micro

Description: Considers all the costs during the normal waste management system operation. Operational costs can be divided in fixed costs such as salary and wages (labour costs), insurance, taxes, and variable costs such as supplies and utilities (e.g., telephone costs, energy requirements).

Units:€ / FU (foreground system)

Reference: Gaasbeek and Meijer, 2013; Martinez et al. 2015; Cimpan and Wenzel, 2016

Box 21. Impact category: End of life expenditure (OELEX)

Indicator: *End of life expenditure* **Impact size**: Micro **Description**: Considers the costs to properly finish operations and dismantle facilities of the waste management system. For instance, management of landfills at the end of their useful life or retirement costs of workers would be in this category. **Units***:* € / FU (foreground system) **Reference**: Gaasbeek and Meijer, 2013

In addition to CAPEX, OPEX and OELEX; the impact category of Revenues (Box 22) was included for completeness, because it covers a part of the costs that is not included in the previous three categories.

Box 22. Impact category: Revenues

Indicator: *Revenues* **Impact size**: Micro **Description**: From the standpoint of the entrepreneur, the revenues of sales of products or incoming fees. **Units***:* € / FU (foreground system) **Reference**: Hogg, 2001

Regarding the data requirements for the definition of these three micro-economics indicators, it will include all the costs along the life cycle of the system. It must be highlighted that the system boundaries for the economic assessment might differ from the one for the environmental assessment, since there will be cases in which elements that do not have environmental impacts do have economic ones and vice versa. Thus, although part of the economic inventory can be defined from the LCI (of the environmental assessment), there will be additional features such as wages, fees and investments.

For further guidance, there are key documents that can be consulted for information regarding 'generic' economic data for WM processes:

- Assessment of the options to improve the management of bio-waste in the EU.
http://ec.europa.eu/environment/waste/compost/pdf/ia_biowaste%20-%20ANNEX%20E%20%20-%20approach%20to%20costs.pdf
- Costs for Municipal Waste Management in the EU
http://ec.europa.eu/environment/waste/studies/pdf/eucostwaste.pdf

- Cost-efficient management of organic household waste http://findresearcher.sdu.dk/portal/files/123116281/SYFRE_AP3_Biowaste_management_and_economy_Genanvend_.pdf

Also, section 5 provides more detailed guidelines regarding economic data collection.

4.3.4 Socio-environmental impact categories

4.3.4.1 AoPs: Human health, ecosystem health

Global warming (Box 23) contributes to both human health and ecosystem health AoP.

Box 23. Impact category: Global warming

Indicator: *Climate change*

Impact size: Macro

Description: This category measures the contribution of certain anthropogenic emissions in increasing the radiative forcing of the atmosphere, which leads to an increment of the global average temperature affecting ecosystems and human health.

Units: kg of CO_2 eq / FU (foreground and background systems)

Reference: Myhre et al. 2013; Joos et al. 2013

4.3.4.2 AoPs: Human health, ecosystem health, natural resources

The impact category water use (Box 24) affects the AoP of human health, ecosystem health and natural resources.

Box 24. Impact category: Water use

Indicator: *Water consumption*

Impact size: Meso

Description: This category measures the total water consumption to evaluate the impact of the extraction of water, which has a potential for damaging ecosystems and human health.

Units: m^3 water-eq consumed / FU (foreground and background systems)

Reference: Boulay et al. 2018

4.3.5 Socio-economic impact categories

4.3.5.1 AoPs: prosperity, human well-being

The **social costs** impact category, related to shadow prices as considered in sLCC (AoP prosperity), is no longer included as it leads to double counting with the social micro-impacts (AoP human well-being). To see the reasoning for its exclusion, see subsections 4.3.3.1 and following.

Box 25. Impact category: Total employment

Indicator: ***Total employment of the waste management sector***
Impact size: Micro
Description: The total employment refers to the amount of jobs available at the activity under assessment.
Units: Number of employees / FU (foreground system)
Reference: (Gaasbeek and Meijer, 2013)

Regarding the impact category of total employment (Box 25), the expert panel mentioned possible pathways towards both the AoP prosperity and human well-being. However, as salary and wages are already considered and quantified within the AoP prosperity (section 4.3.3.2), it is opinion of the authors that the impact category 'total employment', which includes no direct cost factors but amount of jobs created in the foreground system, links better rather to the AoP human well-being than to the AoP prosperity, similar to what was previously defined in the PROSUITE project (Gaasbeek and Meijer, 2013).

To align with the FU which focuses on one key waste flow, a suitable allocation strategy needs to be chosen (case-dependent). For example, one does not have to account for all employees present in the waste treatment facilities but only for those that are involved in treating the respective key flow (FU).

5. Practical guidelines

This section provides practical guidelines to evaluate the sustainability of WMSs and eco-innovative solutions in Europe in a comprehensive way. These guidelines are intended to help researchers in performing the sustainability assessment by providing a concise overview of the selected indicators, the data needs and available data sources, the accessible software packages and training opportunities. On top, a readily available REPAIR method including the indicators for the AoPs ecosystem health and human health is provided in ecospold format. This guide is especially important for those REPAiR project partners involved in data collection (cfr. WP3) and/or sustainability analysis (cfr. WP4) of one or more of the case study areas.

5.1. Methods and indicators

A distinction has been made between those impact categories that cover the full life cycle of the FU (including both foreground and background system), and those categories that only focus on the foreground system.

5.1.1. Life cycle-based impact categories

Table 7 provides the references of the indicators to be used for the midpoint impact categories that have a cause-effect chain towards the AoPs human health, AoP ecosystem health and/or AoP natural resources.

Table 7. Methods used for each of the impact categories in the project (AoP human health, AoP ecosystem health, AoP natural resources).

Impact categories	Indicator	Reference	AoP
Eutrophication	Freshwater eutrophication	Helmes et al. 2012	Ecosystem health
Ecotoxicity	Freshwater, Marine, Terrestrial ecotoxicity	Van Zelm et al. 2009	Ecosystem health
Land use	Occupation and time-integrated transformation	De Baan et al. 2013; Curran et al. 2014	Ecosystem health
Fossil depletion	Fossil resource scarcity	Jungbluth and Frischknecht 2010	Natural resources
Global warming	Climate change	Baseline model of 100 years of the IPCC (based on IPCC, 2013)	Ecosystem health + Human health
Water use/depletion	Water consumption	Available WAter Remaining (AWARE) in UNEP, 2016*	Ecosystem health
Human toxicity	Human carcinogenic and non-carcinogenic toxicity	Van Zelm et al. 2009	Human health
Ozone depletion	Stratospheric ozone depletion	WMO 2011	Human health
Tropospheric ozone formation	Ozone formation, human health	Van Zelm et al. 2016	Human health
Particulate matter	Fine particulate matter formation	Van Zelm et al. 2016	Human health
Ionising radiation	Ionising radiation increase	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	Human health

(*) Recent report of AWARE : Boulay et al. 2018

Regarding the regionalisation of the characterisation factors, it was the intention of the authors to use the regionalised factors provided in the method ReCiPe 2016. However, as reported by PRé Consultants (Simapro LCA software developer) through email communication, these factors are not adapted for Ecoinvent, which complicates considerably their application. For this reason, the use of these characterisation factors was dismissed.

Each of the above mentioned indicators is applicable both for the foreground and the background system and can be used in life cycle-based software tools (for more info about available software packages, see section 5.4). In order to facilitate the application of the analysis by the partners, a calculation method was generated including all the characterisation factors required for the analysis of the impact categories as mentioned in Table 7.

This REPAiR life cycle sustainability method can be downloaded in the Ecospold format from the OSF working environment using the link below:

https://osf.io/7ydvu/ (*)

(*) Acknowledgements: special thanks to Andreas Ciroth from Greendelta (Berlin, Germany) to integrate the AWARE method into a modified ReCiPe 2016 method.

5.1.2. Foreground system based impact categories

For the economic impact categories (boxes 20-23) and social micro-impacts (boxes 11-19), no specific life-cycle based software tools are needed. A 'simple' spreadsheet Excel file should do the work (see further section 5.2). These impact categories focus solely on the foreground system, and do not include impacts from the background processes because of reasons mentioned earlier (e.g, the background databases do not fully support this in terms of data-availability).

5.2. Data requirements of the foreground system

Regarding the foreground system data requirements for the assessment of the impact categories included in the framework, an Excel file has been developed which can be downloaded here:

DATA requirements sustainability assessment

This Excel file provides an overall, yet detailed, overview of the data needs and potential data sources according to the indicators selected in the REPAiR project. However, it is not yet process/activity-specific, i.e. each of the case study areas have to identify the different relevant processes/activities of their foreground system, and gather for each of the processes the information as requested and indicated in the Excel file.

Close collaboration in this sense is required between WP3, WP4 and WP5, with the purpose to collect the required data for the current situations as well as the eco-innovative solutions.

5.3. Background databases

The access to databases is necessary to retrieve environmental information for background processes in the system. In order to enhance consistency and equal system boundaries among the processes used, it is preferable to take all the processes from the same database. However, if a specific process that is not available in the main database appears in another one, it can be used exceptionally. Moreover, specific databases might be required for the calculation of social impacts.

Within the REPAiR project, the database of preference will be ecoinvent, but other databases might also be used if necessary. Below is a summary of the main databases considered for the project, which are also the leading ones for life cycle studies.

5.3.1. Databases requiring payment

- Ecoinvent

Ecoinvent is a leading LCA database, developed by the Swiss Ecoinvent Centre, which comprises LCI data from e.g., the energy, transport, building materials, chemicals, paper and pulp, waste treatment and agricultural sectors, reflecting the production and supply chain. Data is available at Swiss, European and global level. All products and elementary exchanges in ecoinvent version 3 (and following) come with at least six properties, dry mass, wet mass, water in wet mass, water content, carbon content fossil and non fossil. Additionally every single product in the database has a price that can be used among other things for economic allocation. Both an attributional and consequential system model is applied. More info available on: https://www.ecoinvent.org/

- PSILCA

PSILCA – the Product Social Impact Life Cycle Assessment database – is a new database for social LCA developed by GreenDelta. It contains comprehensive generic inventory information for almost 15,000 industry sectors and commodities, for calculating and assessing social impacts of products along their life cycles, and for detecting social hotspots. Also, more than 50 social indicators are available, with an additional 30 upcoming. More info available on: https://psilca.net/

- Gabi

GaBi LCA database has been developed by PE International to support the LCA development by GaBi software. It contains LCI datasets based on primary data collection in the fields of agriculture, building & construction, chemicals & materials, consumer goods, education, electronics & ICT, energy & utilities, food & beverage, healthcare & life sciences, industrial products, metals & mining, plastics, retail, service sector, and textiles. Meanwhile, the user can modify and add elements into a database and apply them when a new lifecycle is to be modeled. More info available on: http://www.gabi-software.com/international/databases/gabi-databases/

5.3.2. Databases freely available

- Agribalyse

LCI database of the main French agricultural products at the farm gate, provided by the French Environment and Energy Management Agency (ADEME) as outcome of the Agribalyse® program. It includes aggregated and unit processes. The database contains over 200 LCIs for agricultural and livestock products, in addition to all the data on agricultural inputs (machineries, fertilizers etc.). More info available on: http://www.ademe.fr/en/expertise/alternative-approaches-to-production/agribalyse-program

- ELCD

The European reference Life Cycle Database of the Joint Research Center comprises LCI data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management. The respective data sets are officially provided and approved by the named industry association. More info available on: http://eplca.jrc.ec.europa.eu/ELCD3/

- Bioenergiedat

Processes for bioenergy supply chains, with German background, developed in the context of the German BioEnergieDat research project, with support from the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2010-2012. More info available on: http://www.bioenergiedat.de/

More information regarding other freely available databases can be found on: https://nexus.openlca.org/databases.

5.4. Software tools

Regarding the software for the calculation of the impacts, the selection depends entirely upon the practitioner providing that it is compatible with the required databases. The software matches the environmental information in the databases and the method used for the calculation. Thus, the use of one or another should not affect the results.

A summary of the main software packages used in life cycle studies can be found below. For REPAiR, each partner will use the software of preference from the list.

5.4.1. Software tools requiring payment

- SimaPro

SimaPro has been the world's leading LCA software package for last 25 years. SimaPro is a well recognised sustainability software package, with which the user can model and analyse complex life cycles in a systematic and transparent way, following ISO 14040 series recommendations (developed by Pré Sustainability). The package requires the user to build a life cycle of product and fill details in each stage of product life cycle such as material, process, transport, recycle, reuse and disposal; and then, the impact results of product life cycle network are presented. SimaPro is developed to help you effectively apply your LCA expertise to drive change – to provide the facts needed to create sustainable value. SimaPro contains the latest in science-based methods and databases. A wide variety of add-ons and reporting features makes it easy to be fully conscious of the choices you make in doing your LCA studies and to address the concerns of your colleagues. More info available on: https://simapro.com/

- Gabi

Gabi software is a well-recognised software tool for modeling products and systems from a life cycle perspective, developed by Thinkstep. The user should build a life cycle of the product in a graphic diagram. Based on the life cycle, the user defines inputs and outputs of material and energy for each stage; and then a sustainability report including resources and emissions is generated. The life cycle modeling in Gabi is in a very clear way to illustrate and represent the whole life cycle of the product. More info available on: http://www.gabi-software.com/international/index/

- Umberto

Umberto LCA+, created by Ifu Hamburg, is the LCA software with the most extensive integrated cost analysis, e.g. for Life Cycle Costing. This enables you to create different scenarios with regard to technological, legal, market, price and demand trends in terms of costs and environmental criteria. Both the ecoinvent and GaBi LCA databases can be used to provide background data for creating a full-scale Life Cycle Assessment. The environmental impacts of your product can be shown as a Sankey diagram or easily exported to other formats. More info available on: https://www.ifu.com/en/umberto/

- EASETECH

EASETECH is an LCA-model for assessment of environmental technologies developed at the Technical University of Denmark. EASETECH is an acronym for "Environmental Assessment System for Environmental TECHnologies". The primary aim of EASETECH is to perform LCA of complex systems handling heterogeneous material flows. EASETECH models resource use and recovery as well as environmental emissions associated with environmental management in a life-cycle context. The two main novelties compared to other LCA software are as follows. First, the focus is put on material flow modelling, as each flow is characterised as a mix of material fractions with different properties and flows in terms of mass and composition are computed throughout the integrated system included rejects, slags, ashes and products as a basis for the LCA calculations. Second, the tool has been designed to allow for the easy set-up of scenarios by using a toolbox, the processes within which can handle material flows in different ways and have different emission calculations. However, tracing back of impacts related to background processes is less straightforward. More info available on: http://www.easetech.dk/

5.4.2. Software tools freely available

- OpenLCA

OpenLCA software is a **free**, professional LCA and footprint software with a broad range of features and many available databases, created by GreenDelta since 2006. It is an open source software; both the software and its source code are freely available. The software is fully transparent and can be modified by anyone. The results can be visualized on a map. Good import and export capabilities. Life Cycle Costing and social assessment smoothly integrated in the life cycle model. There is a continuous improvement and implementation of new features. More info available on: http://www.openlca.org/

5.5 Software training

There are many software training opportunities in the near future. On the following websites, more information can be found on the content of the trainings, the dates, location, teachers, etc.

- https://www.pre-sustainability.com/sustainability-training
- http://www.openlca.org/trainings/
- http://www.easetech.dk/Training-Courses
- https://training.gabi-software.com/our-training-offers-gabi-software
- https://www.ifu.com/en/umberto/trainings/

6. Discussion, conclusion and next steps

This document presents a comprehensive framework, covering the three pillars of sustainability (social, environmental, economics), developed in REPAiR for the assessment of current WMSs and eco-innovative solutions and strategies, potentially leading towards a circular system, in European cities. A graphic representation of the framework can be found in Figure 6. The system under study includes the 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. This is where the life cycle perspective of the (urban) WM service is taken into account (*cfr. system boundary layer in Figure 6).*

Specific to life cycle sustainability assessment, is the collection of many data and, with regard to the projects objectives, different types of data, covering amongst others social, economic and environmental aspects, different spatial scales and time horizons *(cfr. data-inventory layer in Figure 6)*. This is a time-consuming effort but needs to be done carefully (cfr. data inventory layer in Figure 6). An excel sheet is provided which summarizes the basic data needs of the foreground system. This sheet can be easily modified according to the specificities of the case study areas (the processes included in the foreground system, the geographical scales included, etc.).

The impact categories in the framework have been defined involving stakeholders and experts from different areas of expertise *(cfr. modelling layer in Figure 6)*. The impacts considered are categorized in five AoPs (human well-being, human health, ecosystem health, natural resources, prosperity). On top, different selection procedures were applied to identify the most adequate quantitative indicator per AoP and per midpoint impact category. 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 more local impact assessment methods such as local economy indicators or nuisance impact categories such as odour and landscape disamenities.

Looking at the frameworks available in literature to assess WMSs, the integration of both the local and global indicators in combination with the focus on all three pillars of sustainability is certainly innovative. The objective is to inform not only policy-makers at the EU or national level about potential global effects of waste-as-resource systems for decision-making, but also governments at the regional and local level about possible constraints/benefits of certain eco-innovative solutions that are implemented locally. The framework is especially developed to allow comparison of the impacts caused by the present urban metabolism and the eco-innovative solutions, as identified by each case study area separately (cfr. WP5). The framework developed and presented in D4.4 therefore meets the objectives to support decisions towards more efficient WMSs in cities. It must be highlighted that some of the results presented in this deliverable have been recently published in the scientific journal *Sustainability* as an Open Access article (Taelman et al., 2018).

In spite of the advances presented towards a comprehensive sustainability assessment, there are still points that need further development. In particular, more research is required to develop the indicators from impact categories contributing to the AoP human well-being. These impact categories assess micro-impacts (social impacts at local scale), and their development is one of the main contributions in this report because these local impacts had attracted few attention until now. Consequently, the research revealed that the indicators for the assessment of these impact categories in literature were difficult to apply or even lacking. For example, the loss of biodiversity was intended to be included in the framework as a midpoint impact category rather than an endpoint impact category (as considered in traditional environmental LCA). Although this topic is considered of paramount importance for the framework, there are no available indicators or characterisation factors to calculate the direct loss of biodiversity at midpoint level. Moreover, the loss of biodiversity is a final consequence of environmental degradation, and thus it makes sense to consider it as an endpoint indicator rather than a midpoint one.

As mentioned before, another important issue for the assessment of sustainability 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.

Regarding the application of the framework, the indicators of some impact categories will require further development to align/allocate the results to the FU and to be consistent along the project. Especially for the impact categories under the AoP human well-being, further research will be required to make it possible. This research entails critical evaluation of suitable allocation strategies, which will depend on the data available in each of the case study areas.

Finally, it must be highlighted that the framework presented in this report only covers sustainability assessment up until midpoint impact categories. However, note that a method for the aggregation of these impact categories into endpoint indicators at the AoPs level is developed in the project and, as indicated in Figure 1, presented in Deliverable 4.5 *(cfr. aggregation layer and decision support layer in Figure 6)*. Ongoing work entails the translation of the main findings of both D4.4 and D4.5 into a scientific paper, which is intended to be submitted to an A1 journal in the next coming weeks.

Results of applying the sustainability framework and the aggregation strategy (as developed in D4.4 and D4.5) to the pilot cases will be presented in D4.6 and the follow-up cases in D4.7 and visualized in the GDSE.

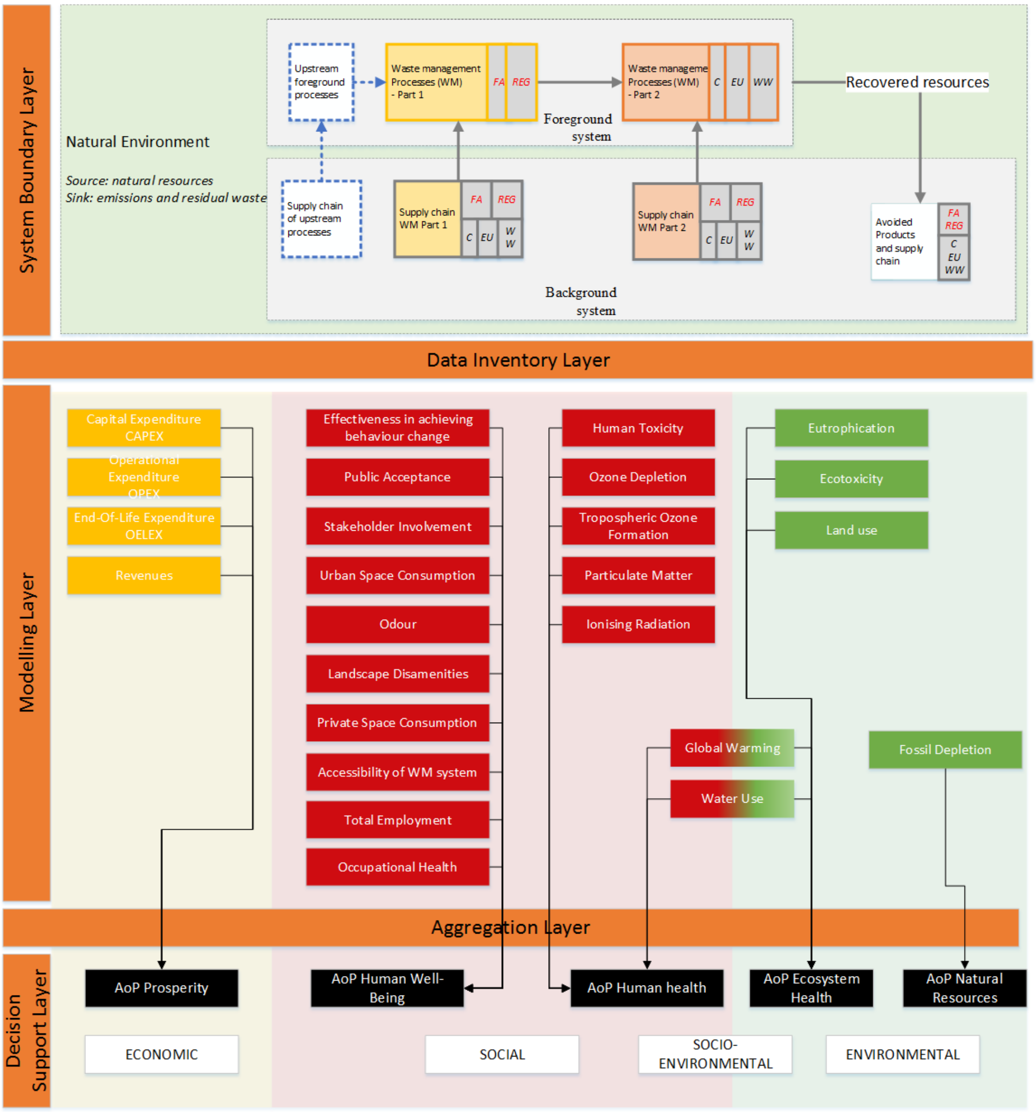

Figure 6. Final sustainability framework as developed within the REPAiR project, applicable to all case study areas.

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