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1. Executive Summary

This document is the first action taken in order to implement the Life Cycle Assessment (LCA) for the NanoPack food packaging. The present report aims to provide the entire methodology which will be used to implement the LCA as well as defining the system boundaries and the related functional units, which are pre-requisites for proceeding with the assessment.

The main objectives of this deliverable are as follows:

- To introduce the LCA concept;
- To analyse and define the concept of system boundaries for this project;
- To explain the importance of a good selection of system boundaries and select the most appropriate option for this particular analysis;
- To analyse and define the concept of functional unit for this project;
- To highlight the importance of an accurate choice of functional units and select the best preference for study;
- To define the further steps of this assessment.

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2. Introduction

In accordance with the Description of the Action (DoA) of NanoPack project, the main objective of this Deliverable 7.1 (M8, first report), is to determine the scope and system boundaries of the Life Cycle Assessment (LCA). For this purpose, the main concept of the LCA approach, the LCA methodology (according to the ISO guidelines) and its application to the NanoPack project are described in the present document.

The LCA methodology presented in this Deliverable will be applied to the whole system proposed in NanoPack, which will consider the food packaging applications (fresh meat, baked and dairy products) related to all the models considered during the project, in order to validate the three pillars of sustainability: social, environmental and economical. Within this report, the major concern is the potential environmental impact from a LCA perspective.

3. Life Cycle Assessment methodology

LCA is a management tool to evaluate the environmental performance of products, goods and/or services. LCA considers the full life cycle of a product, from the extraction of resources and processing raw materials, through production, usage and recycling, to the final treatment of remaining waste (ISO, 2006). Briefly, LCA is an energy and material balance applied to the product's system, combined with an assessment of the potential environmental impacts related to the input and outputs to and from the product system. In this context, LCA provides a powerful framework for decision-making on important issues, e.g. product development, policymaking, strategic planning, among others.

ISO 14040 (2006) defines LCA as a technique for assessing the environmental aspects and potential impacts associated with a product or service, by:

- Compiling an inventory of relevant inputs and outputs within an appropriate system boundary;
- Evaluating the potential environmental impacts associated with those inputs and outputs;
- Interpreting the results of the inventory analysis and impact assessment phases with respect to the objectives of the study.

The methodology is delineated by the International Standards Organisation (ISO) and focused on the evaluation of the environmental burden of the studied process or product, according to different parameters such as waste produced or energy and materials consumed.

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To reach these objectives, information on inputs and outputs of the entire process need to be collected and processed. The standardised LCA framework encompasses four phases, as shown in Figure 1 (ISO, 2006):

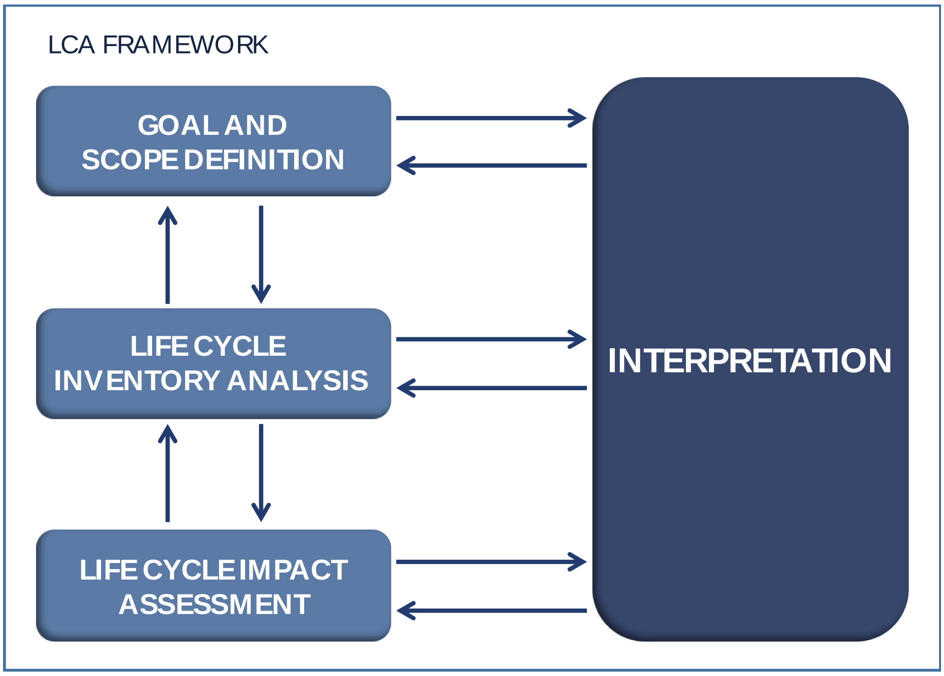

Figure 1. Stages of the Life Cycle Assessment (ISO, 2006).

I. **Goal and scope definition**: this is the first level of the study, and probably the most significant, because the purpose, scope and main hypothesis considered are defined in this stage.
Initially, the goal must be defined, as well as the set of decisions that will be made based on the results obtained. Secondly, the specific scope of the study is determined. The latter should be well defined to ensure that the extent, depth and detail of the study are compatible and consistent to address the stated goal. This action implies defining the system, its boundaries (conceptual, geographical and temporal), quality of data, the main hypothesis and the study limitations. A key subject for the scope is the definition of the functional unit (ISO, 2006). This is the unit of the product or service whose environmental impacts will be assessed and/or compared (it is usually expressed in terms of amount of product, but should be related to the amount of product needed to perform a given function).
The system boundaries outline the unit processes, which will be included in the system. This action is partially based on choices that should be detailed and justified to provide assurance in the analysis. The system boundaries should determine which stages, process units and flows will be included in the study (Figure 2).

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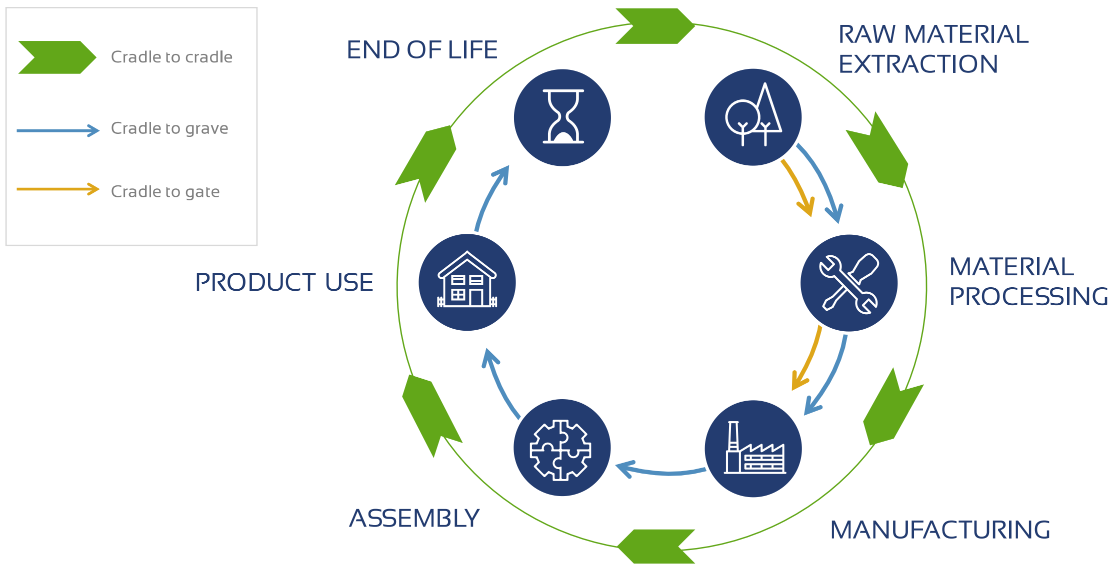

Figure 2. System boundaries definition (ISO, 2006).

II. **Inventory Analysis** (Life Cycle Inventory, LCI): this phase is a technical process of data collection, in order to quantify and measure the inputs and outputs of the system, as defined in the scope. In this stage, all emissions released to the environment (i.e. air, water, soil and solid waste) and resource consumption (e.g. energy and raw materials) along the entire production life cycle, as defined in the scope and with reference to the functional unit will be gathered (ISO, 2006). The main steps are: (1) data collection; (2) relevant and non-relevant element identification; (3) mass and energy balances, and; (4) system burdens allocation. LCI results are the aggregate of elementary flows entering the system and releasing into the environment. This is further explained in Chapter 7 below.

III. **Impact Assessment** (Life Cycle Impact Assessment, LCIA): during this stage, LCI results are translated, applying an impact assessment method, into environmental impacts at the midpoint or at the endpoint. Briefly, it is the procedure to identify and characterise the potential effects produced in the environment by the system analysed. Suitable software will be used for this purpose. These results will be assigned to the impact categories and potential environmental impacts will be calculated in each category, e.g. global warming, acidification, eutrophication, resource depletion, human health, cumulative energy demand, etc. Life Cycle Impact Assessment consists of four steps: classification, characterisation, normalisation and weighting (ISO, 2006).

IV. **Interpretation**: in this phase, the findings obtained are presented in a synthetic way, showing the critical sources of impacts and the possible options to reduce them. The interpretation is useful to indicate the results consistency according to all the aspects defined during the goal and scope stage. First of all, significant problems need to be identified (main process contributing most to the results).

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The interpretation requires consistency checks, ensuring that there is complete information. Sensitivity analysis should also be performed. The uncertainty and accuracy of results is also addressed at this stage.

These steps are clearly ordered; however, LCA studies are iterative, which means that LCA operations are repeated over and over again, to refine the results paying major attention to the most relevant processes, resources and emissions. These will be identified taking into consideration partners' expertise and supported by the assessment previously issued. The accuracy should be studied, and when necessary, corrections may be applied. It is a common practice to carry out one to three iterations before reaching the final results (as shown in Figure 3). Moreover, LCA is also preventing the shift of environmental burdens at geographic, life cycle stages and impacts.

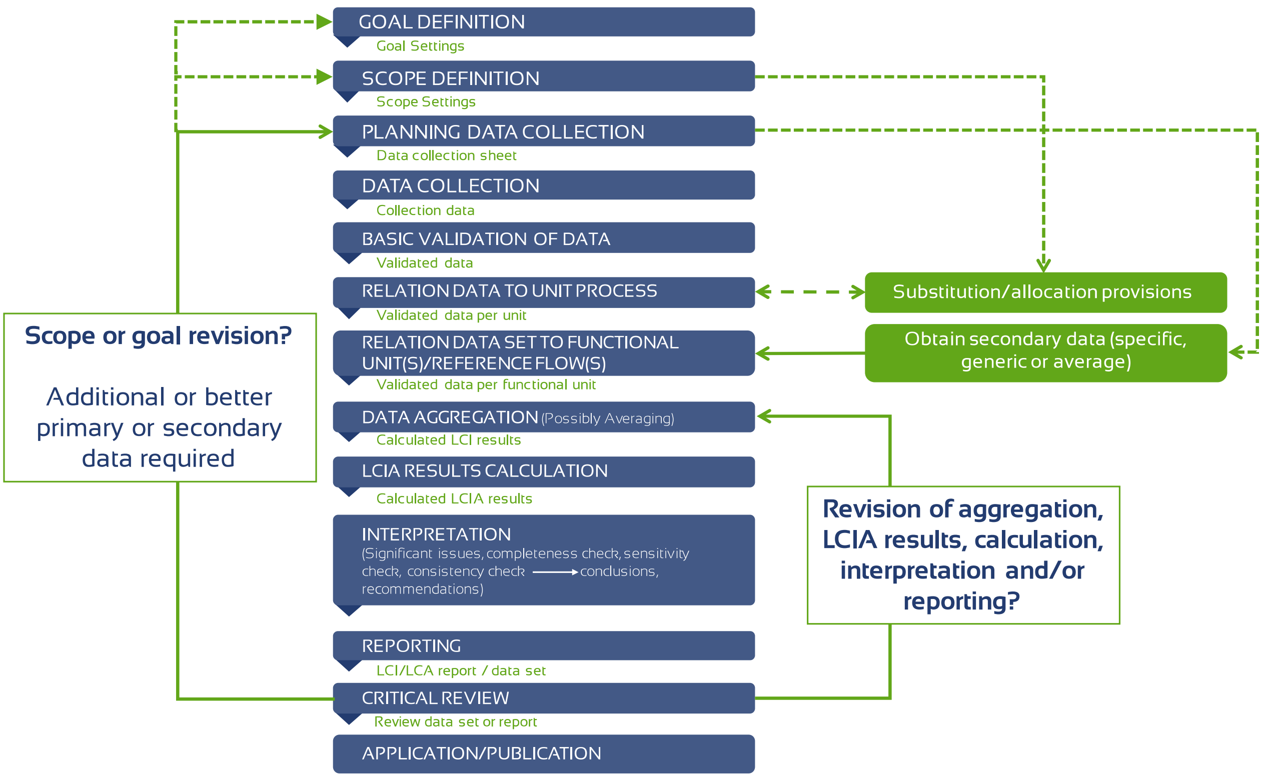

Figure 3. Details of the iterative LCA approach (ILCD, 2010).

LCA was promoted in different European directives as a robust quantitative tool, and a keystone in decision making by producers and stakeholders. It has been used to assess the environmental benefits and burdens related to packaging and mostly concerning the food and beverage industries (Latunussa, 2011).

One important aspect that will be faced along the project is the consumer behaviour, which deeply influences the outcome of a LCA. Many studies have shown that indirect impacts are much higher than those undertaken to minimize the direct ones (Wikström et al., 2016).

Previous LCA studies on packaging solutions, reported in the literature, present different analyses, addressing multiple options for the considered product (Wikström et al., 2016). On the other hand, LCA analyses on the

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nanotechnologies are problematic due to some probable limitations, such as reliance on data from existing industries, difficulties related to boundaries and functional unit definition (Wender, 2013). However, during recent years, the application of this kind of assessment at the nascent stages of nanotechnology development has promoted identification of serious environmental consequences before they pose a threat to human and environmental health. Once identified, threats posed by emerging technologies may be mitigated through integration of environmental concerns into the technical research agenda (Wender, 2013; Upadhyayula et al., 2012; Theis et al., 2011).

4. LCA approach in the NanoPack project

4.1. Goal and scope

This study is carried out in order to assess the environmental benefits and burdens of NanoPack packaging, following an LCA approach. Concisely, this analysis aims to: i) assess the environmental performance of the treatment and recovery system of each NanoPack stream (i. e. for baked products, fresh meat and dairy products), in order to understand if the benefits arising from the material and energy recovery are offsetting the burdens; ii) to compare the NanoPack concept with the conventional recycling and valorisation processes for these flows, e.g. reuse or recycling, from an environmental performance perspective, and iii) to compare the HNTs-based antimicrobial materials with equivalent products in the market, e.g. Ag-Polymers composites, clay-filled composites, in order to identify the different environmental benefits of the proposed technology.

The goal is to evaluate the of environmental impact of HNTs-based antimicrobial films production, bioactive food packaging production and the use of the produced Nano-films as packaging materials for fresh meat, dairy and bakery products.

The geographical scope of the study will be defined in collaboration with the rest of the partners. Different scenarios could be set at European level, where the NanoPack material could be potentially processed without covering long distances.

4.2. Functional unit

The functional unit is the basis for comparisons between different systems in LCA (ISO, 2006). An appropriate selection of a functional unit is crucial, because different functional units can lead to different results for the same product system. The functional unit is usually referred to the output stream of the production system or to the function performed. Nevertheless, when assessing packaging systems, the considered functional unit is normally the amount of food or beverage packed in a certain region (e.g. number of kilograms in case of food, litres in case of beverages); this is the case of some recent studies on packaging procedures (Schäfer, 2017; Corrugated Packaging Alliance, 2017; Latunussa, 2011).

In the case of the NanoPack project, the study will focus on three different products (bakery, dairy and fresh meat products) with a breakthrough material, and where one of the main parameters to be assessed is the shelf life of the product to be packed with HNTs-based antimicrobial film, which is the significant added value of this technology compared to the current market solutions.

In this context, taking into account the previous considerations about other LCA studies and the main objective of the NanoPack project, **1 kg of bakery or fresh meat products packed** and **1 L of dairy product packed** over product specific shelf life for each food product are the selected functional units. The specific time frame for each product type will be defined during the next stages.

4.3. System boundaries

As stated, the boundaries specify the unit processes that will be considered in the studied analysis. The system boundaries are defined through the stages of the products' life cycle. It is essential to define where to stop tracking energy and material uses of upstream processes, otherwise the analysis would be endless and the environmental impacts would be altered in the several processes studied. These boundaries shall be adapted to the potential accuracy that could be obtained from the available data.

Some LCA analyses, within the packaging context, consider various system boundaries taking the materials, production and location into consideration, some of them are excluding the usage phase because it is quite difficult to measure, likewise the second packaging procedures (Latunussa, 2011). Apart from a few exceptions, the system boundaries concerning packaging for nanotechnology studies, are most commonly implemented using the approach, which considers any step, as shown in Figure 4 (Wender, 2013).

Therefore, for NanoPack project, the system boundary **cradle-to-grave** will be implemented. According to the received data, and its quality, some steps in the life cycle might be either approximated or taken as the standard one from the database present in Simapro 8 software (ecoinvent library).

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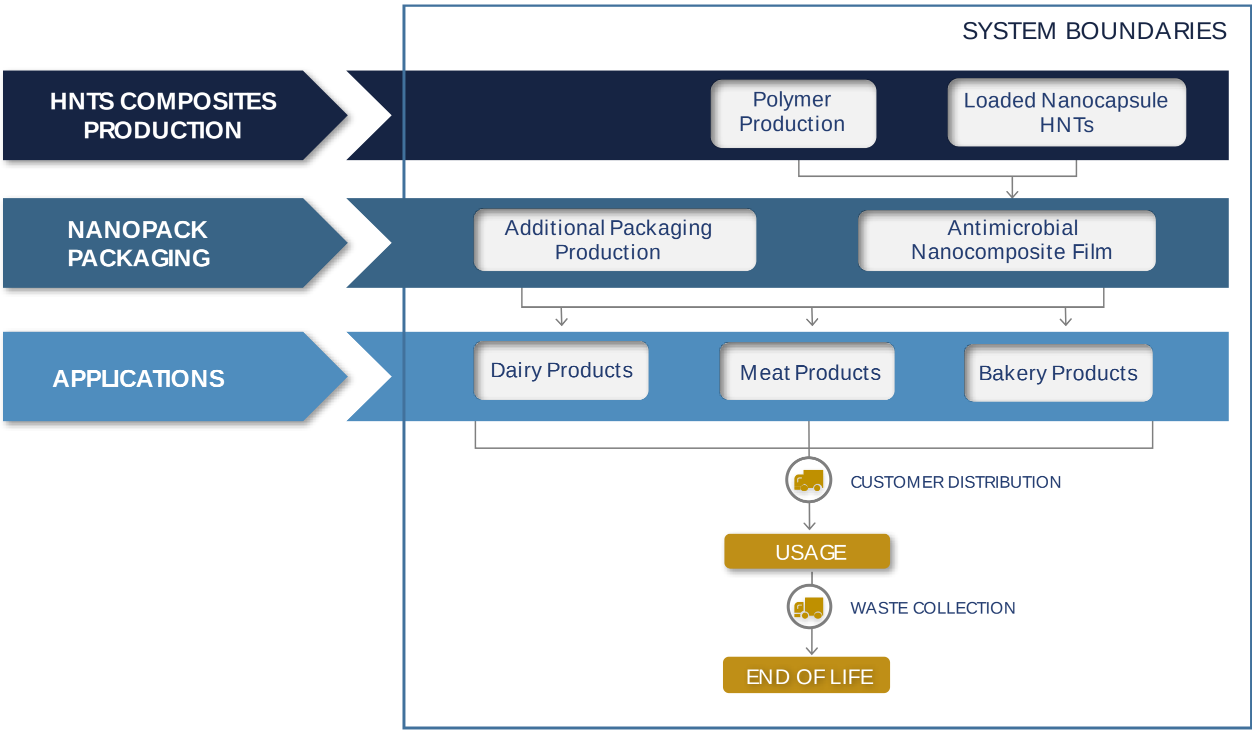

Figure 4. LCA System boundaries.

5. Data quality and critical review

Data quality requirements, such as consistency, timeliness, same geographical coverage, precision, completeness, representativeness, source of the data, and uncertainty will be taken into account for this project.

On the other hand, to verify the methods used, data transparency and consistency, a critical review, in accordance with the ISO guideline, will be carried out (ISO, 2006). For this aim, two people (from the consortium), who will conduct the additional review, will be chosen during the progress of the project.

6. Allocation

When the LCA methodology is applied to complex systems, which involve several products and/or recycling treatments, the burden allocation procedure should be defined. Concerning the systems included in this project, the 'cut-off' methodology defined by Ekvall & Tillman (1997) will be used. Regarding this, the environmental burdens must be assigned to the system, which is directly responsible.

In the 'cut-off' approach, the packaging procedure is relevant since this may be a way to alter the economic impact of the system, as often the production of material has different costs and impacts depending on the material used and the ones finally produced.

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7. Inventory analysis

As previously mentioned, in LCI stage, all emissions released into the environment, specifically to the air, water, soil and solid waste, and resource consumption (energy and raw materials) through the entire life cycle of the processes included in NanoPack project and in relation to the functional units will be grouped in an inventory. For this purpose, a systematic template for data collection was prepared (see Annex section). This document will be useful for integration of the mass and energy data on each single process into the three main products lines.

There are different options for obtaining data for the studies. In this case, a huge exchange of information will be made between the partners responsible for the LCA study and all the partners involved in the pilot tests, at which stage most of the data required for the analysis can be collected and exchanged. This information will be updated continuously. Apart from that, the study will be backed up by the ecoinvent databases and other LCI sources.

8. LCIA methodology

In this phase, all listed inputs and outputs referred to the functional units will be associated to specific environmental impact categories, e.g. global warming potential, acidification, eutrophication potential, human toxicity, resource depletion, cumulative energy demand, among others, supported by characterisation factors (ISO, 2006).

In this LCA study, the Centre for Environmental Studies (CML) 2000 method will be applied to determine the environmental profiles of the processes involved, due to its uses of multiple indicators at midpoint level. The CML method is comprised of several impact categories, such as global warming potential, acidification, eutrophication, ecotoxicity, human toxicity and abiotic depletion (Frischknecht et al., 2007). These impact categories can be considered as single impacts, resulting in an absolute figure or they could be normalized. This method will, therefore, provide detailed information about several environmental impact categories related to climate systems with a relatively low level of uncertainty in the quantification method. The environmental impact categories assessed in the CML 2000 method are a selection of the most commonly used indicators in LCA studies. In the case of NanoPack project, the choice of the valuation system will be decided later during the progress of the project.

The potential environmental impacts will be evaluated using the SimaPro® 8 (PRé Consultants) software and ecoinvent v3.3 databases, as well as other similar sources (Weidema et al., 2013). This analytical tool is in accordance with ISO 14040 standards (ISO, 2006). SimaPro® is widely used and is recognized as the most trustworthy in LCA studies. It will be applied to the inventory and impact assessment phases due to its reliability, interactive potential and facility to adapt and change.

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9. Conclusions

This report is the first step towards developing a full-competence technical LCA. This document explains the scope and the methodology to obtain the results expected. One of the strengths of LCA is that it provides quantitative results, and combined with financial modelling it can lead to complete information on how feasible the studied technology is from all points of view. Considering that this is a preliminary study, the system boundaries and functional units can be susceptible to adjustments based on the data that will be received, mainly from the pilot lines.

Throughout the LCA process, the general environmental impact of the proposed system will be assessed. In order to do so, we have established some quantitative targets that could also be applied as performance indicators of the environmental assessment.

It is important to highlight that the concept is clearly attained and the inputs for the assessment are coherent and well-designed processes, therefore the LCA meets this objective, not only with regard to the laboratory and scale-up work, but also regarding the study itself, considering the assumptions that need to be taken. Regarding the assumptions, it is important to be transparent and to deal with definition issues.

The definition of the overall system is basic to produce an understandable and comparable assessment. This Deliverable defines the NanoPack system (boundaries, allocation options and functional unit) in order to structure the first idea on which the whole LCA will build. Even though some of the questions have been left open for discussion with other members of the consortium, all of them have been pointed out and will be fully specified for the final report.

It is important to highlight that the present report is considered a living document; it will be updated again twice as the project progresses (end of M20 and M36). Screening analyses will be presented before the final assessment, in order to provide preliminary recommendations related to the potential environmental impacts found.

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Annexes

The data collection template (draft) for the LCA, already shared with the corresponding partners is presented below.

Task:	Partner:	WP:
Description of the process:		

Parameter	Unit	Value	Reference
Estimated useful life duration of the production plant	yr		
Total amount of annually used feedstock (main input)	t/yr		
Annual main production capacity	t/yr		
Main product, amount (please, specify)	kg/yr		
By-product 1, amount (please, specify)	kg/yr		
By-product 2, amount (please, specify)	kg/yr		
By-product 3, amount (please, specify)	kg/yr		
By-product 4, amount (please, specify)	kg/yr		
Annual amount of wastewater (please, specify)	m3/yr		
Annual amount of air emissions (please, specify)	m3/yr		
Annual amount of used oil (please, specify)	kg/yr		
Annual amount of solid waste (please, specify)	kg/yr		
main raw materials used in construction - steel	t		
main raw materials used in construction - copper	t		
main raw materials used in construction - (please, specify)	t		
main raw materials used in construction - (please, specify)	t		
Operating hours per year	h/yr		

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Mass and energy streams per unit process			Process 1/ Step 1		Process 2/ Step2		Process 3/ St
Inputs		Unit	Value	Reference	Value	Reference	Value
Used feedstocks							
	Feedstock (specify % by wt)	t					
Auxiliary materials							
	Water (specify source)	kg					
	Other auxiliary (please, specify)	kg					
	Other auxiliary (please, specify)	kg					
	Other auxiliary (please, specify)	kg					
	Other auxiliary (please, specify)	kg					
	Other auxiliary (please, specify)	kg					
	Other auxiliary (please, specify)	kg					
	Other auxiliary (please, specify)	kg					
	Other auxiliary (please, specify)	kg					
Process energy							
	Net Electricity consumption	kWh					
	Net Steam consumption	kg					
	Steam consumption (please specify steam parameter temperature, pressure)	kg					
Outputs							
Main product							
	Main product (please, specify)	kg					
By-products							
	By-product 1 (please, specify)	kg					
	By-product 2 (please, specify)	kg					
	By-product 3 (please, specify)	kg					
	By-product 4 (please, specify)	kg					
Emissions							
	Air emissions (please, specify)	mg/m3					
	water emissions (please, specify)	mg/L					
	Soil emissions - (please, specify)	mg					
Waste							
	Wastewater	m3 or L					
	Oil waste (please, specify)	kg					
	Other liqiud or solid residues (please, specify)	kg					
Other							