OCEAN WISE

Reducing EPS marine litter in the North East Atlantic

Work Package 6. Activity 3

Methodology for the Circularity-Sustainability Assessment of EPS/XPS Products and Applications

sustainn

Interreg Atlantic Area
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EXECUTIVE SUMMARY

This document describes the methodology to perform a circularity – sustainability assessment of EPS/XPS products and applications. Ultimate goal of the methodology is helping to develop the most sustainable (economic, social, environmental) and circular alternatives for the targeted applications.

It applies to both current and potential alternatives solutions for EPS/XPS products and applications targeted by Oceanwise project.

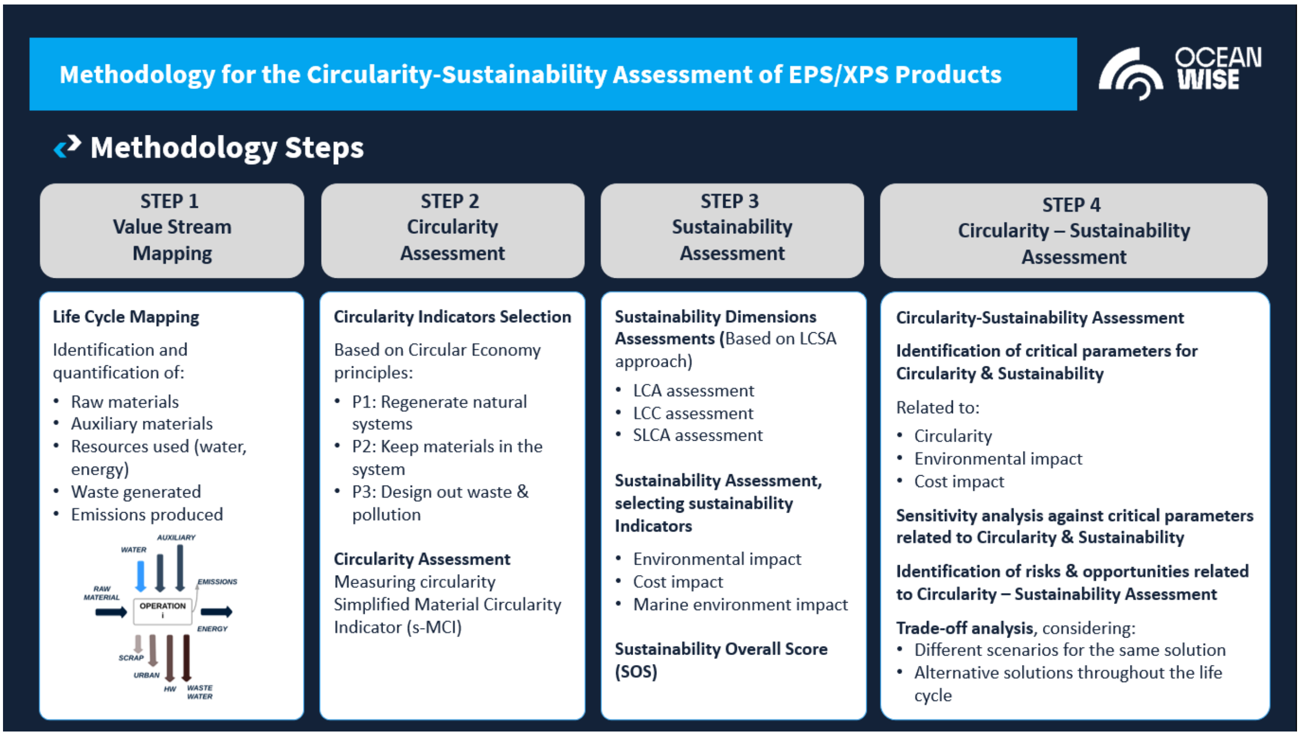
It is not oriented just to materials level. By "solution" it is understood the combination of possible alternatives throughout a life cycle application, using a specific material, a manufacturing and distribution process to different distribution and utilization points (1st level users, 2nd level users, etc), waste collection systems and end of life management processes.

Any of the following options could be combined within a life cycle application solution:

- a specific material used for an application (example: EPS for fish box)
- a collection system of EPS waste (example: compacting EPS waste in harbours)
- a particular recycling system (example: mechanical recycling used for EPS recycling)
- a combination of some or all of them throughout a particular produt/application life cycle

The methodology responds to Oceanwise project challenges, as well as to circularity and sustainability trends, and develops in detail the different steps to perform circularity-sustainability assessment of the life cycle of EPS/XPS application and potential alternatives.

Circularity – Sustainability Assessment Methodology has been conceived in 4 different steps, as showed in the following figure, which are described in detail within this document.



- Step 1: Value Stream Mapping

  In this step the value stream mapping of the life cycle of the application is to be built, identifying all the materials, auxiliary raw materials and resources (water, energy) consumed in the different operations throughout the operations of the life cycle, as well as the waste generated and emissions produced.

- Step 2: Circularity Assessment

  Next, the evaluation of the circularity of the life cycle of the product/application is to be carried out through a simplified Material Circularity Indicator (S-MCI), assesing the alignment of the life cycle of the product/application to the circular economy principles.

- Step 3: Sustainability Assessment

  Sustainability assessment of the life cycle of a product is to be done following the life cycle sustainability assessment approach (LCSA), combining the following assessments in the 3 dimensions:

  - LCA (Life Cycle Assessment) and specific marine environment impact
  - LCC (Life Cycle Cost Assessment)
  - SLCA (Social Life Cycle Assessment)

  Sustainability indicators are extracted from the impact categories assessed for every of the 3 dimensions evaluated, and a Sustainability Overall Score (SOS) is to be built combining the selected sustainability indicators

- Step 4: Circularity - Sustainability Assessment

  In this step a combine circularity – sustainability assessment is to be carried out combining the most relevant circularity and sustainability indicators.

  At this point, the most critical parameters influencing circularity and sustainability indicators have to be identified in order to develop the different sensitivity analyses against these critical parameters.

  Then, identification of risks and opportunities for the different alternatives related to competitiveness, sustainability and circularity is to be carried out, considering mainly availability of raw materials and resources, legislation trends, market, sector and customer requirements and technology trends

  To finish this step, it is described how to perform a trade-off analysis of the different alternatives for the product/application under study, in order the obtain an optimal technical solution in terms of circularity and sustainability.

  - Different scenarios for the same solution
  - Alternative solutions in any phase of the life cycle

Finally, the added value of the methodology to the different stakeholders targeted by Oceanwise project is identified, explaining how every stakeholder could use the methodology to cover their needs related to the implementation of circular economy and sustainability principles.

1 AIM

Aim of this document is to describe the methodology to perform a circularity – sustainability assessment of EPS/XPS products and applications.

2 SCOPE

It applies to both current and potential alternatives solutions for EPS/XPS products and applications targeted by Oceanwise project.

First of all, Chapter 5 defines the aim of the methodology and scope of application and Chapter 6 describes the methodology approach responding to Oceanwise project challenges, as well as to circularity and sustainability trends.

Then, Chapter 7 develops in detail the different steps of the methodology to perform circularity-sustainability assessment of the life cycle of EPS/XPS application.

Finally, Chapter 8 indicates the added value of the methodology to the different stakeholders targeted by Oceanwise project, explaining how every stakeholder could use the methodology to cover their needs related to the implementation of circular economy and sustainability principles.

3 ACRONYMS

Acronyms used in this document and necessary for its follow-up and understanding are:

CE: Circular Economy
EPS: Expanded Polystyrene (see definition in Oceanwise project website)
EPD: Environmental Product Declaration
OW: Oceanwise Project
SDG's: Sustainable Development Goals
WP: Work Package
XPS: Extruded Polystyrene (see definition in Oceanwise project website)

4 DEFINITIONS

Below some definitions of specific terms used in this document.

Circular Economy. A circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems. Reference [1].

Functional Unit. Quantified performance of a product system for use as a reference unit (see reference [2]).

Life Cycle. Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. See reference [2].

Life Cycle Costing. Life cycle costing is the process of economic analysis to assess the total cost of acquisition, ownership and disposal of a product. Reference [3].

5 METHODOLOGY AIM

Aim of the methodology is to guide assessing circularity and sustainability of the life cycle of EPS/XPS products and applications, both current and potential alternative solutions. Ultimate goal of the methodology is to help developing the most sustainable (economic, social, environmental) and circular alternatives for the targeted applications.

This methodology is based on the methodologies for the circularity and sustainability assessment of the life cycle of a generic product developed by Sustainn.

It is not oriented just to materials level. By "solution" it is understood the combination of possible alternatives throughout a life cycle application, using a specific material, a manufacturing and distribution process to utilization points (1st level users, 2nd level users, etc), waste collection systems and end of life management processes.

Any of the following options could be combined within a life cycle application solution:

- a specific material used for an application (example: EPS for fish box)
- a collection system of EPS waste (example: compacting EPS waste in harbours)
- a particular recycling system (example: mechanical recycling used for EPS recycling)
- a combination of some or all of them throughout a particular product/application life cycle

After developing some pilot projects with EPS material and alternative materials solutions for a fish box application, methodology has been developed focusing on fish boxes applications.

This methodology is intended to be a guidance for industry on how to assess circularity of products integrating Circularity Assessment within the conceptual design phase of the different packaging products targeted by Oceanwise project, where EPS/XPS materials have been used, such as:

- Fishing industry packaging (fisheries, aquaculture, sea-food)
- Food goods industry packaging (retail, distribution, supermarket chains, e.g. vegetables, fish, meat, fruit)
- Consumer goods packaging, such as appliances

Moreover, this methodology has been developed thinking to apply it to other similar plastics packaging applications, consider their different particularities.

Considering that there are several stakeholders playing different roles throughout the life cycle of the different EPS/XPS products and applications, the methodology can be oriented to specific needs of the different stakeholders, as will be developed in Chapter 8.

6 METHODOLOGY APPROACH

To reach the aim described above, Circularity - Sustainability Assesment Methodology has to consider the following aspects:

1. **Oceanwise project challenges (OW Challenges)**, which are:
   - In terms of reduction of marine litter perspective, How to prevent EPS/XPS from reaching the marine environment?
   - In terms of the implementation of circular economy principles, How to keep EPS/XPS in the system?
2. **Circular Economy principles (CE Principles).** As described in reference [1], circular economy principles are:

- Principle 1: Regenerate natural systems
  Preserve and enhance natural capital by controlling finite stocks and balancing resource flows, meaning that technology and processes are chosen wisely according to their use of renewable or better-performing resources.

- Principle 2: Keep products and materials in use
  Optimize resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles; meaning designing for remanufacturing, refurbishing and recycling to keep technical components and materials circulating in the economy, preserving embedded energy and other value. It also refers to encouraging biological nutrients to re-enter the biosphere in the safest way possible to become valuable feedstock for a new cycle.

- Principle 3: Design out waste and pollution
  Foster system effectiveness by revealing and designing out negative externalities; this includes reducing damage to human utility, such as food, mobility, shelter, education, health and entertainment, and managing externalities, such as land use, air, water and noise pollution, release of toxic substances and climate change.

3. **Findings from other Oceanwise activities,** resulting from:

- Work Package 6, specifically actions WP6.1 and WP6.2, which deliverables are:
  - WP6.1: State of the Art Report on Circularity Assessment Methodologies (reference [4])
  - WP6.2: State of the Art Report on Circular and Sustainable Design Methodologies (reference [5])
- Work Package 5 (Knowledge Hub), which has been working on:
  - Review of EPS as a raw material; general characteristics, implementations and suppliers
  - Catalogue/ working database of use of EPS products and applications (fishing and aquaculture, food industry and packaging) and end life (reduce, reuse)
  - Catalogue/Database of current available alternatives to EPS products
  - Assessment of EPS in the marine environment
  - State of the art on current solutions to recycle, reuse and repurpose EPS
  - Assessment of the policies, incentives and producer responsibility schemes relative to the subject
- Work Package 7, which has been working on:
  - Expanded and extruded polystyrenes distribution and impact in the marine environment

4. **Principles from Sustainable Development Goals** (SDG's principles, reference [6]), related to:

- People (SDG's 1-5)
- Planet (SDG 6 and SDG's 12-15)
- Prosperity (SDG's 7-11)
- Peace (SDG 16)
- Alliances (SDG 17)

The Circularity - Sustainability Assessment methodology approach proposed in this document is summarized in the next figure.

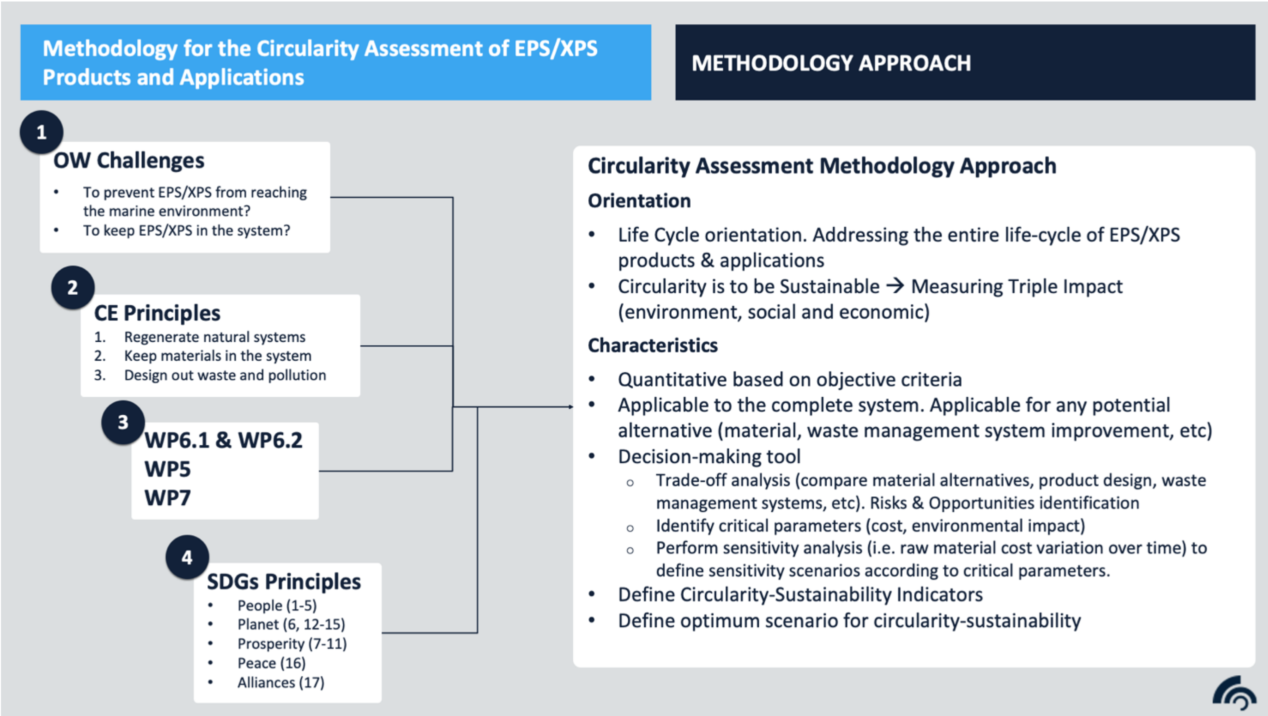


Figure 1. Circularity Assessment Methodology Approach

To respond to these aspects and considering the findings in the deliverable resulting from action WP6.1 (reference [4]), circularity assessment methodology is to be oriented to:

- Addressing the entire life-cycle of EPS/XPS products & applications. The methodology to be developed should cover the complete life cycle of the different products and applications, according to ISO14040 (reference [2]).
- Circularity is to be Sustainable. Circularity shold be understood as a mean to promote sustainability. Although circularity of products should be pursued, improvement of overall sustainability is the final goal. So, circular economy principles should be implemented within product development processes and triple impact measurement (economic, environmental and social) should be carried out at the same time aiming to develop optimum solutions in terms of both sustainability and circularity.

Consideting the orientation, main characteristics that the methodology should have are:

- Methodology should lead to compare alternartives quantitatively based on objective criteria
- It has to be applicable to the complete system, meaning the complete life cycle of the application, being able to consider any potential alternatives throughout the life cycle application (material, distribution system, waste collection and management system, recycling process, etc)
- Decision-making tool. It must allow the following activities:
  - Carry out a trade-off analysis (compare material alternatives, product design, waste management systems, etc)
  - Identify risks and opportunities
  - Identify critical parameters (mainly related to materials and resources criticaliy, cost, environmental impact)
  - Perform sensitivity analysis (i.e. raw material cost variation over time) to define sensitivity scenarios according to critical parameters.
- It has to allow the definition of Circularity-Sustainability Indicators
- It has to lead the definition of the optimum scenario for the product life cycle in terms of circularity-sustainability

7 CIRCULARITY - SUSTAINABILITY ASSESSMENT METHODOLOGY DESCRIPTION

This methodology has been developed oriented to:

- Helping in the design decisions to analyze circularity and sustainability from the early design phases of a product aiming to obtain an optimal technical solution for the life cycle of a EPS/XPS product and potential alternatives
- Compare alternative distribution paths for a specific material, as described in Step 1 (section 7.1).
- Compare alternative solutions throughout the life cycle of a product, understanding solutions as different combinations of material, distribution process, waste collection and management systems, recycling process, etc
- Helping researchers with the assessment of sustainability and circularity of new materials

Considering this and the approach described above, the methodology comprises different steps, as showed in the following figure.

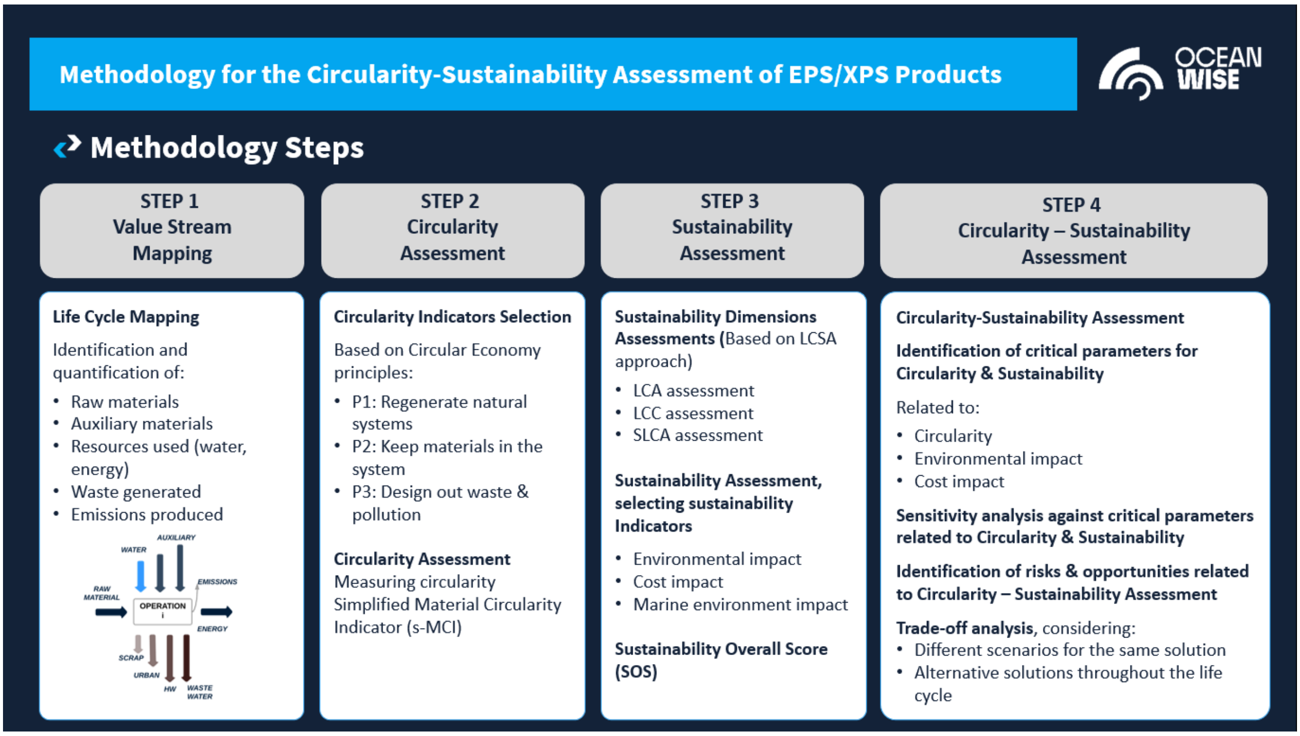


Figure 2. Circularity-Sustainability Assessment Methodology Steps Overview

Assuming that circularity is to be sustainable, as explained in a previous chapter, Oceanwise encourages to assess circularity and sustainability at the same time. Assessing a particular solution just from circularity perspective does not ensure that we are developing the most possible sustainable technical solution, because we would not assessing the environmental impacts of the solution according to international and recognized references and standards.

Below is a brief description of the scope of the different steps, which will be described in detail in the next sections.

- Step 1: Value Stream Mapping

  To start, the value stream of the life cycle of the application is to be mapped, identifying all the materials, auxiliary raw materials and resources (water, energy) consumed in the different operations throughout the whole life cycle, as well as the waste generated and emissions produced.

- Step 2: Circularity Assessment

  At this step, the evaluation of the circularity of the life cycle of the product/application is to be carried out, which is the alignment of the life cycle of the product/application to the circular economy principles.

  A simplified Material Circularity Indicator (S-MCI) is proposed to measure the extent to which linear flows have been minimised and restorative flows maximised for the component materials of life cycle of a product.

- Step 3: Sustainability Assessment

  Sustainability Assessment of the life cycle of a product is to be done following the life cycle sustainability assessment approach (LCSA), as recommended in deliverable resulting from WP6.1 activity (reference [4]). It combines the following assessments, considering the 3 dimensions of sustainability (environmental, cost and social impact):

  - Life Cycle Assessment (LCA) and specific marine environment impact
  - Life Cycle Cost Assessment (LCC)
  - Social Life Cycle Assessment (SLCA)

  Sustainability indicators are extracted from the impact categories assessed for every of the 3 dimensions evaluated and a Sustainability Overall Score is to be built combining the selected sustainability indicators.

- Step 4: Circularity-Sustainability Assessment

  In this step a combine circularity – sustainability assessment is to be carried out combining the most relevant circularity and sustainability indicators, to be identified according to the scope of the analysis defined within Step 1.

  Evaluation would be based on a set of circularity indicators with a sustainability score, based on LCSA approach, developed within Step 3. This way, we would have an evaluation of circulatity of a particular solution with a sustainability assessment.

  At this point, the most critical parameters in terms of circularity and sustainability have to be identified in order to develop later the different sensitivity analyses against these critical parameters.

  Later on, identification of risks and opportunities related to circularity and sustainability is to be carried out, considering mainly the following aspects:

  - Availability and cost volatility of raw materials and resources
  - Legislation trends (Europe, national, regional)
  - Market, sector & customer requirements trends
  - Technology trends

  Finally it is described how to carry out a trade-off analysis of the different alternatives for the product/application under study, in order the obtain an optimal technical solution in terms of circularity and sustainability.

7.1 STEP 1: VALUE STREAM MAPPING

As a previous step to the circularity-sustainability assessment of the product/application, all the operations throughout its life cyle are to be mapped. Then, we proceed to identify all the materials, auxiliary raw materials and resources (water, energy) consumed in the different operations, as well as the waste generated and emissions produced.

Next figure shows an overview of the step for a fish box case study.

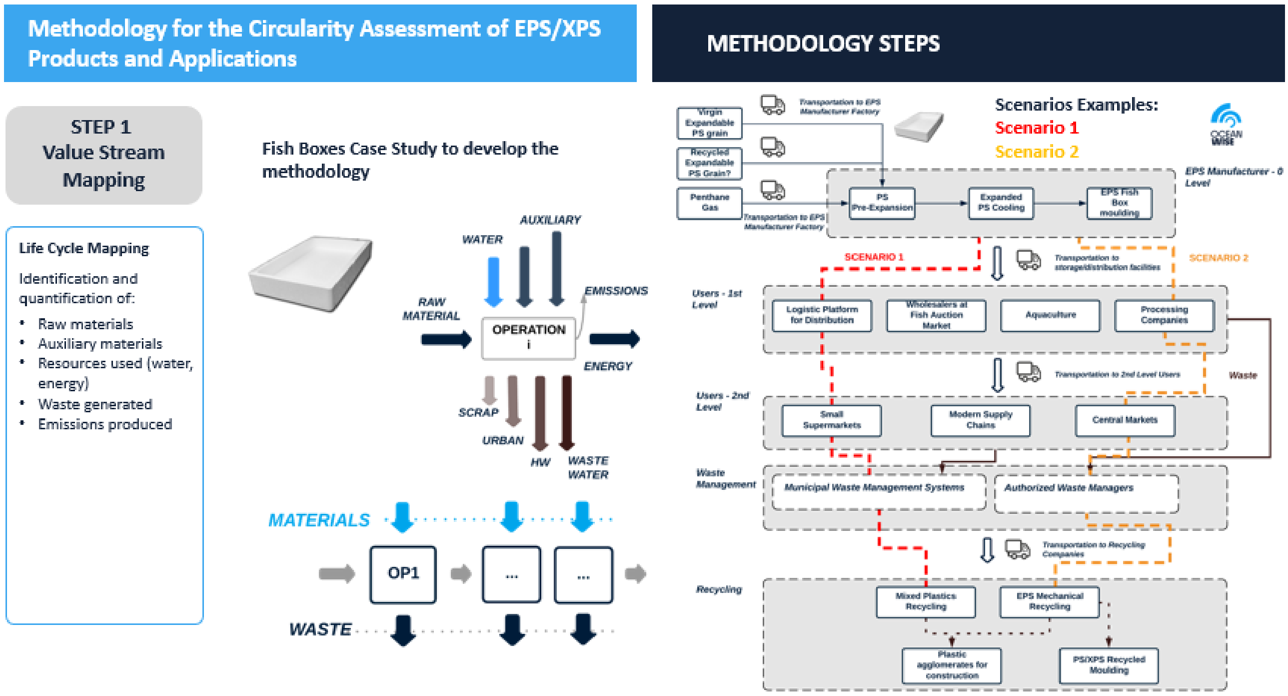


Figure 3. Overview of Step 1: Value Stream Mapping

First of all, we must identify all the operations that are carried out all along the life cycle phases. To point out that the common life cycle phases to consider, according to ISO 14040 (reference [2]) and IEC 60300-3-3 (reference [3]) are:

Figure 4. Typical Life Cycle Phases

A detailed description of activities within the different phases is provided in deliverable resulting from activity WP6.1 (reference [4]).

Within each phase, all operations must be mapped to the maximum detail possible, identifying the inputs and outputs in each operation (environmental aspects), showed as arrows in "Operation i" in Figure 5, such as:

- Inputs
  - Consumption of resources (water, energy)
  - Consumption of raw materials
  - Consumption of auxiliary materials

- Outputs
  - Waste, considering its different types (urban solid waste, hazardous waste, scraps, waste water, etc)
  - Emissions, considering emissions to air as the environmental aspect, if generated (for example in a chimney)

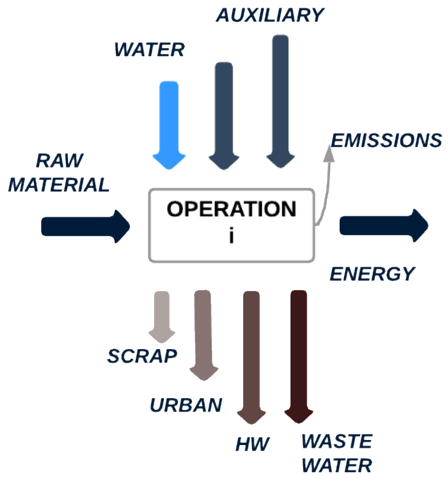


Figure 5. Operation i scheme with common inputs and outputs

The following figure shows, as an example, a scheme of mapping of a part of product life cycle.

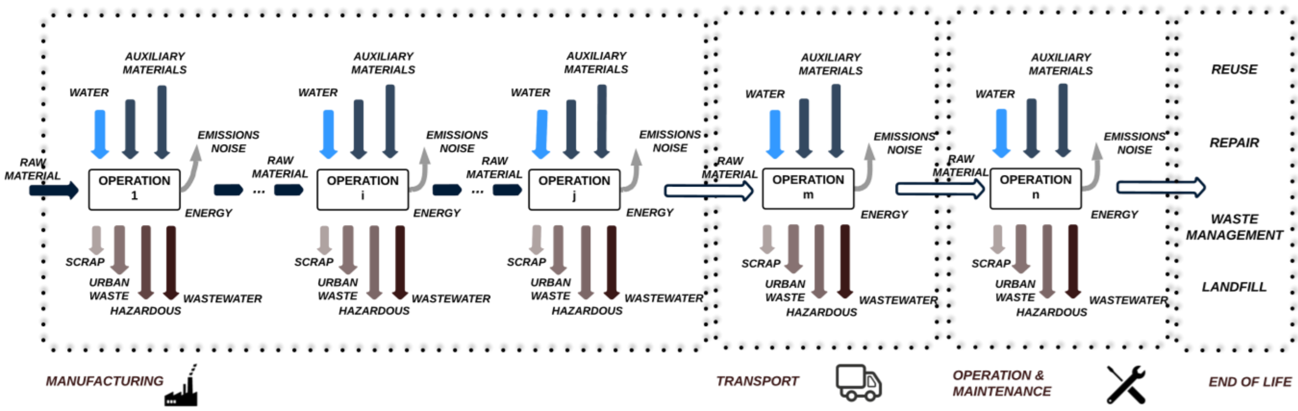


Figure 6. Scheme of phases and activities of a life cycle.

At this point, it is key to consider the different scenarios that can occur and the boundaries of the system or application to be analyzed, taking into account the possible flows of the product throughout the activities carried out by all the players in the life cycle. These scenarios should be built following the cradle-to-grave[1] approach to assess the impacts throughout all the life cycle phases in the next steps.

[1] 'Cradle-to-grave' assessment considers impacts at each stage of a product's life-cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, and ultimately, disposal. European Environment Agency

Considering the different distribution flows from the manufacturing shop, the different users downstream (1st user level, 2nd user level), the waste management and recycling systems, different scenarios can happen for the product unit to be analyzed.

The following figure shows, as an example, schemes of 2 different possible scenarios (Scenario 1, Scenario 2) for an EPS fish box.

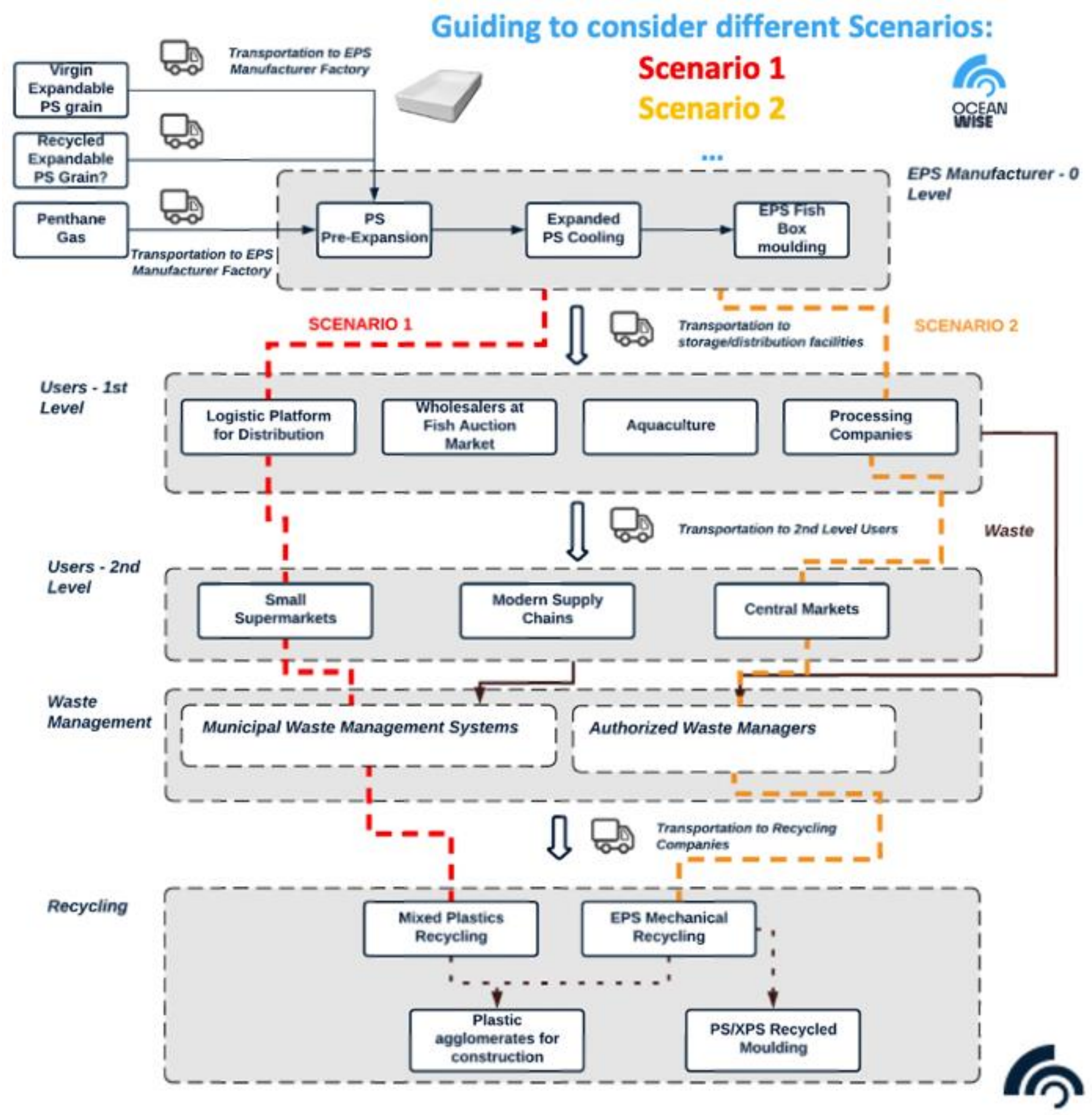


Figure 7. Overview of different potential scenarios

For each defined scenario, once the operations have been mapped and the inputs and outputs identified, it is time to assign values to each of them in the corresponding units.

Before assigning values, the unit of the product that is being studied has to be clearly defined and measurable. As described in ISO14040 (reference [2]), life cycle assessments are structured around a *functional unit* [2]. This functional unit defines what is being studied and the quantification of the identified functions (performance characteristics) of the product. All subsequent analyses are relative to that functional unit, as all inputs and outputs in the value stream mapping, LCI (Life Cycle Inventories) and consequently the life cycle assessments to be carried out.

Functional unit definition depends on the type or category of products. Specific Product Category Rules[3] (PCR) are available for different product categories, which define the corresponding functional unit to use. The following PCR references can be used for the packaging applications targeted in OW project (described in Chapter 5), depending on its characteristics and materials:

- PCR 2019:13 Packaging (1.1), from The International EPD System
- NPCR 023 Packaging products and services, from the Norwegian EPD Foundation

For the case study of an EPS fish box application, and according to NPCR023, the functional unit for cradle-to-grave analysis for a single and multiple use packaging product is defined as "one delivery of one unit of packaging for a defined good or group of goods". According to PCR 2019:2013, the functional unit is 1 packaging unit.

Considering this, it is fundamental in the first place to define the main characteristics of the unit to be analyzed in order to have a measurable, recognized and unequivocal reference. For example, defining:

- External dimensions
- Internal dimensions
- Capacity
- Weight

So then, all the inputs and outputs values should be calculated/estimated per unit of EPS fish box (the functional unit defined) for all the operations as described above in order to map the whole life cycle. For doing this, it is recommended to use value stream mapping tools, which helps to map all the operations and identify inputs, outputs and assign the corresponding values to raw materias, auxiliary materials and resources consumed, as well as waste generated.

Next figure shows an extract of VSM (Value Stream Mapping) Tool developed by *Sustainn*, which guides how to do the value stream mapping of the life cycle of a generic product. This extract shows a simulation of what is to be built to assign values to the different for the functional/declared unit of the product.

[2] As per ISO14040 (reference [2]), the primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis

[3] Product Category Rules or PCRs provide the rules, requirements, and guidelines for developing an EPD (Environmental Product Declaration) for a specific product category (https://www.environdec.com/product-category-rules-pcr/the-pcr)

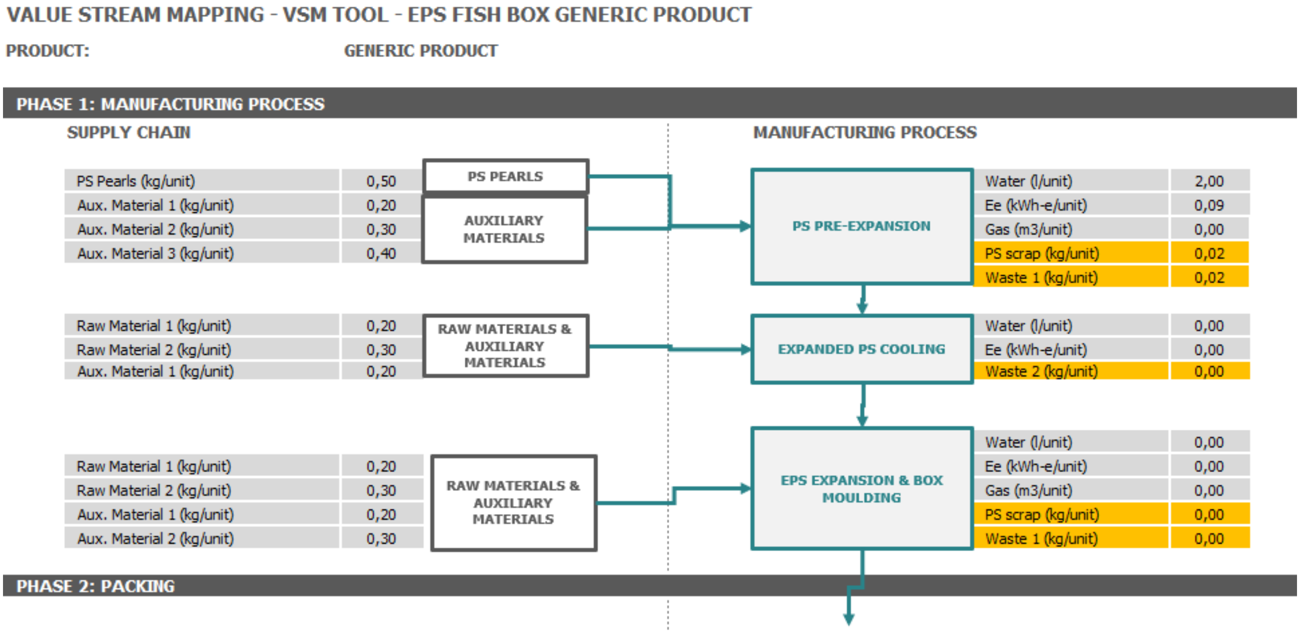


Figure 8. Extract of Value Stream Mapping Tool. Simulation of Operation 1 of Manufacturing Process of an EPS fish box

On top of that, information about the supplier of every raw material or resource can be added, even including the transportation distances, transport type (road, sea, train) and even including the type of transport equipment.

All the information identified and displayed here will be needed for the next steps, such as:

- for building the circularity indicators and performing the circularity assessment
- for the construction of Life Cycle inventory for the LCA (Life Cycle Assessment)
- for the LCC (Life Cycle Costing), connecting easily the unitary data to unitary costs and then compiling all the costs throughout the product/application life cycle.
- for the SLCA (Social Life Cycle Assessment)

7.2 STEP 2: CIRCULARITY ASSESSMENT

In this step, the evaluation of the circularity of the life cycle of the product/application is to be carried out, which is the alignment of the life cycle of the product/application to the circular economy principles, such as:

- Principle 1: Regenerate natural systems
  Preserve and enhance natural capital by controlling finite stocks and balancing resource flows, meaning that technology and processes are chosen wisely according to their use of renewable or better-performing resources.

- Principle 2: Keep products and materials in use
  Optimize resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles; meaning designing for remanufacturing, refurbishing and recycling to keep technical components and materials circulating in the economy, preserving embedded energy and other value. It also refers to encouraging biological nutrients to re-enter the biosphere in the safest way possible to become valuable feedstock for a new cycle.

- Principle 3: Design out waste and pollution
  Foster system effectiveness by revealing and designing out negative externalities; this includes reducing damage to human utility, such as food, mobility, shelter, education, health and entertainment, and managing externalities, such as land use, air, water and noise pollution, release of toxic substances and climate change.

As explained within WP6.1 deliverables (reference [4]):

- although there are some ISO standards under development (ISO59004), no standard has been published yet to assess circularity of a product
- no adhoc methodology has been found at this moment to carry out a circularity assessment of EPS/XPS products and applications
- diverse generic methodologies and metrics has been worked out up to date to assess circularity of a product, as compiled in Orienting project (reference [7]).

From these generic methodologies, *Material Circularity Indicator (MCI)*[4] could be used as a reference to carry out a circularity assessment of a product at an advanced level, including information on BoM, use and end of life. Methodology, case studies and a dynamic tool can be found in reference [8].

The MCI measures the extent to which linear flows have been minimised and restorative flows maximised for the component materials of a life cycle of a product.

Next table shows an overview of parameters and equations for the MCI (extract from Orienting project deliverables) just focused exclusively on technical cycles and materials from non-renewable sources. An extended version of the method including the treatment of biological materials and energy recovery can be found in reference [8].

[4] The Material Circularity Indicator (MCI) tool, which is part of a broader 'Circular Indicators Project' developed by The Ellen MacArthur Foundation and Granta Design, allows companies to identify additional, circular value from their products and materials, and mitigate risks from material price volatility and material supply. See reference [8].

Parameter	Definition	Formula
M	Mass of a product	input parameter (kg)
F_R	Fraction of mass of a product's feedstock from recycled sources	input parameter (%)
F_U	Fraction of mass of a product's feedstock from reused sources	input parameter (%)
C_R	Fraction of mass of a product being collected to go into a recycling process	input parameter (%)
C_U	Fraction of mass of a product going into component reuse	input parameter (%)
E_C	Efficiency of the recycling process for the portion of a product collected at the end-of-life for recycling	input parameter (%)
E_F	Efficiency of the recycling process used to produce recycled feedstock used as input material in a product	input parameter (%)
L	Actual average lifetime of a product	input parameter (unit of time)
L_{AV}	Actual average lifetime of an industry-average product of the same type. According to EMF this can be estimated from literature or expert analysis. When estimates cannot be established, L_{AV} should be equal to L.	input parameter (unit of time)
U	Actual average number of functional units achieved during the use phase of a product	input parameter (FU)
U_{AV}	Actual average number of functional units achieved during the use phase of an industry-average product of the same type. According to EMF this can be estimated from literature or expert analysis. When estimates cannot be established, U_{AV} should be equal to U.	input parameter (FU)
V	Mass of virgin feedstock used in a product	M*(1-FR-FU)
W	Mass of waste that cannot be recovered by reusing or recycling	W0+(WF+WC)/2
W_0	Mass of waste generated from a product that is not reused nor recycled (e.g., because going into landfill, waste to energy, or other type of processes)	M*(1-CR-CU)
W_C	Mass of unrecoverable waste generated in the process of recycling parts of a product	M*(1-EC)*CR
W_F	Mass of unrecoverable waste generated when producing recycled feedstock for a product	M*[(1-EF)*FR/EF]
LFI	Linear Flow Index	(V+W)/(2M+(WF-WC)/2)
F(X)	Utility factor built as a function of the utility X of a product. The constant 0.9 was defined to penalize products whose LFI is fully linear (LFI=1).	0.9/X
X	Utility of a product. According to EMF, this parameter should be calculated with either lifetime or MCI's functional unit, but not both. This is to avoid double counting the effects that lifetime can have on the use phase and vice versa.	$(L/L_{AV})*(U/U_{AV})$
MCI	**Material Circularity Indicator of a product**	**MAX(1-LFI*F(X),0)**

Table 1. Overview of parameters and equations for the Material Circularity Indicator (MCI)

To point out that MCI is oriented to measure circularity of material flows mainly, so resources used (energy, water) and emissions generated throughout the life cycle, which are relevant aspects covered within the circular economy principles, are not considered. Environmental impacts provoked by them will be addressed on Life Cycle Assessment.

During Oceanwise project, some pilot projects have been developed with manufacturers of EPS fish boxes and alternative materials to analyze how circularity could be assessed, leading to the conclusion that there is a general lack of data and transparency regarding material flows, waste management and recycling systems volumes and efficiency.

Anyway, assuming that some of the data could be obtained from literature or experts analyses, and not considering the comparison against industry averages (lifetime, functional units used), OW proposes to start with a simplified material circularity indicator (S-MCI), whose parameters and formulas are described in the next table.

Parameters	Formula	Description
M	Input (kg)	Mass of a product
FR	Input (%)	Fraction of mass of a product's feedstock from recycled source
FU	Input (%)	Fraction of mass of a product's feedstock from reused sources
CR	Input (%)	Fraction of mass of a product being collected to go into a recycling process
CU	Input (%)	Fraction of mass of a product going into component reuse
EC	Input (%)	Efficiency of the recycling process for the portion of a product collected at the end of-life for recycling
EF	Input (%)	Efficiency of the recycling process used to produce recycled feedstock used as input material in a product
V	M*(1-FR-FU)	Mass of virgin feedstock used in a product
W0	M*(1-CR-CU)	Mass of waste generated from a product that is not reused nor recycled (e.g., because going into landfill, waste to energy, or other type of processes)
WC	M*(1-EC)*CR	Mass of unrecoverable waste generated in the process of recycling parts of a product
WF	M*[(1-EF)*FR/EF]	Mass of unrecoverable waste generated when producing recycled feedstock for a product
W	W0+(WF+WC)/2	Mass of waste that cannot be recovered by reusing or recycling
LFI	(V+W)/(2M+(WF-WC)/2)	Linear Flow Index (takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow)
S-MCI	MAX(1-LFI,0)	**Simplified Material Circularity Indicator of a product**

Table 2. Overview of parameters and equations for the Simplified Material Circularity Indicator (S-MCI)

Next table shows circularity assessment of a generic product application case simulated.

Parameters	Description	Simulation 1
M	Mass of a product	0,25
FR	Fraction of mass of a product's feedstock from recycled source	0
FU	Fraction of mass of a product's feedstock from reused sources	0
CR	Fraction of mass of a product being collected to go into a recycling process	0,2
CU	Fraction of mass of a product going into component reuse	0
EC	Efficiency of the recycling process for the portion of a product collected at the end of-life for recycling	0,8
EF	Efficiency of the recycling process used to produce recycled feedstock used as input material in a product	0,8
V	Mass of virgin feedstock used in a product	0,250
W0	Mass of waste generated from a product that is not reused nor recycled (e.g., because going into landfill, waste to energy, or other type of processes)	0,200
WC	Mass of unrecoverable waste generated in the process of recycling parts of a product	0,010
WF	Mass of unrecoverable waste generated when producing recycled feedstock for a product	0,000
W	Mass of waste that cannot be recovered by reusing or recycling	0,205
LFI	Linear Flow Index (takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow)	0,919
S-MCI	**Simplified Material Circularity Indicator of a product**	**0,08**

Table 3. Simplified Material Circularity Indicator (S-MCI) of a generic EPS product

7.3 STEP 3: SUSTAINABILITY ASSESSMENT

At this point, Sustainability Assessment of the life cycle of the product/application is to be carried out following the LCSA (Life Cycle Sustainability Assessment) approach, as recommended in deliverable resulting from WP6.1 activity (reference [4]). Next figure shows an overview of the step.

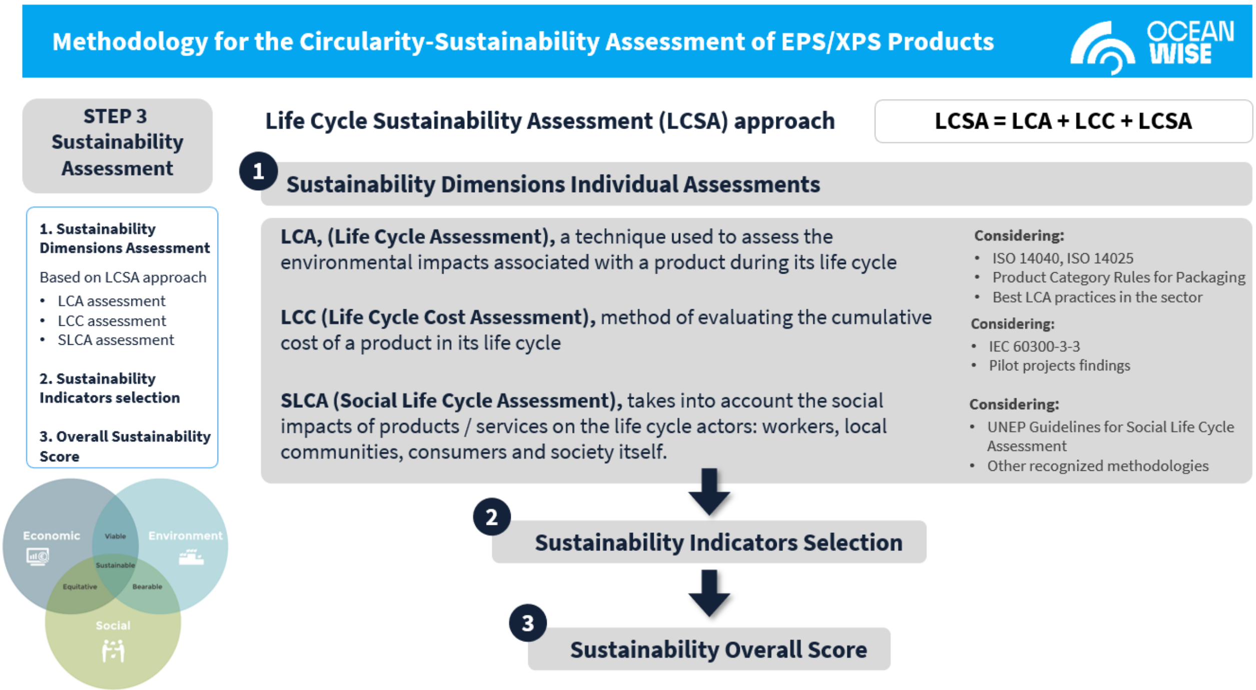


Figure 9. Overview of Step 3: Sustainability Assessment

It combines the following assessments, considering the 3 dimensions of sustainability (environmental, cost and social impact):

- Life Cycle Assessment (LCA)
- Life Cycle Cost Assessment (LCC)
- Social Life Cycle Assessment (SLCA)

Sustainability indicators will be selected later after these individual assessments, extracted from every of the 3 dimensions evaluated, according to the scope of the analysis defined within Step 1.

Finally, a Sustainability Overall Score based on LCSA approach will be calculated according to the prioritization done by the user to have an evaluation of sustainability of the life cycle (section 7.3.4).

7.3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA), as defined in ISO14040 (reference [2]), is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, addressing from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. Environmental impacts in the LCA context refer to adverse impacts on the areas of concern such as ecosystem, human health, and natural resources.

According to ISO14040, LCA studies comprises four phases:

- Goal and scope definition
- Inventory analysis
- Impact assessment and
- Interpretation.

First step is to define the goal and scope of the assessment. Corresponding applicable Product Category Rules to the product under study guides to define the functional unit, systems boundaries and life cycle phases to consider. For packaging applications, Product Category Rules for Packaging (PCR 2019:2013, see reference [9]) should be followed.

A *cradle to grave* approach should be applied to assess the environmental impacts throughout all the life cycle phases according to the corresponding applicable Product Category Rules (PCR) to the product under study.

Scope of the assessment should include the identification of the potential scenarios (see Figure 7), as described in Step 1 (Value Stream Mapping), in order to have a clear perspective of the variability of environmental impacts to the different scenarios and to identify later on the critical parameters related to circularity and sustainability assessment.

Life Cycle Inventory has been done previously in Step 1 mapping all the operations throughout life cycle of the product, and identifing inputs and outputs fot the functional unit defined, which are all the materials, auxiliary raw materials and resources (water, energy) consumed in the different operations, as well as the waste generated and emissions produced.

Then, all the Life Cycle Inventory data have to be imported to a recognized LCA software, such as GaBi, Simapro or openLCA, to build Life Cycle Inventory as a needed step to perform Life Cycle Impact Assessment and calculate environmental impacts. Following picture shows an example of system life cycle of EPS fish box (grey stages are not taken into account), extracted from reference [10].

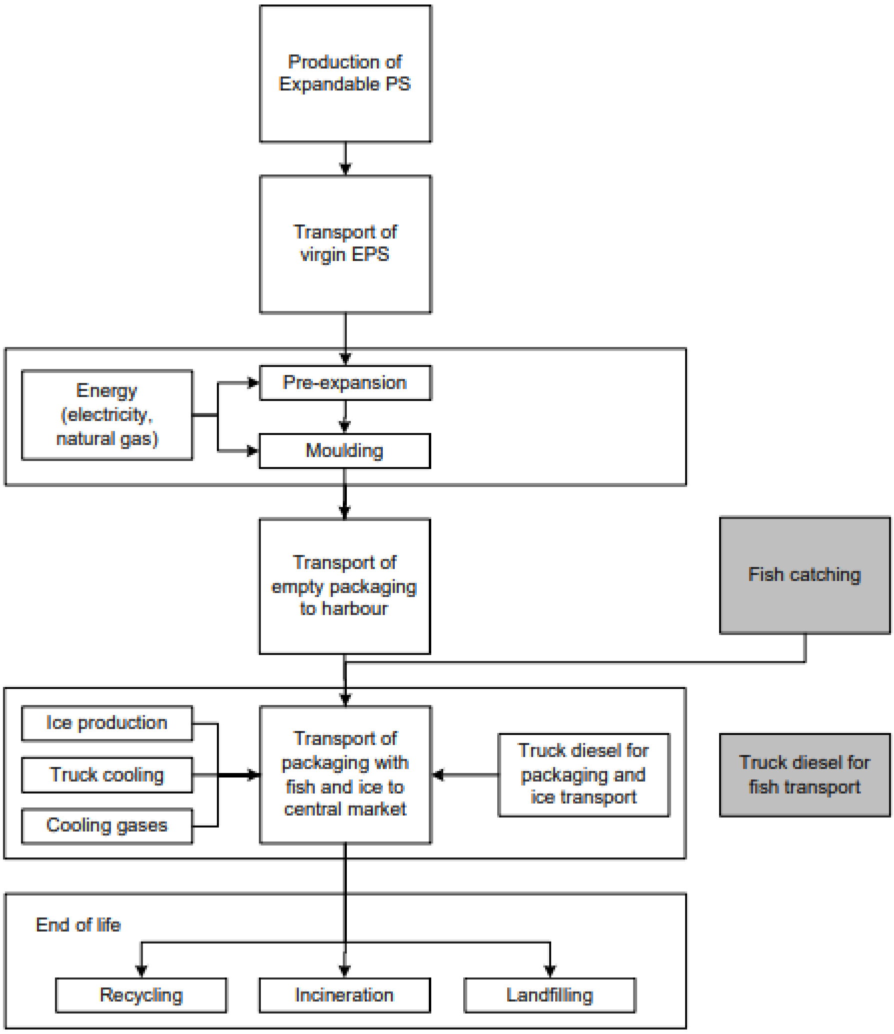


Figure 10. Example of LCI built of the life cycle of an EPS fish box in LCA software

Applicable PCR (Product Category Rules) also defines the environmental impact categories and impacts assessment methods for the estimation of environmental impacts.

PCR2019:2013 for packaging refers to the default list of environmental performance indicators defined in the International EPD System[5] with a corresponding impact assessment method (CML Baseline, EN15804, etc) to use for the impacts assessment in the LCA software. Here is the list of default environmental impact categories and indicators.

[5] Environmental Performance Indicators (https://www.environdec.com/indicators). The International EPD System

Environmental Impact Categories	Unit
Global Warming Potential (GWP)	kg CO2 eq
Acidification potential (AP)	mol H+ eq
Eutrophication potential (EP)	kg P eq
Photochemical ozone creation potential (POCP)	kg NMVOC eq
Ozone depletion potential (ODP)	kg CFC 11 eq
Abiotic depletion potential (ADP) for minerals and metals (non-fossil resources)	kg Sb eq.
Abiotic depletion potential (ADP) for fossil resources	MJ
Water deprivation potential (WDP)	m3 eq.

Table 4. List of the default environmental impact and inventory indicators according to the International EPD System

A brief description of these environmental impact categories:

- Global Warming Potential: Indicator of potential global warming due to emissions of greenhouse gases to air. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) bio-based resources and (3) land use change.
- Acidification: Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
- Eutrophication is defined as the potential to cause over-fertilisation of water and soil, which can result in increased growth of biomass
- Photochemical ozone creation potential (POCP), quantifies the relative abilities of volatile organic compounds (VOCs) to produce ground level ozone
- Ozone depletion potential (ODP), indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and chlorinated hydrocarbons (HCs) for depleting the ozone layer
- Abiotic depletion potential (ADP) for minerals and metals (non-fossil resources), refers to the removal of abiotic resources from the earth, or the depletion of non-living natural resources. In this case for non-fossil based resources (minerals and metals)
- Abiotic depletion potential (ADP) for fossil resources
- Water deprivation potential (WDP). It quantifies the potential of water deprivation, to either humans or ecosystems, and serves in calculating the impact score of water consumption at midpoint in LCA or to calculate a water scarcity footprint as per ISO 14046

So, once life cycle inventory is built within the LCA software for the scope and scenarios defined, impact assessment method is chosen and then environmental impacts for these impact categories are obtained.

Next table shows environmental impacts indicators of a generic product application case simulated.

Environmental Impact Categories	Value	Unit
Global Warming Potential (GWP)	0,08	kg CO2 eq
Acidification potential (AP)	3,20	mol H+ eq
Eutrophication potential (EP)	0,15	kg P eq
Photochemical ozone creation potential (POCP)	1,60	kg NMVOC eq
Ozone depletion potential (ODP)	1,73	kg CFC 11 eq
Abiotic depletion potential (ADP) for minerals and metals (non-fossil resources)	6,30	kg Sb eq.
Abiotic depletion potential (ADP) for fossil resources	3,20	MJ
Water deprivation potential (WDP)	2,10	m3 eq.

Table 5. Environmental impacts indicators of a generic EPS product

Finally, the interpretation of the results is to be carried out identifying significant issues from inventory analysis and impact assessment, which will be done in Step 4 (Circularity and Sustainability Assessment).

In addition to this assessment, Work package 5 of OW project has identified that LCA methdology and current environmental impact categories (like the ones described above) are not yet capable to assess macro, meso, and microplastics impact on the ecosystems and in human health, which is still under development. Also the environmental impacts to human health and environment of biodegradable, compostable and biobased alternative materials to foamed plastics need to be improved. Specifically the analysis of impacts of microplastics and chemicals on aquatic and marine environmental is still in its infancy.

That is why additional tests should be carried out to know specific impacts of foamed plastics (e.g.: EPS, XPS) and plastics in general on marine environments. Therefore, OW has developed the tool *"Marine Impact Assessment Toolkit"* for the development of assays to assess the potential environmental impact of plastic materials on the marine environment" (see reference [11]).

The toolkit proposes to do assays in 3 categories:

- Weathering, colonization leading to a species transport and degradation leading to a release of micro/nanoparticles
- Transfer of hazardous chemicals
- Toxicity on marine organisms

48 assays that can be used to evaluate these three categories of impacts were identified. This selection constitutes a "toolkit" of assays to assess the potential impact on the marine environment of plastic materials.

The methodology guides the user to select a minimum of 8 assays in the toolkit: 2 assays of weathering type, 3 from transfer of chemicals and 3 from toxicity on amine environment category. Then, after selecting a minimum of two materials, the user will conduct the assays selected, attribute the scores defined in the toolkit and make an average, obtaining the total Impact Score. The lower the Impact Score, then the lower is the impact on the marine environment.

The following table shows the results of tests done by CEDRE to 6 materials for the development of the toolkit. Complete information can be found in reference [11].

Environmental Impacts	EPS-F	EPS-I	XPS-O	PHBH-F	PLA-F	PLA+PBAT-F
Weathering	0.7	0.7	0.7	0.3	0.3	0.3
Transfer of hazardous chemicals	0.3	0.5	0.7	0	0	0
Toxicity on marine organisms	0.3	0.6	0.4	0	0.1	0.1
Impact Score	**1.3**	**1.8**	**1.8**	**0.3**	**0.4**	**0.4**

Table 6. Impact Score (IS) of six materials regarding the three categories of impacts.

So, to have a clear perspective of environmental impacts and specifically on the marine environment (priority of the project), OW proposes to combine analysis of environmental impacts according to LCA methods with tests results according to Marine Impact Assessment Tool, as showed in the following figure. How to combine both is explained within section 7.3.4.

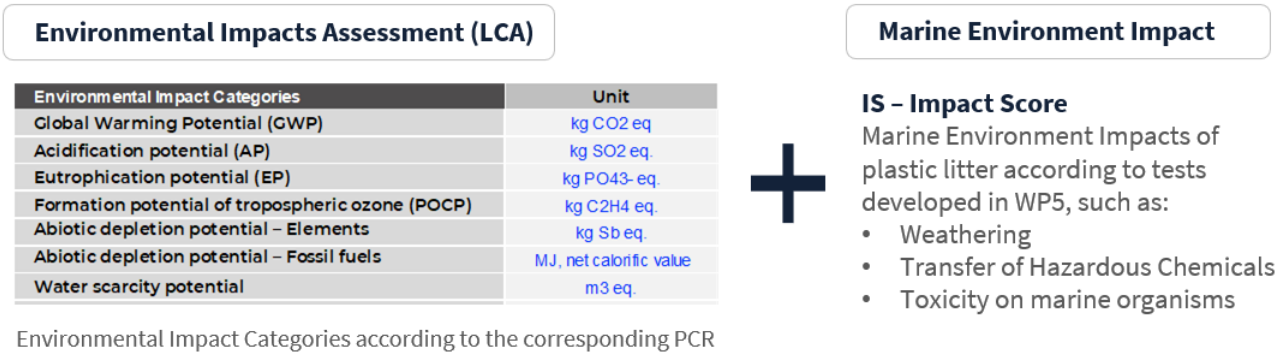


Figure 11. Scheme for the combination of LCA environmental impacts and marine environment impacts

7.3.2 Life Cycle Cost Assessment (LCC)

Life Cycle Cost is defined as the cumulative cost of product/service throughout the life cycle. As described in deliverable WP6.1 (see reference [4]), Life Cycle Cost Assessment is the technique proposed in most of references to assess sustainability of the life cycle of a product on the economic domain.

The primary objective of life cycle costing is to provide input to decision making in any or all phases of a product's life cycle. An important objective in the preparation of LCC models is to identify costs that may have a major impact on the LCC or may be of special interest for that specific application. This technique could be used, as proposed herein, as a measurement of life cycle costs of existing solutions and for the estimation of costs on new solutions all along the life cycle.

Assessign the life cycle cost guides also researchers for the development of alternative materials or products to make decisions at the early design and development phases and have a perspective of the critical parameters related to costs on the different phases of the life cycle of the product.

International Standard IEC 60300-3-3 (see reference [3]) is an application guide to carry out life cycle costing of a product, defining a clear scope of the different life cycle phases in terms of costs, as follows.

- Concept and Definition (CD). Concept and definition costs are attributed to various activities conducted to ensure the feasibility of the product under consideration, such as market research, preparation of a requirement specification of the product or product concept and design analysis.

- Design and Development (DD). Design and development costs are attributed to meeting the product requirements specification and providing proof of compliance, including activities such as:

    - design engineering, including reliability, maintainability and environmental protection activities,
    - prototype fabrication,
    - testing and evaluation,
    - producibility engineering and planning,
    - vendor selection, and
    - demonstration and validation

In this methodologu, CD and DD phases are combined together into the phase Design & Deevelopment (as showed in Figure 4), aiming to evaluate if conception, definition, design and development phases of a product are addressed.

- Manufacturing (MAN). Manufacturing costs refer to making the necessary number of copies of the product or providing the specified service on a continuous basis, including transportation to distributors or final user. Main activities included are:

    - construction of facilities,
    - supply chain development and acquistion of bill of materials
    - fabrication (labour, materials)
    - testing of manufacturing processes
    - production management and engineering,
    - facility maintenance,
    - quality control and inspection,
    - packaging, storage, shipping and transportation

- Installation (INS). It refers to all costs related to the assembly on site, installation, check-out and commisioning of product at the final destination. Main activities included are:

    - testing of installation processes
    - assembly, installation and checkout,
    - commissioning
    - quality control and inspection,

- Operation and Maintenance (O&M). Refers to the costs attributed to all the activities related to operation, maintenance (predictive, preventive and corrective) and supply support of products throughout the expected life of the system/product. It includes training, pThese costs typically include the following:

- Disposal (DIS). Costs incurred throughout all activities related to decommissioning and disposal of older versions of the products, including system shutdown, disassembly and removal, recycling or safe disposal.

First step is to estimate unitary costs for the different inputs and outputs (resources, raw materials, waste generated, …) for every phase and operation of life cycle of the product identified in the Value Stream Mapping (Step 1). These unitary costs will be prorrated to the functional unit defined. Following table shows a scheme of unitary costs (Ci) for the typical cost batches.

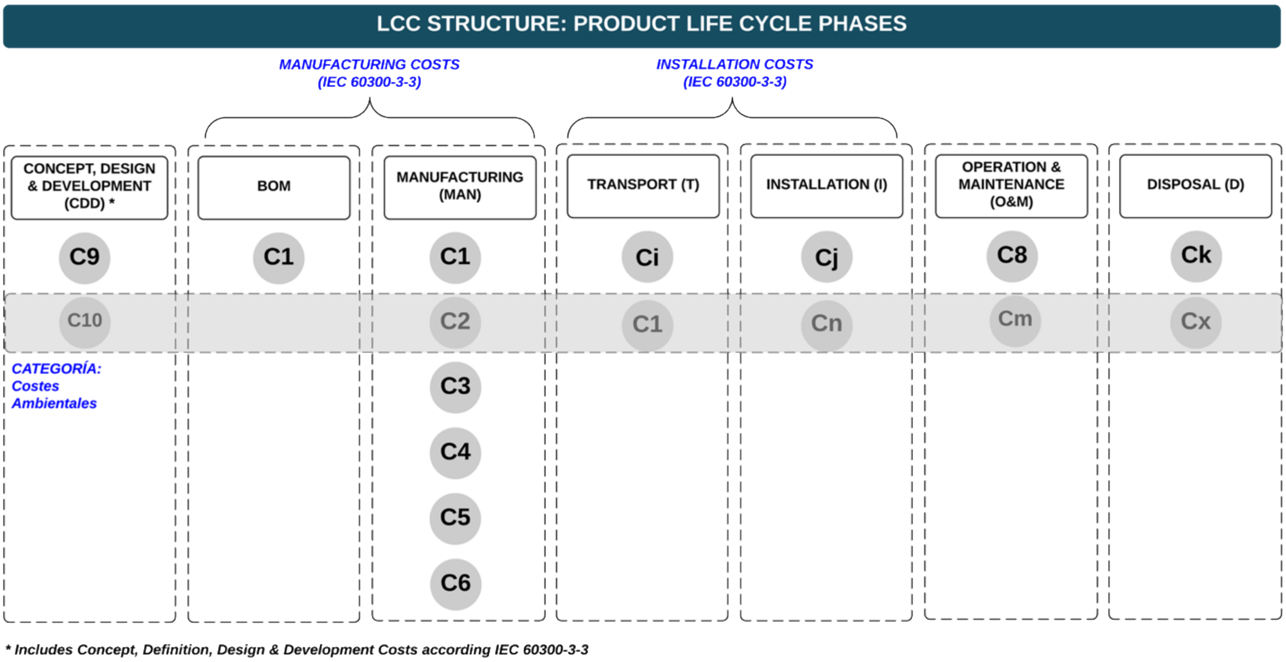


Table 7. LCC structure with typical costs batches

To calculate or estimate unitary costs prorrated to the functional unit, different type of costs should be taken into consideration:

- Recurring cost (REC): "usual" cost incurred repeatedly or for each unit produced or unit of service (cost of machining a part). These recurrent costs could be incurred with different periodicity, such as per unit, monthly, annually, etce
- Non-recurring cost (NREC): unusual cost, which is unlikely to be repeated in the normal course of business or the life of the product (engineering hours, initial training, investment costs, etc.). Sometimes called "extraordinary" cost.

Then, we are able to have a clear view of the distribution of costs of the different life cycle phases and most relevant batches (material costs, consumption of resources like water and anergy, manufacturing, transport , end of life, etc), and even for every operation. See example in the following figure.

Product Alternative	Design & Development	Bill of Materials	Manufacturing (MAN)	Transport & Installation	Operation & Maintenance	End of Life
Product 1	1,09	3,67	0,37	0,45	0,12	0,01

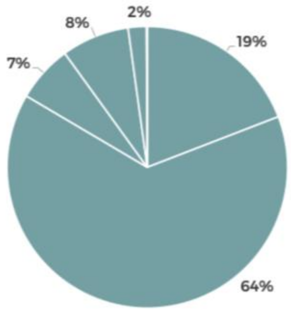


Figure 12. Distribution of costs by phase of the life cycle (product example)

On top of that, if we consider uncertainty and variability of most relevant costs, we could have the perspective of variability of costs per batches and phases, as showed in the following figure, which will be useful for sensitivity analysis against critical parameters, to be done in section 7.4.2.

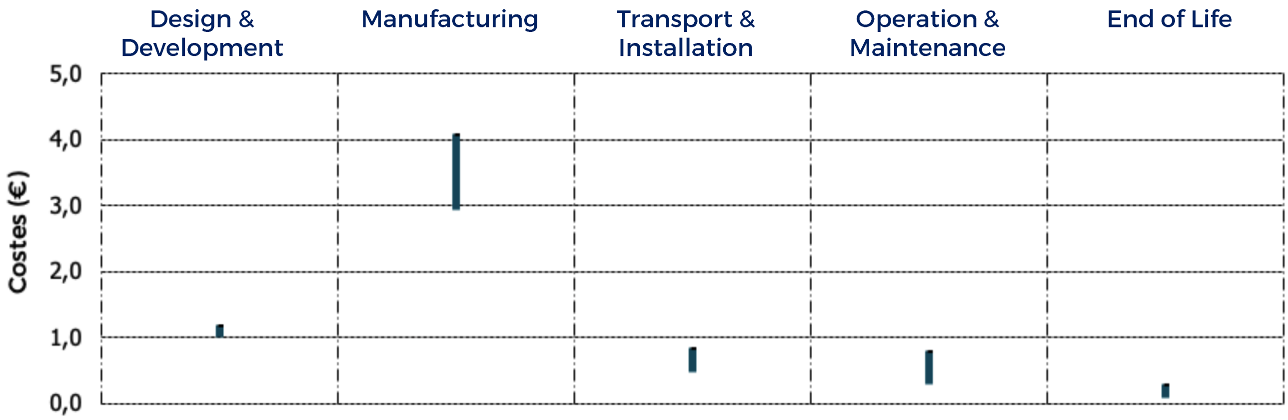


Figure 13. Variability of costs per life cycle phase (product example)

7.3.3 Social Life Cycle Assessment (SLCA)

Social Life Cycle Assessment referes to the evaluation of positive and negative effects of products with social and socioeconomic impact throughout their life cycle, identifying impact categories or key issues for social analysis and relevant stakeholders to consider: workers, the local community , consumers, society in general and the agents of the value chain.

It can be quantitative, semi-quantitative or qualitative and complements LCA and LCC with the evaluation of the life cycle on the social domain of sustainability. Since there is relatively little experience applying this assessment to a product life cycle, it will not be detailed here in this methodology.

Some references to carry out the SLCA are:

- Guidelines for Social Life Cycle Assessment of products and organizations. V3 Draft. 2021. UNEP, United Nations Environmental Programme
- Social Life Cycle Metrics for Chemical Products. WBCSD. 2016
- Other recognized methodologies (GRI, etc)

Next table shows an example of stakeholders and impact categories according to UNEP guidelines.

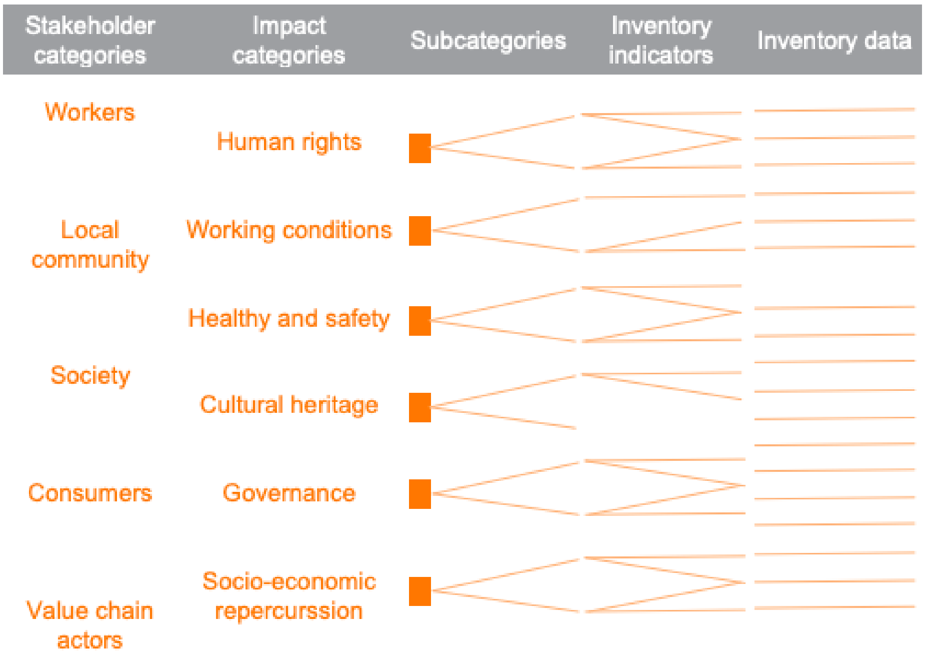


Table 8. Example of stakeholders and impact categories according to UNEP guidelines

7.3.4 Sustainability Assessment

As mentioned above, circularity is to be sustainable. Therefore, measuring triple impact is needed, so then, the three dimensions of sustainability (economic, environmental and social) are to be considered to analyze sustainability of the life cycle of a particular solution.

Life Cycle Sustainability Assessment (LCSA) approach should be followed in order to combine environmental impact (Life Cycle Analysis - LCA), cost impact (Life Cycle Cost - LCC) and social impact (Social Life Cycle Analysis - SLCA).

Sustainability indicators are to be defined in the first place. Since SLCA is not being considered in this methodology, sustainability indicators should cover environmental impacts and costs domains, as follows.

- Environmental dimension: environmental impact indicators from Life Cycle Assessment combined with Impact Score resulting from marine environment
- Cost dimension: life cycle cost or specific batches costs' could be chosen

Overview of the selection of sustainability indicators in both domains is showed in the following figure.

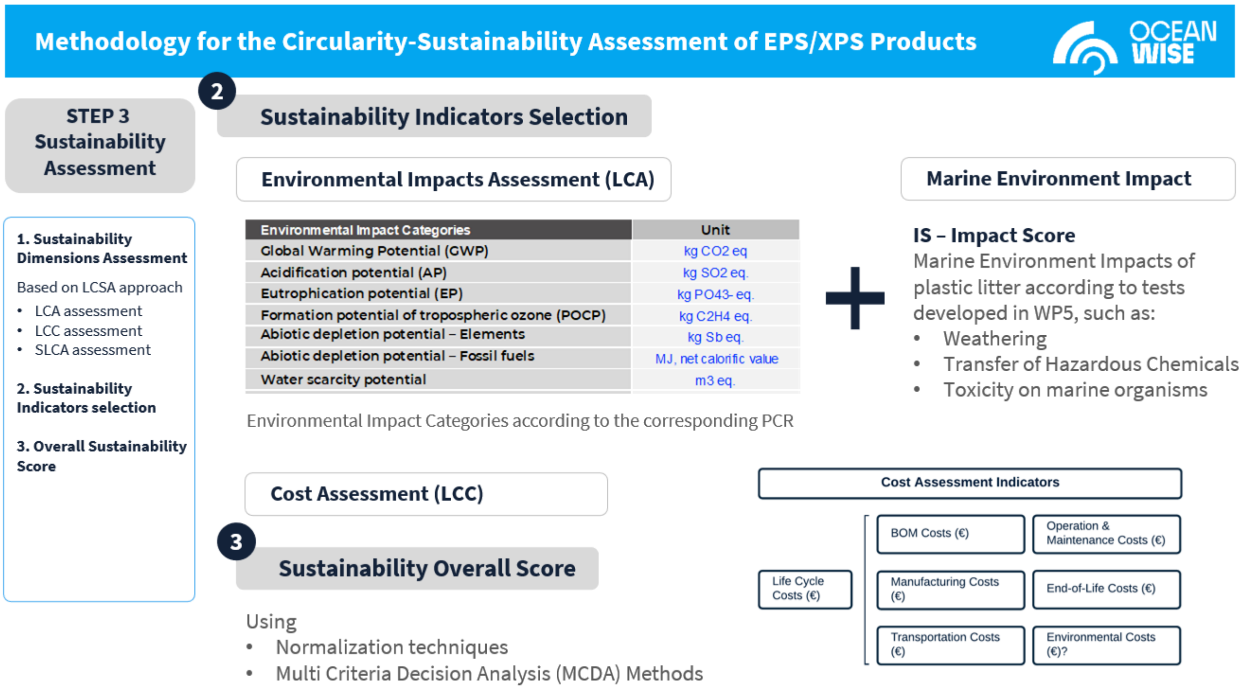


Figure 14. Identification of Sustainability Indicators for Sustainability Assessment

Then a sustainability overall score is to be built combining sustainability indicators both in environmental impact and cost domains.

Point out that the sustainability indicators are of different magnitudes and units, even within the environmental domain, so specific techniques are needed to combine them.

Since there could be several criteria to follow, multiple objectives to achieve and requirements to meet, Multi Criteria Decision Analysis (MCDA) and Multi Objective Decision Making (MODM) methods should be used to compare solutions with the environmental impact indicators and costs indicators selected (see reference [12]). For this reason, sustainability will be evaluated by comparison, either between alternative solutions or comparing a specific solution against maximum or minimum values of specific indicators that can be established as requirements. These kind of methods should be used for material or product development to compare different alternatives, since there is always a need to meet multiple requirements, such as:

- Cost requirements from the market
- Environmental impacts requirements from customers to reduce their carbon footprint
- Continuous improvement measures taken internally by a company to reduce the carbon footprint or environmental impacts.
- Potential threshold values from future legislation to specific impacts, such as carbon footprint
- Etc…

Since there is relatively little experience applying them to sustainability assessment (see reference [12]), the following simplified method is proposed.

It is proposed to use normalizaton and weighting techniques to combine and compare them properly. Normalization and weighting is a very widely used technique for supporting multi-criteria decision making process based of heterogeneous inputs.

The following formula is proposed to normalize the different indicators, both in environmental and costs dimensions. It is oriented to normalize a specific indicator compared to maximum and minimum values of product alternatives for the same indicator.

$$v_i = \frac{a_i - \min a_i}{\max a_i - \min a_i}$$

Next tables shows an example of application of the formula to environmental impact indicators for simulated cases.

DATA

Product Alternative Solution	Environmental Impact [pt]							
	Global Warming Potential (GWP) [kg CO2 eq]	Acidification potential (AP) [mol H+ eq]	Eutrophication potential (EP) [kg P eq]	Photochemical ozone creation potential (POCP) [kg NMVOC eq]	Ozone depletion potential (ODP) [kg CFC 11 eq]	Abiotic depletion potential (ADP) for minerals & metals [kg Sb eq.]	Abiotic depletion potential (ADP) for fossil resources [MJ]	Water deprivation potential (WDP) [m3 eq]
Product 1	0,077	3,20	0,145	1,600	1,730	6,300	3,200	2,100
Product 2	0,081	3,52	0,16	1,36	1,90	6,615	3,360	2,520
Product 3	0,085	3,87	0,14	1,16	1,64	6,946	3,528	2,394
Product 4	0,089	4,26	0,15	0,98	1,81	7,293	3,704	1,915

NORMALIZATION PROCEDURE $v_i = \frac{a_i - \min a_i}{\max a_i - \min a_i}$

Product Alternative Solution	Environmental Impact [pt]							
	Global Warming Potential (GWP)	Acidification potential (AP)	Eutrophication potential (EP)	Photochemical ozone creation potential (POCP)	Ozone depletion potential (ODP)	Abiotic depletion potential (ADP) for minerals and metals	Abiotic depletion potential (ADP) for fossil resources	Water deprivation potential (WDP)
Product 1	0,000	0,000	0,333	1,000	0,333	0,000	0,000	0,306
Product 2	0,317	0,302	1,000	0,611	1,000	0,317	0,317	1,000
Product 3	0,650	0,634	0,000	0,281	0,000	0,650	0,650	0,792
Product 4	1,000	1,000	0,633	0,000	0,633	1,000	1,000	0,000

Table 9. Example of application of normalization formula to environmental impact indicators (simulated case study of 4 product alternatives)

On top of that, we need to combine different indicators from different dimensions, considering that the goal of the solutions are usually to be competitive in costs with the minimum environmental impacts.

Therefore, in addition to normalization, the simplified method to obtain a SOS (Sustainability Overall Score) proposes to carry out weighting in 2 different levels:

- 1^{st} level: Weighting within environmental impacts dimension and costs dimension
- 2^{nd} level: Weighting of environmental and costs dimension indicators

For the 1^{st} level weighting, it is to be considered that LCA is providing different environmental impact indicators according to PCR rules (8 environmental indicators according to PCR2019:2013) and marine environment impact assessment proposed by OW project is providing Impact Score as an unique indicator.

Some of the impacts assessment methods (e.g.: EF Method 3.0, see reference [13]) used within LCA propose specific normalization (to get impacts in Pt, unit points) in combination with weighting procedures across the impact categories to apply to the individual environmental impacts indicators aiming to obtain environmental impacts in end-point categories like:

- Human Health
- Ecosystems
- Natural Resources

However, most of the existing Product Category Rules to assess environmental impacts and obtain an Environmental Product Declaration (EPD), which is one of the most recognized certifications for a LCA of a product, are not proposing a method to weight the different environmental impac indicators. EPDs just present the results for all the environmental impact indicators proposed by the corresponding PCR's.

For those cases where there is no normalization and weighting method or to combine conventional indicators from LCA and Impact Score (IS), a simplified method of weighting is proposed according to the company strategy or to the importance given by the user to specific environmental impact categories.

Next table shows an example of product alternatives with a proposed weighting to the different environmental impacts and Impact Score (IS). In this case the user has decided that GWP (carbon footprint) and Impact Score have more relevant weight than the others, because a reduction of carbon footprint is demanded by the customer of the product and assumes a commitment to reduce the impact on the marine environment.

Product Alternative Solution	Environmental Impacts (LCA)								Marine Environment
	Global Warming Potential (GWP)	Acidification potential (AP)	Eutrophication potential (EP)	Photochemical ozone creation potential (POCP)	Ozone depletion potential (ODP)	Abiotic depletion potential (ADP) for minerals and metals	Abiotic depletion potential (ADP) for fossil resources	Water deprivation potential (WDP)	Marine Environment Impact Score (IS)
Weight	0,6	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,2
Product 1	0,000	0,000	0,333	1,000	0,333	0,000	0,000	0,306	0,667
Product 2	0,317	0,302	1,000	0,611	1,000	0,317	0,317	1,000	1,000
Product 3	0,650	0,634	0,000	0,281	0,000	0,650	0,650	0,792	0,000
Product 4	1,000	1,000	0,633	0,000	0,633	1,000	1,000	0,000	0,067

Table 10. Example of weighting to environmental impact indicators and Impact Score (IS)

For the 2nd level, a similar weighting technique can be done to be able to combine the importance given by the company to costs and environmental impacts indicators, including marine environment impact (Impact Score).

Following table shows an example of product alternatives with a proposed weighting to environmental impacts and life cycle cost. The user has decided to give a high importance to life cycle cost because competitiveness in the market is based mainly on costs. It is also obtained the Sustainability Overall Score (SOS) for the product alternatives considering the weighting selected.

DATA

Product Alternative Solution	Environmental Impacts (LCA)								Marine Environment	Life Cycle Cost [€]		
	Global Warming Potential (GWP) [kg CO2 eq]	Acidification potential (AP) [mol H+ eq]	Eutrophication potential (EP) [kg P eq]	Photochemical ozone creation potential (POCP) [kg NMVOC eq]	Ozone depletion potential (ODP) [kg CFC 11 eq]	Abiotic depletion potential (ADP) for minerals & metals [kg Sb eq.]	Abiotic depletion potential (ADP) for fossil resources [MJ]	Water deprivation potential (WDP) [m3 eq]	Marine Environment Impact Score (IS)	BOM	Man	EoL
Product 1	0,077	3,20	0,145	1,600	1,730	6,300	3,200	2,100	1,300	3,67	0,37	0,005
Product 2	0,081	3,52	0,16	1,36	1,90	6,615	3,360	2,520	1,800	3,85	0,35	0,013
Product 3	0,085	3,87	0,14	1,16	1,64	6,946	3,528	2,394	0,300	3,91	0,37	0,008
Product 4	0,089	4,26	0,15	0,98	1,81	7,293	3,704	1,915	0,400	3,25	0,29	0,005

NORMALIZATION PROCEDURE

$$v_i = \frac{a_i - \min a_i}{\max a_i - \min a_i}$$

Product Alternative Solution	Environmental Impacts (LCA)								Marine Environment		Life Cycle Cost [€]			
	Global Warming Potential (GWP)	Acidification potential (AP)	Eutrophication potential (EP)	Photochemical ozone creation potential (POCP)	Ozone depletion potential (ODP)	Abiotic depletion potential (ADP) for minerals and metals	Abiotic depletion potential (ADP) for fossil resources	Water deprivation potential (WDP)	Marine Environment Impact Score (IS)	Environmental Impact	BOM	Man	EoL	Cost Assessment
Weight	0,6	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,2	1,0	0,3	0,4	0,3	1,0
Product 1	0,000	0,000	0,333	1,000	0,333	0,000	0,000	0,306	0,667	0,810	0,64	1,00	0,00	0,407
Product 2	0,317	0,302	1,000	0,611	1,000	0,317	0,317	1,000	1,000	0,480	0,91	0,73	1,00	0,132
Product 3	0,650	0,634	0,000	0,281	0,000	0,650	0,650	0,792	0,000	0,524	1,00	1,00	0,42	0,175
Product 4	1,000	1,000	0,633	0,000	0,633	1,000	1,000	0,000	0,067	0,265	0,00	0,00	0,00	1,000

Company Strategy	
Environmental Impact	0,3
Cost Assessment	0,7

SoS (Sustainability Overall Score) Quantification	
Product 1	0,528
Product 2	0,236
Product 3	0,279
Product 4	0,779

Table 11. Example of weighting to environmental impact indicators and costs. Sustainability Overall Score (SOS)

SLCA could be integrated in the same way to the sustainability assessment as another additional dimension to environmental impact and cost assessment. Normalization and weighting techniques should be applied with the same logic to the social impact categories and then social dimension should be weigthed with environmental and cost dimensions according to the company strategy.

7.4 STEP 4: CIRCULARITY – SUSTAINABILITY ASSESSMENT

This step is about combine circularity and sustainability assessment. As explained before, circularity is a means to promote sustainability and a tool for the development of more sustainable solutions.

Measuring circularity, as described in section, is just giving information about material flows and how much materials are kept as long as possible in the productive systems, trying to reduce waste not recoverable all along the product life cycle. But is not giving direct information about neither environmental impacts, nor costs and marine environment impact. Higher circularity does not mean directly that environmental impacts or costs are better. Therefore circularity and sustainability assessments have to be provided together.

Next table shows an example of 4 product alternatives with a particular circularity index (S-MCI) and the Sustainability Overall Score (SOS) calculated for the corresponding sustainability indicators (environmental impacts, costs and marine environment) displayed in Table 11.

Product Alternatives	S-MCI (Simplified Material Circularity Indicator)	SoS (Sustainability Overall Score) Quantification
Product 1	0,17	0,5283
Product 2	0,16	0,2365
Product 3	0,21	0,2794
Product 4	0,19	0,7794

Table 12. Circularity-Sustainability Assessment of product alternatives (example)

7.4.1 Identification of critical parameters for Circularity and Sustainability

Once circularity and sustainability assessment have been carried out, critical parameters from circularity and sustainability are to be identified to know the hot spots and to be able to make sensitivity analysis against them and to identify risks and opportunities related to adapt the solution (material, product, waste management system, recycling process) to the upcoming trends coming from the market, sector, customer requirements or legislation changes.

Regarding circularity, we should analyze first which parameters are having a bigger impact on the simplified Material Circularity Indicator (S-MCI) and their impact on sustainability, both environmental impacts (conventional and marine environment impact) and costs impacts. Parameters having usually higher impact on S-MCI are:

- Fraction of mass of a product's feedstock from recycled source
- Fraction of mass of a product's feedstock from reused sources
- Fraction of mass of a product being collected to go into a recycling process
- Fraction of mass of a product going into component reuse

Regarding environmental impacts, we should follow the next steps, analyzing every of the different environmental impact indicators obtained from LCA:

- Identify the phase of the life cycle (manufacturing, transport, utilization, end of life) provoking greater impact on the specific indicator (for example GWP, Global Warming Potential)
- Identify the operation of this phase (expanding, moulding, recycling, etc) where impact on the specific indicator is higher.
- Identify the parameter (energy consumption, fuel consumption, material, etc) of this operation producing higher impact

Repeating this process for every of the environmental impact indicators, critical parameters are to be identified.

Next tables show an example of the identification of critical parameters regarding environmental impacts of a generic product.

		Critical Phases, Operations & Parameters					
Environmental Impacts	Impact Value - Full Life Cycle	Life Cycle Phase	% Impact in total Impact	Manufacturing Operation	% Impact in total Impact	Critical Parameters	% Impact in total Impact
Acidification (mol H+ eq)	0,00	Manufacturing	94,27%	Operation 1	62%	Material 1	57%
Climate Change (kg CO2 eq)	0,00	Manufacturing	90%	Operation 1	56%	Material 1	53%
Climate Change - Biogenic (kg CO2 eq)	0,00	Manufacturing	98%	Operation 1	63%	Material 1	59%
Eutrophication, Terrestrial (mol N eq)	0,00	Manufacturing	94%	Operation 1	63%	Material 1	59%
Particulate Matter (disease incidence)	0,000000	Manufacturing	86%	Operation 1	61%	Material 1	57%
Resource Use, Fossils (MJ)	0,00	Manufacturing	90%	Operation 1	48%	Material 1	45%
Water Use (m3 world eq)	0,00	Manufacturing	98%	Operation 2	41%	Water consumption	27%

Table 13. Identification of critical parameters regarding environmental impacts (example)

In this example, manufacturing process appears as the phase of life causing the greatest environmental impact, so the identification of operations and parameters are focused on manufacturing phase. To point out that this phase is considering the raw materials used to manufacture the product, their transport to the manufacturing factory, as well as the consumption of resources (water and energy) and the generation of waste in the different process operations.

Regarding costs, the same process can be followed analyzing the data obtained from LCC assessment. Usually the following parameters are the most relevant regarding costs:

- Material costs
- Manufacturing labour
- Energy consumption
- Transportation to the user
- Recycling costs

7.4.2 Sensitivity analysis against the most critical parameters

After the identification of critical parameters related to circularity and sustainability, a sensitivity analysis is to be carried out. Sensitivity analysys will be done simulating product alternatives (alternative scenarios) combining different values of the critical parameters selected. Next table shows an example of how to build alternative scenarios with a set of critical parameters.

Critical Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Material	EPS	PP	Cardboard	EPS
Mass of of main material of the functional unit (kg)	0,25	0,22	0,24	0,30
Transport distance from material supplier to factory (km)	200	500	10000	200
Fraction of mass of a product's feedstock from recycled source (%)	0	20	30	50
Fraction of mass of a product being collected to go into a recycling process (%)	20	30	50	80

Table 14. Simulation of alternative scenarios

To asign values to the critical parameters, following aspects should be considered:

- Volatility of costs of raw materials and resources (energy, water)
- Scenarios for the life cycle (different distribution paths, users, waste management systems, recycling processes
- Legislation trends, such as for example incorporating recycled content, ban or restrictions on specific materials

The different product alternatives (alternative scenarios) built varying the critical parameters will have different life cycle costs and provoke different conventional environmental impacts (obtained from LCA) and marine environment impact, so circularity and sustainability assessment should be done for every of the alternatives.

Comparative LCA, LCC and marine environment impact assessments of the different scenarios simulated should be carried out then following the process described in Step 3 (section 7.3).

Next table shows an example of LCC assessment of alternative life cycle scenarios.

ID	Alternative Scenario	Design & Development	Bill of Materials	Manufacturing (MAN)	Transport & Installation	Operation & Maintenance	End of Life	LCC (€)
ID1	Scenario 1	1,09	3,67	0,37	0,45	0,12	0,01	**5,71**
ID2	Scenario 2	1,09	3,85	0,35	0,54	0,10	0,01	**5,95**
ID3	Scenario 3	1,09	3,91	0,37	0,41	0,10	0,01	**5,89**
ID4	Scenario 4	1,09	3,25	0,37	0,60	0,10	0,01	**5,42**
ID5	Scenario 5	1,09	4,02	0,28	0,37	0,08	0,01	**5,86**

Table 15. LCC assessment comparison of different alternative scenarios

Regarding costs, we could even consider uncertainty of the different costs and their distribution by phases and of the final value, as displayed in the following figure.

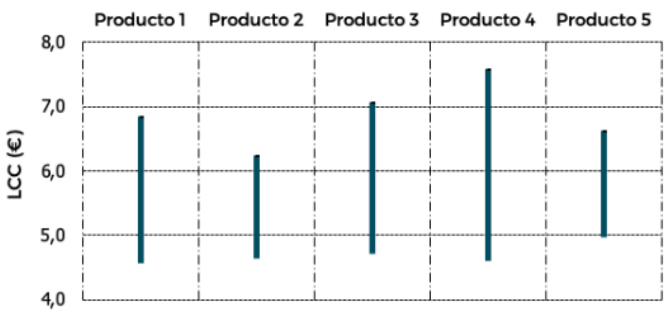


Figure 15. LCC assessment comparison. Uncertainty of LCC value

Next table shows an example of comparative environmental impacts assessment of alternative life cycle scenarios.

Alternative Scenarios	Environmental Impacts (LCA)								Marine Environment
	Global Warming Potential (GWP) [kg CO2 eq]	Acidification potential (AP) [mol H+ eq]	Eutrophication potential (EP) [kg P eq]	Photochemical ozone creation potential (POCP) [kg NMVOC eq]	Ozone depletion potential (ODP) [kg CFC 11 eq]	Abiotic depletion potential (ADP) for minerals & metals [kg Sb eq.]	Abiotic depletion potential (ADP) for fossil resources [MJ]	Water deprivation potential (WDP) [m3 eq]	Marine Environment Impact Score (IS)
Scenario 1	0,077	3,20	0,145	1,600	1,730	6,300	3,200	2,100	1,300
Scenario 2	0,081	3,52	0,16	1,36	1,90	6,615	3,360	2,520	1,800
Scenario 3	0,085	3,87	0,14	1,16	1,64	6,946	3,528	2,394	0,300
Scenario 4	0,089	4,26	0,15	0,98	1,81	7,293	3,704	1,915	0,400

Table 16. LCA assessment comparison of different alternative scenarios

Finally comparison of sustainability of the alternative scenarios to have a Sustainability Overall Score comparison as described in section 7.3.4.

7.4.3 Identification of risks & opportunities related Circularity and Sustainability

Identification of risks and opportunities is a crucial step to have a perspective about the adaptability of the different solutions and scenarios to upcoming trends, and to detect opportunities to reduce environmental impacts and to improve the sustainability of the solution in the 3 dimensions. Aspects to consider at the time of identifying risks and detecting opportunities are:

- Availability of raw materials and resources
- Volatility of costs of raw materials and resources (energy, water)
- Market, sector and customer requirements trends, such as:
  - green procurement requirements
  - decarbonization and reduction of environmental impacts of supply chains
  - certifications of environmental performance (carbon footprint, EPD, etc)
- Legislation trends (Europe, national, regional), such as
  - incorporation of recycled content to materials and products
  - recycling rates targets for plastics and other materials
  - ban or restrictions on specific materials
  - initiatives to fight greenwashing
  - reduction of hazardous substances
- Technology trends for
  - materials
  - recycling processes

7.4.4 Trade-off analysis

Trade off analysis techniques should be used for:

- Helping in the design decisions to analyze sustainability from the early design phases of a product
- Compare alternative distribution paths for a specific material, as described in Step 1 (section 7.1).
- Compare alternative solutions throughout the life cycle of a product, understanding solutions as different combinations of material, distribution process, waste collection and management systems, recycling process, etc
- Helping researchers with the assessment of sustainability and circularity of new materials

Trade off analysis will be carried out following the process mentioned above from Step 1 to Step 4 for every of the scenarios defined, as described in section 7.4.2.

When designing a new product, as described in deliverable WP6.2 (reference [5]), trade off analysis to be carried out aiming to obtain the optimal technical solution in terms of circularity and sustainability should be integrated from early design phases. The following picture shows how a typical workflow of a conceptual design phase of a generic product should integrate circularity-sustainability assessment and trade off analysis.

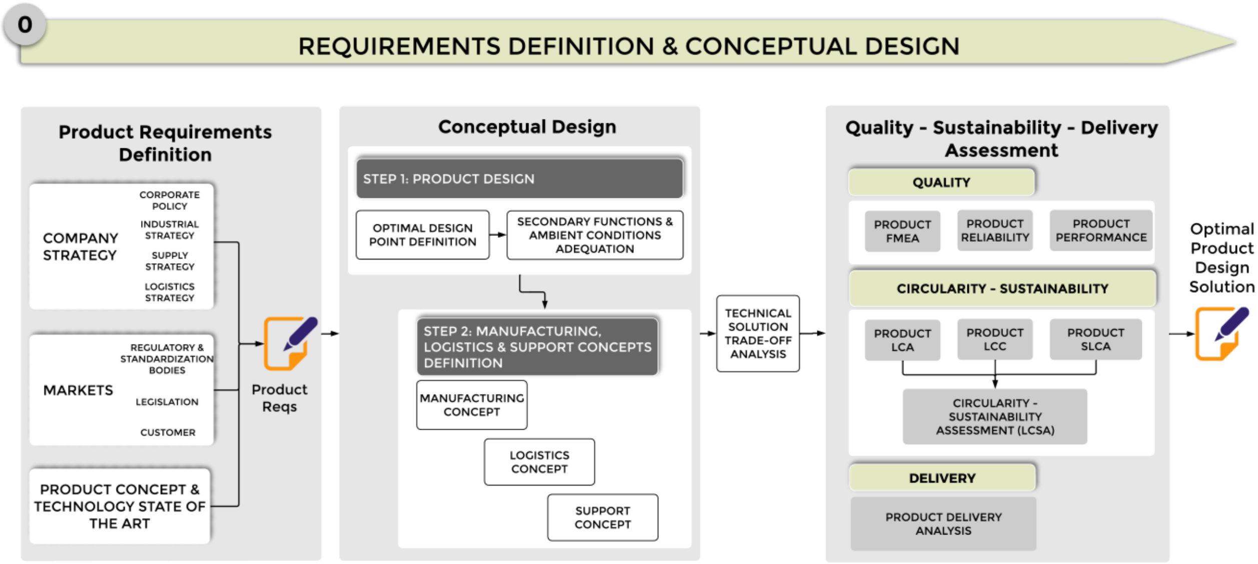


Figure 16. Conceptual Design Phase Overview integrating circularity-sustainability assessment

8 APPLICABILITY - METHODOLOGY ADDED VALUE FOR TARGET STAKEHOLDERS

Circularity-Sustainability Assessment Methodology has been conceived to be useful for the different stakeholders around the current and potential future EPS/XPS applications. An identification of the main stakeholders has been carried out, considering the main players within the life cycle of an EPS/XPS application and others that can promote the implementation of sustainability and circular economy principles on these applications in the next future, such as policy makers and public administrations. The next figure shows the map of the main stakeholders considered.

Figure 17. OW Circularity Assessment Methodology Stakeholders Map

The added value that the methodology aims to bring to the different stakeholders is indicated below and describes how each group of stakeholders can use the methodology to implement the principles of sustainability and circularity in their main activities with respect to the matter in question.

Methodology for the Circularity Assessment of EPS/XPS Products and Applications

METHODOLOGY ADDED VALUE FOR TARGET STAKEHOLDERS

Stakeholder	Role (in this field)	Methodology Added Value
Research Centers	Research about materials, processes or technologies to improve waste management and recycling of EPS/XPS applications	Help assessing circularity and sustainability of application of materials, technologies and processes under investigation
Raw Material Suppliers	Development and supply of raw materials for EPS/XPS products and applications	Help assessing circularity and sustainability of raw materials and their impact throughout EPS/XPS products and applications life cycle
EPS/XPS products Industry	Manufacturing EPS/XPS products and applications	Help assessing circularity and sustainability of the life cycle of EPS/XPS products and applications Helping making decisions about selection of materials, product and process development
Users	1st Level users (distribution, aquaculture, fishing industries, central markets)	Help selecting the most sustainable and circular solutions for EPS/XPS products and applications (or alternatives)
Waste Management Companies	Companies managing waste from users to end-of-life management companies	Help assessing impact of their technologies and processes on circularity and sustainability of EPS/XPS products and applications (or alternatives)
Recycling Companies	Companies recycling EPS/XPS products	
Policy Makers (EU, National, etc)	Public organizations in charge of policies making	To consider the methodology applicability to identify sustainability and circularity hot spots in EPS/XPS products and applications, plastic products and other products in general, to address in future policies development
Public Administrations	Public administrations developing and implementing policies	Help extrapolate the methodology approach to green public procurement policies implementation to other plastic products and other products in general

Figure 18. Summary of the methodology added value for target stakeholders.

Following sections describe the role of each stakeholder, the added value of the methodology for them, and how they can use the proposed methodology.

8.1 RESEARCH CENTERS

Role:

Research about materials, processes or technologies to improve waste management and recycling of EPS/XPS applications.

Added Value:

Help assessing circularity and sustainability of application of materials, technologies and processes under investigation.

Methodology use:

Research centers can use this methodology to assess circularity and sustainability of technologies, processes and materials they are developing, considering these particularities:

- If they are developing new materials, they should use the methodology to estimate circularity and sustainability of the life cycle of potential applications for these materials carrying out trade off analysis of the different alternatives in order to select the optimum solution in terms of competitiveness, sustainability and circularity.
- For the development of new technologies, they should use the methodology with the same orientation considering the potential applications to products, services or processes.

8.2 RAW MATERIALS SUPPLIERS

Role:

Development and supply of raw materials for EPS/XPS products and applications

Added Value:

Help assessing circularity and sustainability of raw materials and their impact throughout EPS/XPS products and applications life cycle.

Methodology use:

Raw materials suppliers can use this methodology to identify and implement improvement opportunities related to circularity and sustainability for all the potential applications on packaging or other products.

8.3 EPS/XPS PRODUCTS INDUSTRY

Role:

Manufacturing EPS/XPS products and applications

Added Value:

Help assessing circularity and sustainability of the life cycle of EPS/XPS products and applications. Helping decisions making about selection of materials, product and process development.

Methodology use:

EPS/XPS products industry can use this methodology to identify and implement improvement opportunities related to circularity and sustainability, cooperating with other players, in order to develop the optimum solution in terms of competitiveness, circularity and sustainability throughout the complete life cycle.

8.4 USERS

Role:

1st Level users (distribution, aquaculture, fishing industries, central markets).

Added Value:

Help selecting the most sustainable and circular solutions for EPS/XPS products and applications (or alternatives).

Methodology use:

1st level users can use this methodology to analyze the different solutions and to select the optimum solution in terms of competitiveness sustainability and circularity all along the life cycle of the application.
Associations and clusters of 1st level users could develop adhoc tools and methodologies, following this methodology approach, taking into account their particularities and needs to establish a common reference.

8.5 WASTE MANAGEMENT COMPANIES

Role:

Companies managing waste from users to end-of-life management companies.

Added Value:

Help assessing impact of their technologies and processes on circularity and sustainability to the life cycle of EPS/XPS products and applications (or alternatives).

Methodology use:

Waste management companies can use this methodology to assess the impact on circularity and sustainability of their processes and technologies to the complete life cycle of a particular application or solution. A collaborative work with raw materials suppliers, products industry and recycling companies could lead to better solutions in the different scenarios throughout the life cycle of products.

8.6 RECYCLING COMPANIES

Role:

Companies recycling EPS/XPS products.

Added Value:

Help assessing impact of their technologies and processes on circularity and sustainability of EPS/XPS products and applications (or alternatives).

Methodology use:

As the waste management companies, recycling companies can use this methodology to assess the impact on circularity and sustainability of their processes and technologies on the complete life cycle of a particular application or solution.

8.7 POLICY MAKERS

Role:

Public organizations in charge of policies making.

Added Value:

To consider the methodology applicability to identify sustainability and circularity hot spots in EPS/XPS products and applications or alternatives, plastic products and other products in general, to address in future policies development.

Methodology use:

Policy makers can use the application of this methodology to identify barriers, improvement opportunities and funding topics to improve sustainability and circularity of the life cycle of different products and applications.

Moreover, they could analyse the possibility of introducing this methodology approach in the future directives and strategies to ensure that new technologies, processes and materials to be developed in the future will ensure the conception and development of better life cycle solutions related to sustainability and circularity.

8.8 PUBLIC ADMINISTRATIONS

Role:

Public administrations developing and implementing policies.

Added Value:

Help extrapolate the methodology approach to green public procurement policies implementation to other plastic products and other products in general.

Methodology use:

Public administrations can use the application of this methodology to identify barriers, improvement opportunities and funding topics to foster and promote the development of better life cycle solutions of different products and applications related to sustainability and circularity.

For administrations playing the procurement role, they could analyse the possibility of introducing this methodology approach in the tenders to ensure that the products or materials they acquire are better in terms of sustainability and circularity.

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