Deliverable D4.2

Scientific Case Study Reports and Evaluations, ILCD datasets

Grant Agreement number:	**265096**
Project Acronym:	**LCA to go**
Project title:	**Boosting Life Cycle Assessment Use in European Small and Medium-sized Enterprises**
Funding Scheme:	Small or medium-scale focused research project
Project starting date:	January 1, 2011
Project duration:	48 months
Delivery date:	September 17, 2013
Deliverable number:	D 4.2
Workpackage number:	4
Lead participant:	Tele and Radio Research Institute (ITR)
Nature:	Report
Dissemination level:	PU
Lead Author:	Janusz Sitek (ITR)
Project co-ordinator:	Karsten Schischke Fraunhofer IZM Tel: +49-30-46403-156 Fax: +49-30-46403-211 E-mail: schischke@izm.fhg.de
Project website:	www.LCA2go.eu

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Abbreviations	
B2B	Business-to-Business
CFP	Carbon Footprint of Products
ELCD	European Life Cycle Database
EU	European Union
GHG	Greenhouse Gases
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data System
KEPI	Key Environmental Performance Indicators
LCA	Life Cycle Assessment
PCB	Printed Circuit Board
PCF	Product Carbon Footprint
PCR	Product Category Rules
PWB	Printed Wiring Board (PCB)
WP	Work package
CEO	Chief Executive Officer
PE	Polyethylene
PLA	Polylactide; Polylactic Acid
PET	Polyethylene Terehptalate
PBS	Polybutylene Succinate
PHB	Polyhydroxybutyrate
HDPE	High Density Polyethyelene
LLDPE	Linear Low Density Polyethylene
LDPE	Low Density Polyethylene
PVC	Polyvinyl Chloride
KEPI	Key Environmental Performance Indicator
LCC	Life Cycle Costing
SME	Small and Medium sized Enterprise
DQI	Data Quality Indicator
ISO	International Standard Organisation
PLLA	Poly L-lactic acid
CED	Cumulative Energy Demand

TPS	Thermoplastic Starch
GW	Global Warming
OD	Ozone Depletion
AC	Acidification
POF	Photochemical Oxidant Formation
EU	Eutrophication
AD	Abiotic Depletion
EPD	Environmental Product Declaration
POCP	Photochemical Ozone Creation Potential
GHG	Green House Gases
NREU	Non-renewable Energy Use
ABS	Acrylonitrile-butadiene-styrene
MBS	Methyl methacrylate-butadiene-styrene
CPE	Chlorinated polyethylene
EVA	Ethylene-vinyl acetate polymer
UCTE	Union for the Co-ordination of Transmission of Electricity
OPP	Oriented PolyPropylene
MEG	MonoEthylene Glycol

Executive Summary

The D4.2 deliverable is the outcome of all Tasks in WP4. It contains conclusions from each case study realized according to the Scientific Case Study Concepts described in the deliverable D4.1 for each sector. It summarize the achievements of the case study implementation, lessons learned, targets achieved and inform about needs for further web tool and methodological revisions. The results and conclusions presented in the D4.2 are the input for the beta version of the web tool and a basis for the dissemination activities in WP6.

The D4.2 deliverable comprises from 2 parts: the first one – concerned mainly the software related aspects and the second one contain the scientific case study results and achievements from each sector.

ILCD compatible datasets for those case studies implementing a full-scale LCA are documented in D4.3 as part of the 33 LCA datasets and 100 sub-datasets the project is obliged to deliver under D4.3.

Part 1 - Software related aspects.

1.1. VALSAY Case Study on bio-based plastics

Development of the sectoral software tool for bio-based plastics

The development of the bio-based plastics tool begun with a first approach (Figure 1) considering the converting point of view proposed in the first version of CEO summary.

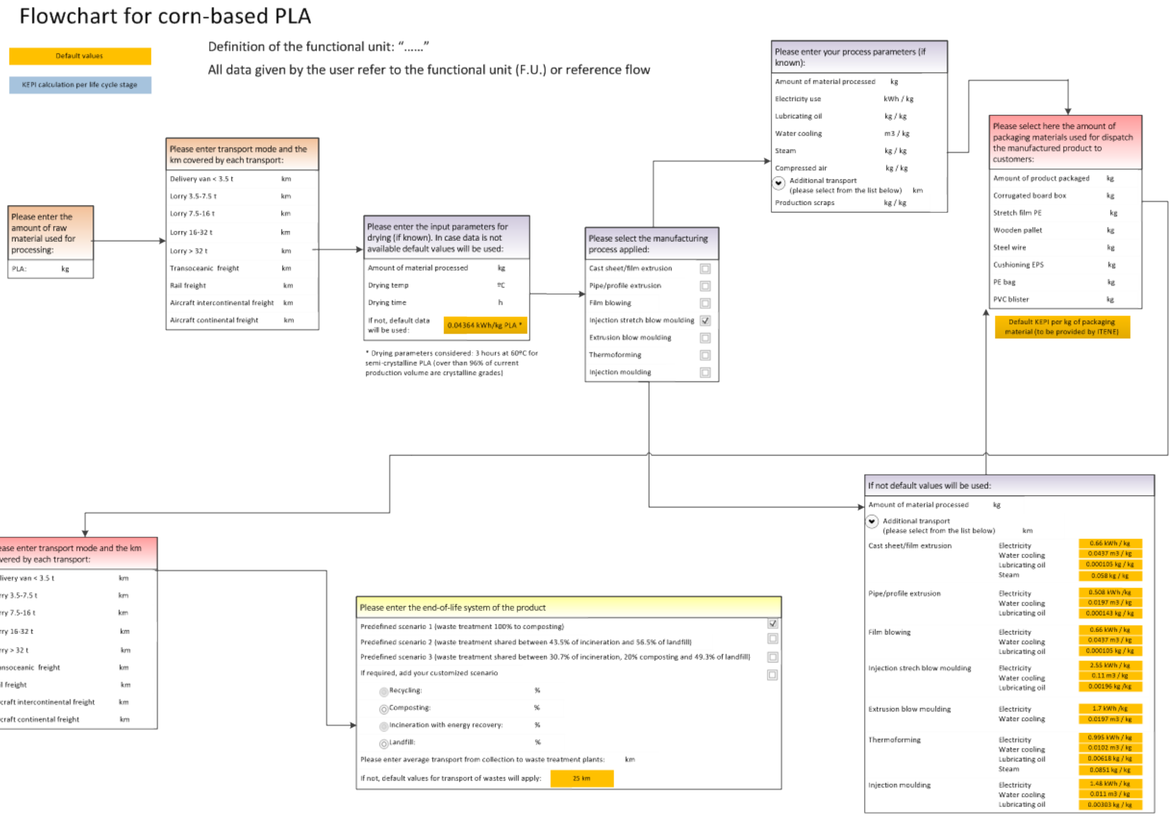


Figure 1. First layout suggested for the LCA to go bio-based plastics sectoral tool (example for PLA)

The first layout (Figure 1) was complemented with a continuous exchange with Simpple and feedback from Valsay. It was also considered the participation of ITENE's senior experts in the area of plastic manufacturing (although not in LCA issues), which complemented the points of view of Simpple, Valsay and ITENE's Sustainability Department.

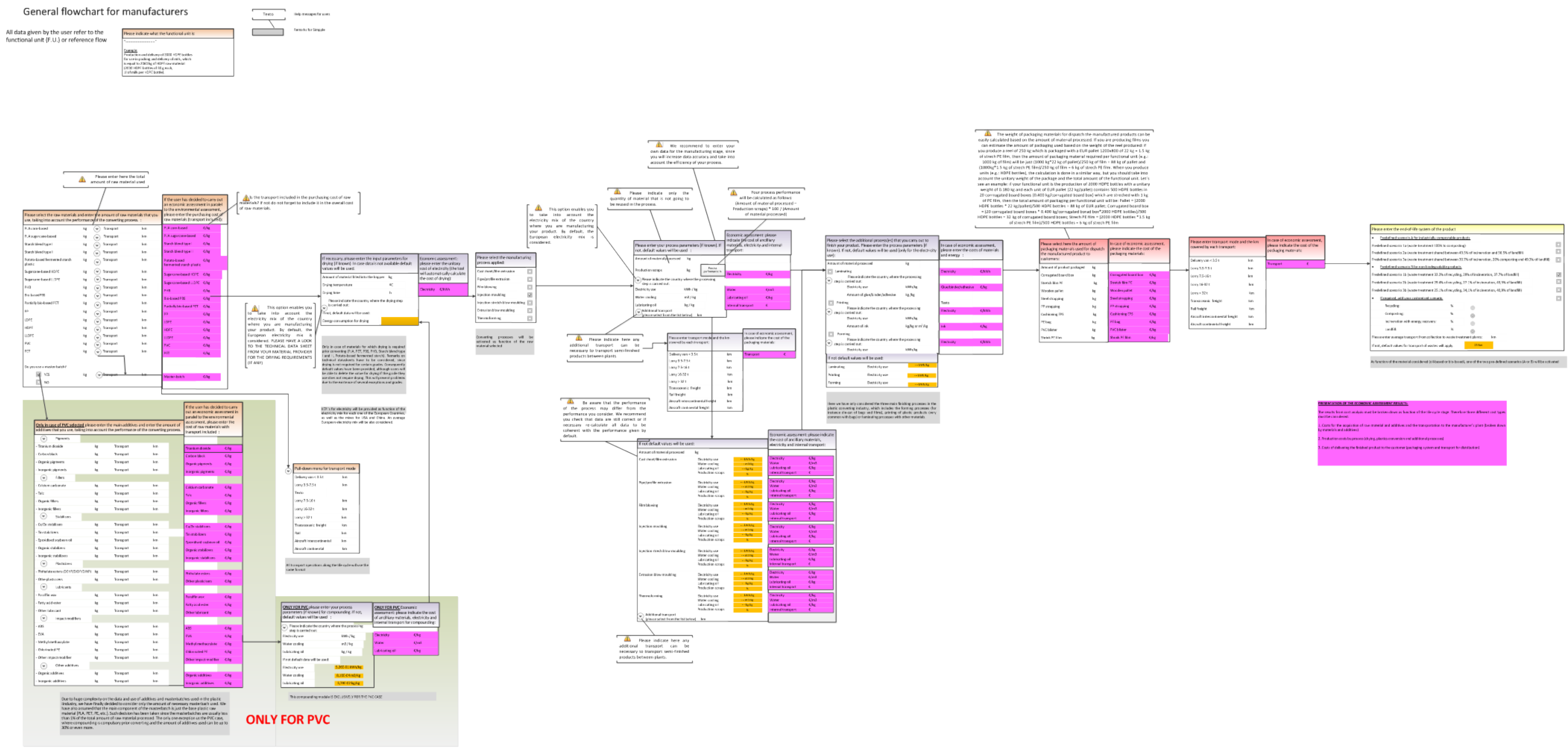


Figure 2. Final layout suggested for the LCA to go bio-based plastics sectoral tool (general template for all the materials)

As a result of this work, an advanced version of the software layout was prepared by ITENE aimed at the implementation of the first beta version of the software tool (Figure 2). Both bio-based and oil-based plastics were considered in the software layout which was comprised by several modules:

1) Raw materials module (Figure 3): where the users will enter their own data about amount of raw materials used to manufacture the product as well as the transport requirements necessary to deliver the raw materials to the plastic converter. Users will also be asked about the use of masterbatch (if used), but only the amount main component of the masterbatch is required (usually the base plastic raw material like PE, PLA, etc). Such decision was taken since masterbatches are usually less than 1% of the total amount of material processed (except for PVC). Raw material purchasing costs (including transport) will be also considered if the user decides to carry out a gate-to-gate cost assessment.

2) Processing module (Figure 4): this module is specifically dedicated to the different converting processes for both bio-based and oil-based plastic materials. The module covers from preparation processes like drying, which is a common issue for bio-based plastics like PLA (NatureWorks LLC, 2013) although for some oil-based as well (e.g.: PET (Plastics Technology, 2013)). The manufacturing module contains also main converting processes which are also connected to each one of the materials, since processability may change as function of the materials selected. This resulted in a matrix of processes and materials which is described in Table 1. Internal transport processes between plants were also considered, since some plastics products are delivered in intermediate form to other production plants (e.g.: transport of injection moulded PET pre-forms to a stretch blow moulding machine to produce PET bottles). Moreover, the most common finishing processes are also considered: (a) laminating, (b) printing and (c) forming with die-cut. In the processing module users may decide either between use their own data or default data. The aim of use default data is in order to make easier the modeling for non-LCA experts, although use own data is recommended for more accurate results. Users are also able to enter costs related to electricity, water, transport, etc. if a gate-to-gate cost assessment is preferred.

3) Distribution module (Figure 5): the distribution module covers all the materials and transports necessary to deliver finished plastic products to customers. The module was comprised by two sub-modules: (a) packaging materials and (b) transport processes. Users only need to enter the amount of packaging materials used from a pre-defined list plus the distance for delivery and the product weight loaded.

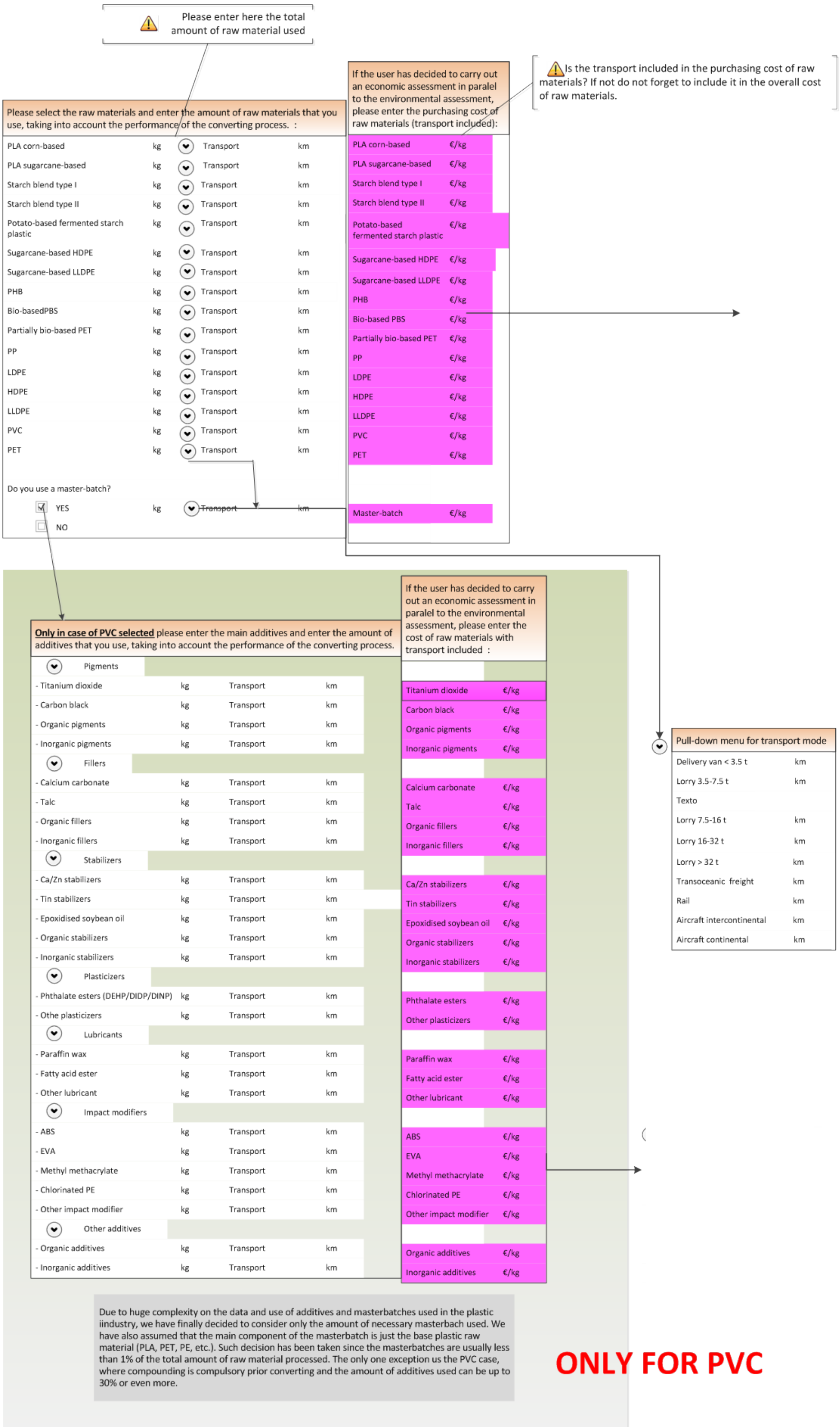
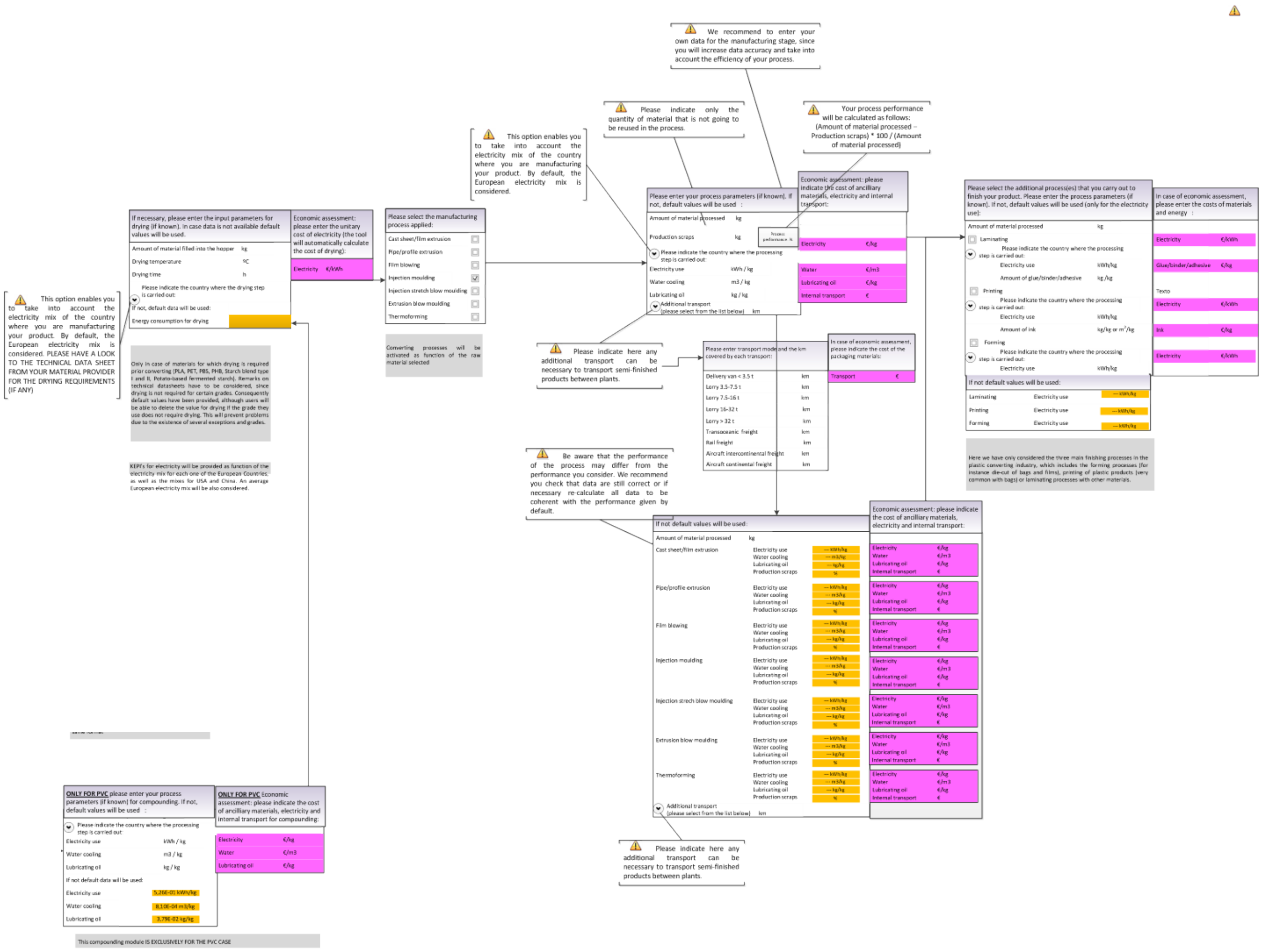


Figure 3. Details on the raw materials module for the final software layout



ONLY FOR PVC

Figure 4. Details on the processing module for the final software layout

Table 1. Matrix of materials and converting processes

	Material	Master Batch		Additionnal processes	Converting processes						
		Compound	Material base	Drying of pellets	Cast film /sheet extrusion	Extrusion (pipe, profile)	Film Blowing	Injection blow moulding	Extrusion blow moulding	Thermoforming	Injection Moulding
Bio-based plastics	Polylactic acid, corn-based	-	-	x	x	x	x	x	x	x	x
	Polylactic acid, sugarcane-based *	-	-	x	x	x	x	x	x	x	x
	Starch blend type I	-	-	x	x	-	x	-	-	-	-
	Starch blend type II	-	-	x	x	-	x	-	-	-	-
	Potato-based fermented starch plas	-	-	x	x	x	x	-	-	x	x
	Sugarcane-based HDPE	x	LDPE	-	x	x	x	-	x	x	x
	Sugarcane-based LLDPE	x	LDPE	-	x	x	x	-	x	x	x
	PHB	-	-	x	x	-	x	-	-	x	x
	Partially sugarcane-based PET *	(x)	PET	x	x	x	x	x	-	x	x
	PBS *			x	x	x	x	-	x	x	x
Oil based plastics	PP	x	PP	-	x	x	x	x	x	x	x
	LDPE		LDPE	-	x	x	x	-	x	-	x
	HDPE		LDPE	-	x	x	x	-	x	x	x
	LLDPE		LDPE	-	x	x	x	-	x	x	x
	Rigid PVC compound	x	PVC	-	-	x	-	-	x	x	x
	Flexible PVC compound	x	PVC	-	x	-	x	-	-	-	-
	PET	(x)	PET	x	x	x	x	x	-	x	x

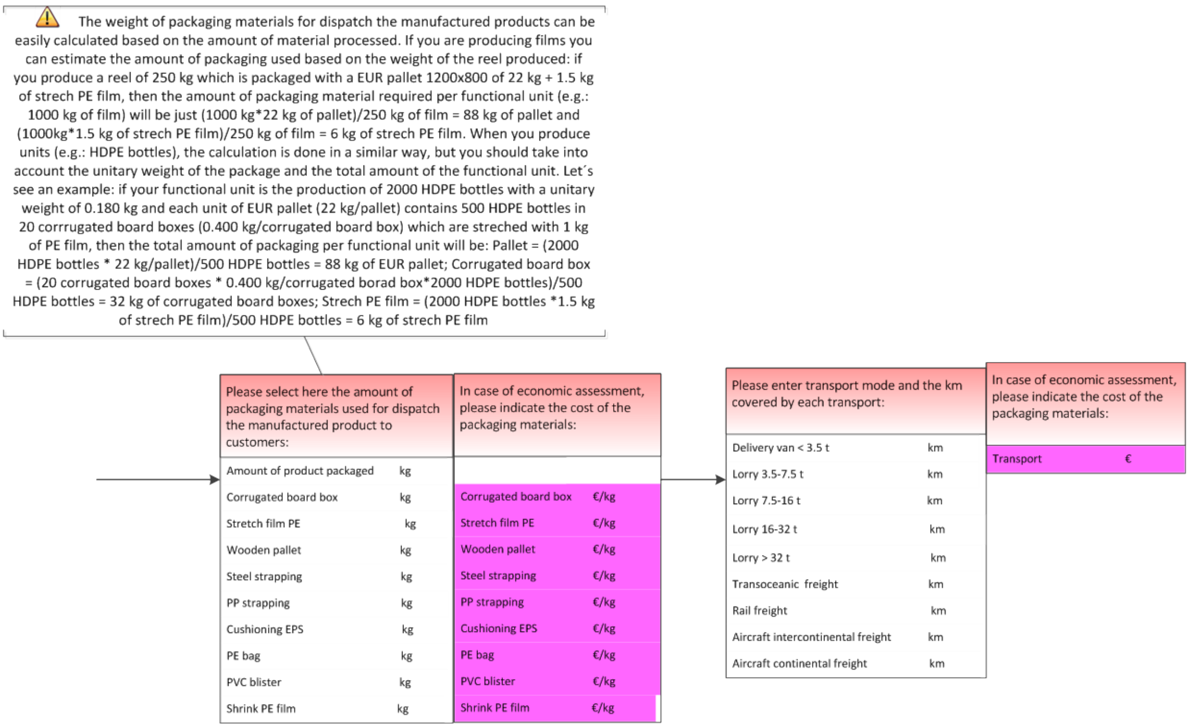
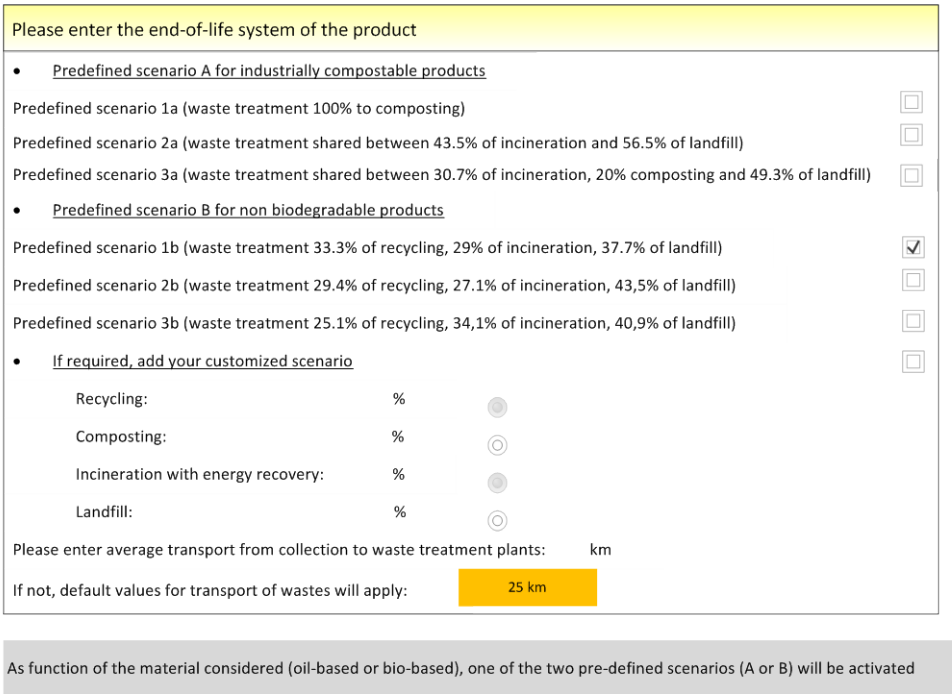


Figure 5. Details on the distribution module for the final software layout

4) The end-of-life module (Figure 6): Even though in the Deliverable 2.1 of LCA to go project it was finally concluded that end-of-life stage will not be covered in the bio-based plastics sector due to the lack of reliable data, it was finally decided to include this step based on estimations from scientific literature. A deep research was made by ITENE in that field during the first

quarter of 2013, which resulted in a set of estimated KEPI's for the end-of-life of several bio-based plastics. However, these KEPIs only covered impacts related to Climate Change (in kg CO_2-eq) due to the scarce of data available for other impact categories beyond that. A distinction was made as function of the biodegradability of the materials which resulted in a matrix of materials and possible end-of-life routes (Table 2).

It should be also pointed out that the use stage was directly omitted from the software since bio-based plastic products are not usually energy consuming.


Please enter the end-of-life system of the product

- Predefined scenario A for industrially compostable products

Predefined scenario 1a (waste treatment 100% to composting)

Predefined scenario 2a (waste treatment shared between 43.5% of incineration and 56.5% of landfill)

Predefined scenario 3a (waste treatment shared between 30.7% of incineration, 20% composting and 49.3% of landfill)

- Predefined scenario B for non biodegradable products

Predefined scenario 1b (waste treatment 33.3% of recycling, 29% of incineration, 37.7% of landfill)

Predefined scenario 2b (waste treatment 29.4% of recycling, 27.1% of incineration, 43,5% of landfill)

Predefined scenario 3b (waste treatment 25.1% of recycling, 34,1% of incineration, 40,9% of landfill)

- If required, add your customized scenario

Recycling: %

Composting: %

Incineration with energy recovery: %

Landfill: %

Please enter average transport from collection to waste treatment plants: km

If not, default values for transport of wastes will apply: 25 km

As function of the material considered (oil-based or bio-based), one of the two pre-defined scenarios (A or B) will be activated

Figure 6. Details on the end-of-life module for the final software layout

Table 2. Matrix of materials and end-of-life routes

	Material	Predefined scenario A	Predefined scenario B
Bio-based plastics	Polylactic acid, corn-based	x	-
	Polylactic acid, sugarcane-based	x	-
	Starch blend type I	x	-
	Starch blend type II	x	-
	Potato-based fermented starch	x	-
	Sugarcane-based HDPE	-	x
	Sugarcane-based LLDPE	-	x
	PHB	x	-
	Partially sugarcane-based PET	-	x
	PBS	x	-
Oil based plastics	PP	-	x
	LDPE	-	x
	HDPE	-	x
	LLDPE	-	x
	Rigid PVC compound	-	x
	Flexible PVC compound	-	x
	PET	-	x

After sending the final software layout programming of the tool begun in May 2013. During the programming of the tool, several changes were made compared to the final layout sent by ITENE. The most important ones were:

a) The gate-to-gate economic cost module (LCC) was completely separated from the environmental analysis (Figure 7), in order to reduce the complexity of programming of the tool as well as to keep the same scheme as in other sectors.

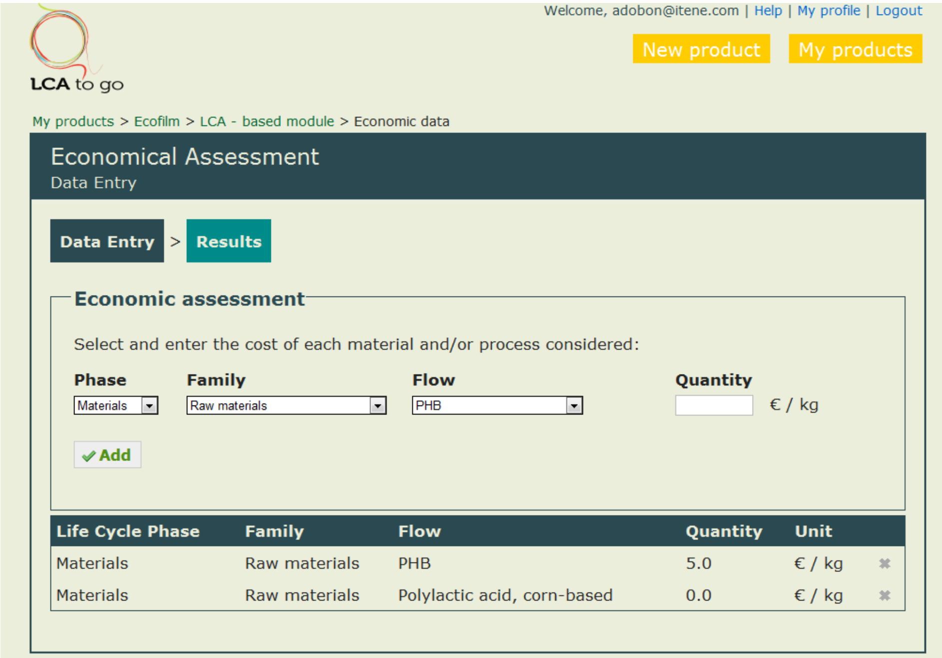


Figure 7. Gate-to-gate economical assessment module for bio-based plastic sector (Beta version July 15th 2013)

b) The raw material data entry module was simplified compared to the original final layout. This change was made in order to allow enter data for main raw materials, masterbatches and additives separately (Figure 8).

c) The raw material module was also split in two parts: On the one hand, the raw material data entry module, where users can enter data about main raw materials as well as use of masterbatches[1] and/or additives[2] (Figure 8). On the other hand, a specific transport data entry module was created, where users should enter data about transport for raw material acquisition by selecting

[1] Masterbatches are a concentrated of certain materials which are added to the plastic product in very low proportions to provide certain characteristics. The most common masterbatches are those related for instantce to colouring of the plastics. The amount of additive/colourant is added in very low proportions (10% maximum) to the base raw material in which is embedded.

[2] Additives are usally added in larger proportions, like in the case of PVC, where the percentage of additives is around 20-30% in mass.

between different transport modes, transport distances and payload transported (Figure 9).

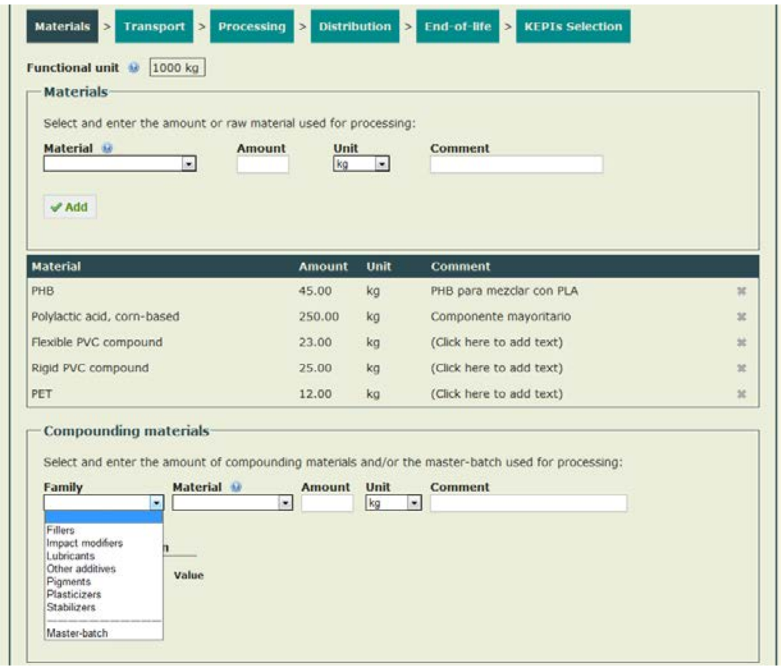


Figure 8. Raw material data entry module (Beta version July 15th 2013)

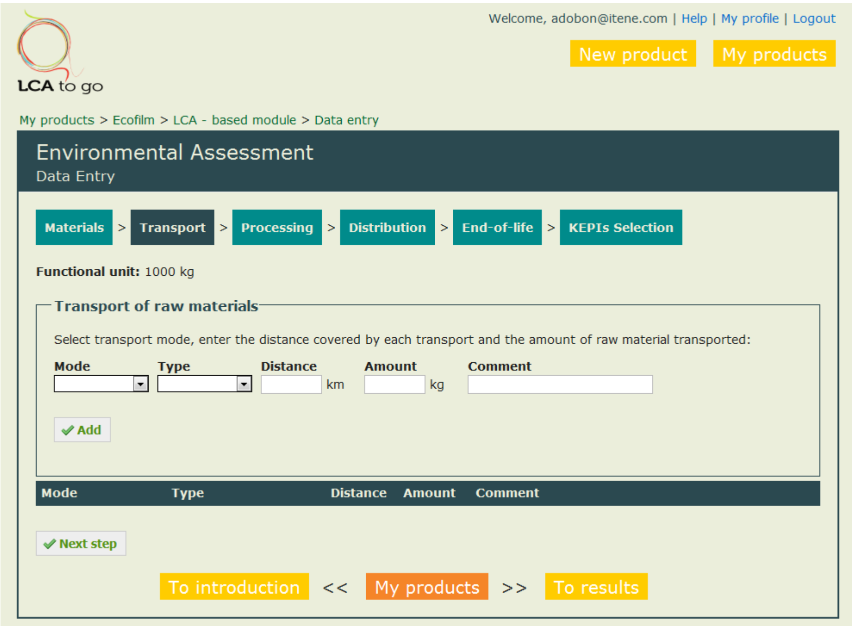


Figure 9. Transport for raw material data entry module (Beta version July 15th 2013)

As a result of all these changes a final beta version of the bio-based plastics software tool was ready at the end of July 2013. Table 3 summarizes the level of implementation of SME needs in accordance with Valsay's case study.

1.2. CDAMC Case Study on Industrial Machines

1.2.1. Objectives

The main objectives of the Industrial Machines sector case studies was to:

- Identify suitable case study candidates from the Industrial Machines sector.
- Test the methodological approach as previously defined.
- Gather actual data from real SMEs under normal working conditions.
- Develop new ILCD datasets from the case study work.
- Feedback results of the case study work to the SMEs to determine what improvements could potentially be implemented.
- Carry out workshops with the SMEs to ensure that they fully understand the process and what improvements could be implemented.
- Use the case study process to influence the development of the LCA to go tool.

1.2.2. Methodology

The scientific methodology adopted was a 2 stage process. In all cases references were made to ISO14955 parts 1 and 2 for guidance.

The methodology developed was based around carrying out a needs assessment, taking case study feedback into consideration as well as legislation and standards. Figure 10 illustrates the development of the methodological approach.

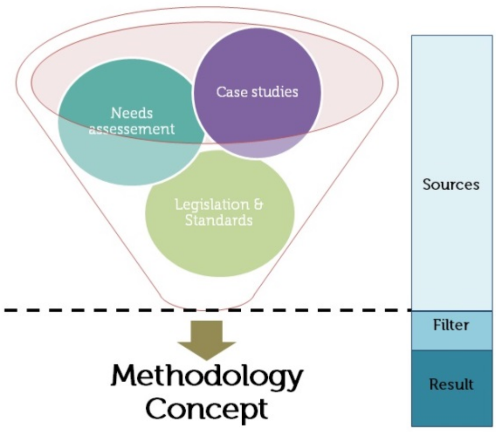


Figure 10. Development of the methodology concept

The 2 stage approach was considered the most appropriate approach for this sector as developed in Workpackage 2. Figure 11 shows a flow chart of the 2 stage process. Step 2 is now just one step and not divided into step 2A and 2B. 2A should focus on the full life cycle of a machine tool and 2B just on the energy consumption. In the tool it now should be possible to focus on one life cycle phase only and therefore 2A & 2B merged to Step 2.

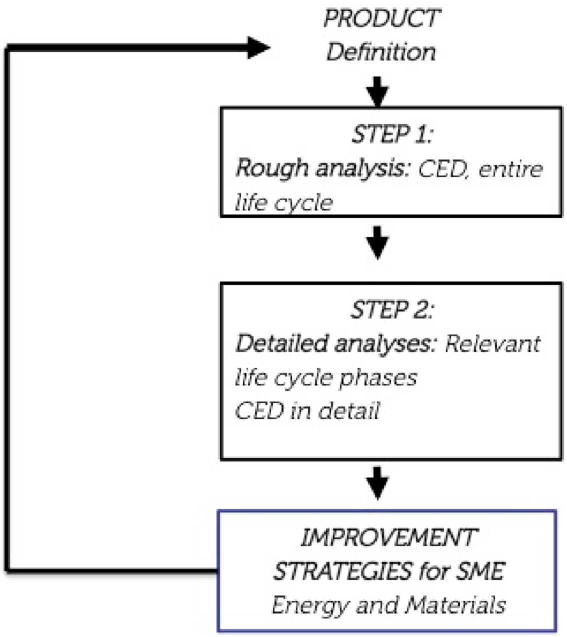


Figure 11. Webtool flow

CED (Cumulative Energy Demand) was selected as the most appropriate quantiative measurement method to meet the needs of SMEs in this sector. By using CED it makes the tool more universal and should result in more companies engaging with the method.

As detailed in Figure 11 the user carries out an initial study of the 5 life cycle phases as used in the case of industrial machines:

1. Materials
2. Manufacture
3. Distribution
4. Use
5. End of life

The quality of the data at this stage is expected to be at a minimum illustrative or indicative according to the data quality indicators defined in Deliverable 4.1. For the second stage the relevant phases from stage 1 are focused on, and the quality of the data is expected to be robust. Figure 12 gives an example of the output from stage 1. In this particular example the material and use phases will be investigated in more depth with data that is robust from a data quality point of view.

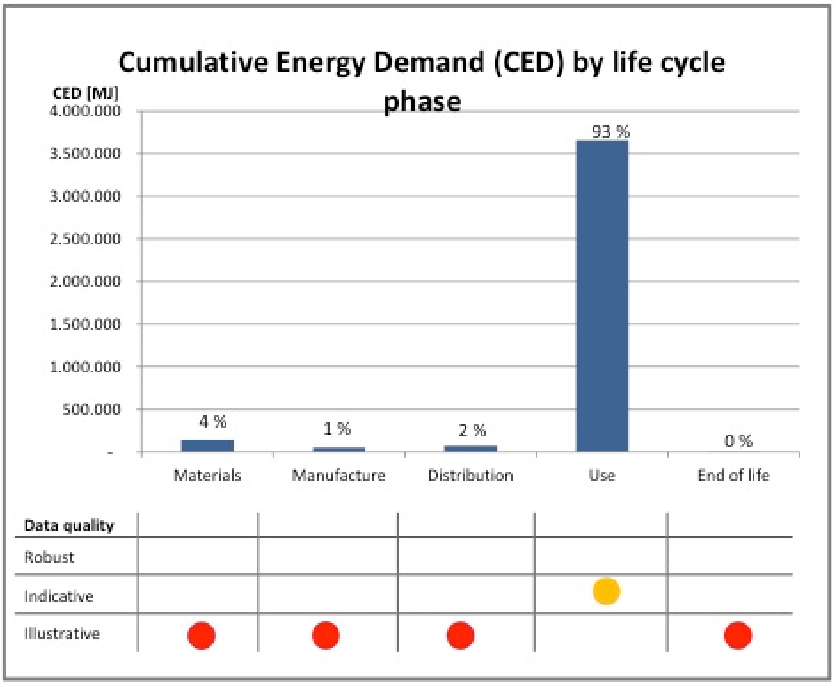


Figure 12. Result stage 1: Environmental profile including quality indicator.

Figure 13 gives an illustration of the output from stage 2 of the study using data that is considered robust from a data quality point of view. In this example the materials and use phase were investigated in phase 2 and the outcome is illustrated as shown. The methodology as summarised above and described in detail in deliverable 2.2 worked well in practice with the case study SMEs. The data quality process is described in detail in deliverable 2.2 however in summary Illustrative data can be described as general information gathered e.g in terms on energy consumption about the energy balance of an entire plant used to illustrate the energy demand of a specific product within the plant. Indicative data could be described as measurements carried out using a company's own parameters and standards. Robust data could best be described as data gathered according to a general energy measurement standard like the new ISO/CD 14955, available in a draft version.

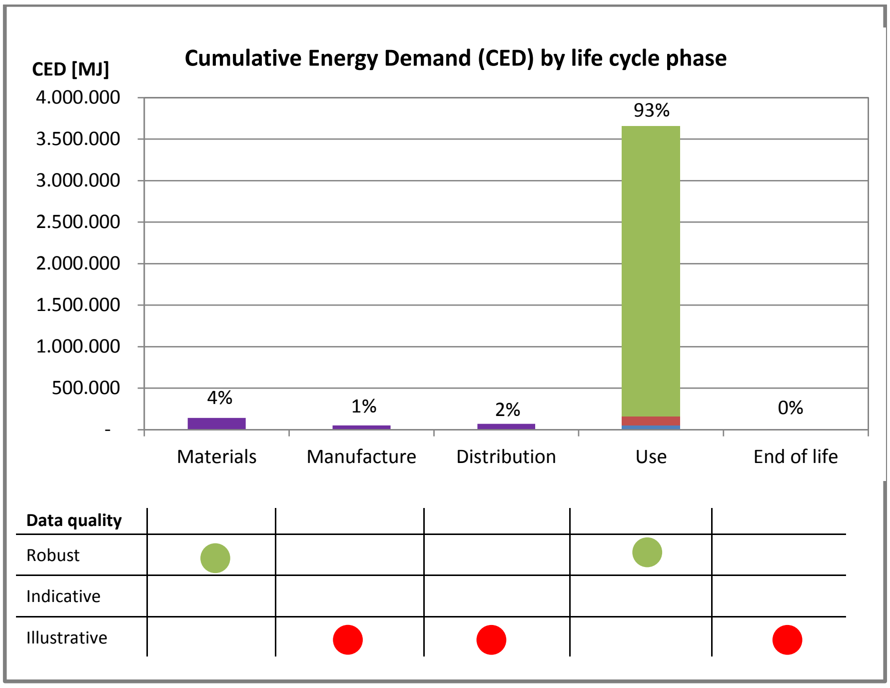


Figure 13. Result stage 2: Environmental profile including quality indicator.

The output of the analysis is the CED of each phase studied in MJ. The process can be iterative and further focus can be placed on specific phases and it is possible to go in more detail (see figure 14) as more detail results are shown per Life cycle stage. This is important when deriving improvements.

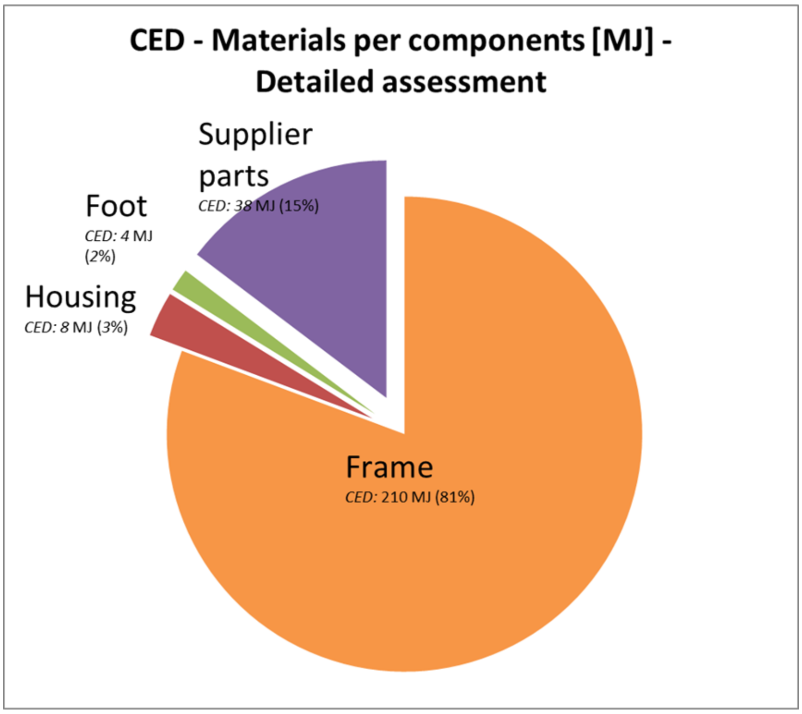


Figure 14. Detailed results stage 2: Material phase

The tool will output improvement strategies based around generic improvements as described in ISO/CD 14955. Figure 15 gives an illustration of what an improvement suggestion could look like.

Improvement measures					
Function: Machining					
Measure	Improvement potential	Relevance	Realization		Argumentation
Drive units			YES	NO	Why Not?
Regenerative feedback of inverter system	6%	X			
Use of energy efficient motors for auxiliary units and intelligent magnetic flux control	4%		X		
etc.	etc.			X	
Process conditioning and cooling					
Discontinous operating pumps, adjustable pressure for cooling lubrication, controlled flow rate	3%	X			
etc.	etc.				
Sum Improvement Potential		**XX %**			

Figure 15. Results improvement stage

1.2.3. Achievements

Case studies were carried out with 2 SMEs in the Industrial Machinery Sector. Kapp Grinding machines and Posalux EDM machines were investigated. In all cases the USE phase proved to be the most energy intensive life cycle phase. The detailed case study reports are contained in deliverable 4-4.

All of the companies found the exercise very helpful as they had not carried out any LCA previously. It gave their employees in different departments an opportunity to learn about LCA and to work on gathering data to carry out our LCA case study exercises.

In the case of Posalux which is an EDM (Electrodischarge machining) machine producer, they discovered that the Use phase is the most significant phase and that they should focus on their electricity and compressed air consumption initially to have the biggest impact on their overall CED. This proved a good exercise as it re-iterated demands from Asian customers to reduce the use of compressed air in their machines.

Work will continue with the case study SMEs in the form of workshops and the testing of the software in October 2013 when it is available to compare results from the software tool.

The Grinding machine case study has been presented at the 20th CIRP International Conference on Life Cycle Engineering (LCE) 2013 in Singapore and the research paper for the EDM case study has been accepted at the 30th International Manufacturing Conference at University College Dublin. This case study has also been presented by invitation at a seminar run by the TEMPO project in Ireland by Limerick Institute of Technology.

Through their contacts with VDW the TUW secured a position on their stand at Hanover EMO Messe in September 2013 to demonstrate the LCA to go software for industrial machinery.

Software recommendations

The case study exercise has highlighted that the proposed model for the software is a suitable model for SMEs to engage with. The 2 stage process enables SMEs to plug in data in a straight forward manner initially without being too heavy on detail or too time consuming, which could act as a deterrent. The software will prompt the user through the five different life cycle phases with a list of prepared raw materials that are typical for the industrial machinery sector. There will be a series of pull down menus and prompts for the user to fill in. It will be important for the software to give guidance and to have links to any relevant standards or data sets as well as simple explanations to assist users in the initial phase. In these particular case studies ISO/CD 14955 parts 1 and 2 proved very useful in defining certain aspects such as the definition of what constitutes Stand-by, idle and in operation modes, what should be considered as system boundaries.

For the more detailed study, step 2 in the methodology, it will be important to guide the user to ensure that they have more specific data relating to their product and actual readings and measurement for energy consumption.

ISO/CD 14955 has a list of standard recommendations that should be considered for the industrial machines sector. Additionally more improvement options will be researched and implemented. The recommendations are also graded based on their potential impact from an energy consumption point of view.

Additionally the tool should have a new performance indicator called energy-production rate. This is calculated by the energy consumption in kWh divided by the good or within specification parts produced by the process. When you just look at the energy consumption without the quality/output off good parts a statement on the overall efficiency cannot be made, therefore this performance indicator should be included.

There should be an opportunity for users of the software to include their own recommendations and generic results for other users to learn from their experience.

Users of the software should also understand how any calculations in the background are carried out so as to ensure that the tool is useful from the point of view of learning.

In summary the software should be developed as originally planned. A paper has been accepted by the reviewing panel for the 30th International Manufacturing Conference which will be held at University College Dublin on the 3rd and 4th of September 2013.

Further recommendations will be made once the software is available in October 2013 and in its test phase.

Summary

The industrial machinery case study exercise has been very successful from the point of view that the case study SMEs are very happy with the results of the work. The SMEs have been introduced to LCA and specifically LCA to go they are aware of the terminology and the concept of life cycle assessment. The results have been surprising for them especially when they have seen the impact that the use phase of their products has. The exercise has also been helpful in testing the methodology that was developed and has allowed modifications and improvements to be made. It has not been possible to date to test the beta version of the software, however this will be carried out with the case study SME's when the beta version of the software is made available for testing in October 2013.

1.3. MicroPro Case study on electronics

1.3.1. Objectives

The case study concept specified for the electronics sector an exemplary assessment of the **iameco v3** by the "LCA to go" tool. As a staged implementation plan for the tool was agreed by the consortium, the tool in its beta version is not yet readily available at the time of case study implementation. As the general concept for the tool is readily developed, use of the tool can be simulated in the course of the case study.

What shall be assessed:

1- Energy - in manufacture, in use, in EoL
2- Carbon Footprint – in manufacture, in use, in EoL
3- Waste generation – in manufacture, in use, in EoL
4- Resource consumption (selected elements) – in manufacture, in use, in EoL

Goals of the assessment where set as follows:

1 – Eco-design and modeling

Used by MicroPro to model design decision in existing and new models.

2- Service structure design and modeling

Use by MicroPro an industrial network agents to suggest improved service structures and arrangements (e.g. leasing), thus creating a business model which incentivizes longevity

3- Green procurement and marketing

Used by MicroPro to promote awareness, appeal to market segments, and justify green procurement bid to private and public buyers.

Description of: the key parameters and processes of data collection; Measurement program for data collection.

Key parameters:

1. Reduction in Energy Use – in Kwh
2. Reduction in Carbon Footprint – Tonnes
3. Reduction in waste – in %
4. Reduction of (selected) resource consumption – in %

MicroPro tests the methodology against its own aspirations: MicroPro is interested in an easy to use LCA tool, which could be used in the eco-design and industrial network structuring process, to make decisions on both.

The case study reflects the interests of MicroPro as an exemplary SME, motivated to implement a sustainable business strategy:

- We are assuming there will be a baseline of a conventional PC and laptop, based on usual components. This might be divided into 3 ranges for each model, low, medium and high specs.
- We assume that some components could be pre-programmed (e.g. wood, recycled aluminum, specific makes of components) but it might be easier if the tool allowed the feeding in of specific alternatives (energy efficiency ratios, new materials).
- It is possible that a simple tool will branch out into other uses, but we are looking for a default, simple, basic tool to begin with, so the case study needs to assess the user friendly-ness of the tool.

1.3.2. Achievements

1 – Eco-design and modeling

The iameco v3 and its predecessors were designed with the benefit of a simplified Life Cycle Analysis, which helped to adjust the design concept, but nevertheless was a complex undertaking, not suitable to be implemented on a regular basis in SME's business processes. MicroPro's evident interest in an eco-design of future products and a need to know which service and reuse strategy leads to minimized environmental impacts means that simplified assessment tools are key. MicroPro's historical aspirations and experience has led to understanding and insights that could be helpful in the implementation of the LCA to Go project, which intends to develop such tools for SMEs.

MicroPro has contributed a Case Study to the Project, based on the needs of establishing the best Ecodesign solutions for the iameco range of PC's and laptops that the company is currently developing.

This involved:

- inputting its Eco-design needs to the Project Team

- assessing proposals made by the Project Team in relation to the LCA package to be developed
- feeding back response to proposals made by the Project Team
- testing the LCA prototypes as they are developed
- providing feedback to the project team on such prototypes

2- Service structure design and modeling

The Life Cycle Assessment exercise has helped inform decisions regarding the Service Structure and how its designed, by

- identifying materials, both new, reused and recycled, that provide the lowest impact and therefore the corresponding services needed to best use those materials

- identifying logistics that would have the lowest environmental impact (e.g. in terms of transport GHG emissions) and therefore the best locations for different operations

- Other?

3- Green procurement and marketing

Information on key environmental impacts of the iameco PC's provide by LCA to go have been useful in providing credible information to support green procurement data required by potential clients, on Life Cycle energy efficiency and carbon footprint of products.

Information on key areas of impact, like energy and carbon savings and waste reduction, are also valuable as part of marketing of the iameco v3. MicroPro is currently engaged in a pilot marketing campaign with the support of Enterprise Ireland, which is advised by the Irish marketing company Doherty White. This campaign is making use of Life Cycle impact information produced by LCA to go.

1.4. TAIPRO Case study on Sensors

1.4.1. Recap on the case studies

Following the case study concept outlined in D4.1, TAIPRO has identified 3 case studies to be implemented on a metal sheet production plant:

- The sensor node application (also called TAMMI)
- The smart grease pump
- The automatic smart greasing system.

At the time of writing D4.1, the most promising one was the sensor node application. Due to different events (mainly internal decisions of metal production plant customers), the picture is now a bit different and the interest for the smart grease pump becomes the more important one for the moment.

The Key Environmental Performance Indicators (KEPIs) as defined in WP2 are addressed in the case study and the current beta version of the web tool as listed below.

Table 3. KEPI Case Study Strategy Sensors Sector

KEPIs defined in WP2	Case study strategy
(1) Energy (gate-to-gate: use phase of the sensor system only, final energy) ▪ **Energy consumption per year** (kWh/a) ▪ **Energy consumption per product output** (i.e. energy efficiency in kWh/kg or kWh/unit) ▪ **Energy savings per year and per product**	Gate-to-gate energy consumption is a dominating parameter for the overall calculation; as it is used as an entry data se, and covered indirectly by carbon footprint and the economic analysis, no separate display of results
(2) Resources ▪ **Resource consumption per year** (kg/a) ▪ **Resource consumption per product output** (i.e. resource efficiency in kg/kg or kg/unit) ▪ **Resource savings per year and per product**	Resources are not relevant in all cases of the assessment, only if yield losses or auxiliaries consumption changes; both aspects are clearly depicted by means of carbon footprint
(3) Carbon footprint ▪ **Carbon footprint per year** (kg CO_2-eq./a) ▪ **Carbon footprint per product output** (i.e. carbon efficiency in kg CO_2-eq./kg or kg CO_2-eq./unit) ▪ **Carbon footprint per year and per product**	Key environmental performance indicator depicted in the results sheet of the LCA to go tool for the sensors sector
(4) Costs (gate-to-gate: upstream costs as to be paid by the system operator, use phase of the sensor system) ▪ **Costs per year and per product**	Separate economic analysis, covers also costs for energy and cost differences related to resources consumption

Already as a mid-term outlook, TAIPRO wants to focus the LCA to go web tools on the most promising application, which are at the moment of completing the current case study:

- Monitoring of mobile equipment like bridge cranes, ball bearings or rotating tools
- Health monitoring of civil engineering structures like bridges, dams, wind turbines…
- Temperature monitoring in industrial fridges, oven, trucks (perishable goods)
- Shock/vibration monitoring on equipment, goods during transport, …

1.4.2. Main achievement versus the road map in D4.1

The D4.1 roadmap foresaw to identify the main indicators which are directly linked to the efficiency of the metal sheet production plant.

As a first step a certain number of inputs has been identified to be able to give a diagnosis on the positive effect of using one of the case studies (mainly smart grease gun and TAMMI) at customer level.

System boundaries

Setting the system boundaries right for the case study is a first important step. Potentially up- and downstream processes might be affected by excessive downtimes of a process line. It might be the case, that upstream processes have to be interrupted as well as process output cannot be processed further and stock piling is not an option. Similarly, downstream processes might suffer from downtimes through supply shortages and have to be shut down as well.
Both cases were ruled out for the case study application of a cold rolling mill as it was confirmed by industry insiders, that for now and for the next few years there is enough capacity to replace a cold rolling mill and that up- and downstream processes are not affected. This simplifies tremendously the approach as secondary effects on other processes can be neglected. For other application cases, e.g. paper calendaring following a paper machine, or steel hot rolling following steel casting the situation might be different.
This aspect of potentially extending the system boundaries to up- and downstream processes should be addressed in the course of the mentoring program. At this stage bilateral discussions can help to identify, in which cases and industries respectively such an extension is required and how appropriate guidance can be provided.

Case Study Data Needs

Initially, data requirements for the case study and the application of the tool respectively are listed in the text box below for the case of a metal sheet production line.

Case Study Data Needs

Production and productivity of the monitored production line

1. Raw material specification (type of steel, sheet thickness or else); required to choose the right upstream dataset
2. Maximum operational time per year [h/a]
3. Downtimes before installation of sensor system [h or % of max. operational time]
4. Estimated downtimes after installation of sensor system [h or % of max. operational time]
5. (or a more detailed distinction of downtime levels / occurrence / duration with and without Sensor system)
6. Production output at normal operational times [kg/h]
7. Yield losses without sensor system [%]
8. Estimated yield losses with sensor system [%]

Environmental data

9. Electricity consumption machine, operational times [kWh]
10. Electricity consumption machine, downtimes [kWh]
11. Electricity consumption overhead, infrastructure, at all times [kWh]
12. Other types of energy consumed?
13. Grease consumption with and without sensors [kg/a]
14. Any other auxiliaries affected by sensor usage? (electroplating chemicals…)

Cost data

15. Electricity price [Euro/kWh]
16. Other energy costs
17. Grease costs [Euro/kg]
18. Other auxiliaries cost
19. Machine-hour rate [Euro/h] (energy costs excluded, if possible; for the scenario without sensor system only, hypothetical machine-hour rate for the scenario with sensor system will be calculated based on stated running times)
20. Personnel costs for machine operation with and without sensor system [Euro/a]
21. Machine maintenance costs with and without sensor system (costs of sensor system itself and its operation to be stated separately below) [Euro/a]
22. Spare parts storage costs with and without sensor system [Euro/a]
23. Raw materials costs (steel) [Euro/kg]
24. Price premium for steel products in case of sensor controlled production line [ΔEuro/kg]

Sensor system data

25. Sensor system acquisition and installation costs [Euro]
26. Depreciation period for sensor system and installation [years]
27. Maintenance and running costs sensor system [Euro/a]
28. Number of sensor nodes employed
29. Abridged BOM of sensor nodes (chipsets, memory, PCB spec, housing, battery spec)
30. Additional infrastructure components to make the system work (cabling, card / RFID / handheld readers, computers, internet backbone required)
31. Grid electricity consumption of the sensor system [kWh/a]

This indicated amount of data is considered to be appropriate for a simplified assessment without too much burden to gather data. Note, that for the environmental assessment alone approximately 14 data entries are required only, plus 7 data entries for the sensor system as such. Cost calculations require other 10 data entries. However, data gathering remains to be challenging, in particular for an SME, which is from sensor system design and production, but not from the mechanical heavy industry, in which the sensor system is supposed to be used.

As part of the case study TAIPRO explored internally and jointly with clients the feasibility to get hold of relevant input data for the assessment. The different necessary inputs are listed with their status in the following sub-paragraphs, reflecting on the likely overall importance to address these.

1.4.2.1. Production and productivity of the monitored production line

The productivity of the production line is crucial to determine the potential saving at customer level, but beyond control of a sensor system provider.

The different criteria selected are the following ones:

- Existing available data base: The goals for that need are:
    - To help in the validation of all inputs we can receive from a customer
    - To be able to be proactive by anticipating calculation without any input from the customer. Indeed, that kind of information is clearly confidential and it is important to install a lot of trust with the customer before starting that exchange of "touchy" information.
      Remark: That kind of information is very difficult to obtain
        - No such generic data is readily available, but from various public sources it might be possible to establish data for some generic production lines. As part of the case study the attempt is made to establish such kind of generic production line

- Maximum operational time per year of the production line [h/a]: the goal of that input is clear, if you can prove with the LCA tools that you can produce x hours more per year the result is evident from an economic point of view, but also in terms of environmental effects the impact per product will be lower, if the production line runs more efficiently. Some confidential data are available at TAIPRO for the smart grease gun and the TAMMI.
- Downtimes before installation of sensor system [h or % of max. operational time]: Same situation than for Maximum operational time per year of the production. For the application case condition monitoring this is expected to be the dominating factor, as downtimes and related productivity losses will be reduced through better monitoring.
- Production output at normal operational times [kg/h]: Crucial information to be obtained from the customer, important to allocate impacts and costs per output. The overall costs and environmental impacts of a more productive production line is likely to increase, and only on a "per product output" basis the costs and impacts will go down. In general, such data is confidential but easy to obtain, so data is available in confidential talks with the client. For any calculations in advance or for a first client briefing, a generic data model based on a typical production output is considered very valuable background information to be used in conjunction with the LCA to go tool.

- Yield losses without sensor system [%] & Estimated yield losses with sensor system [%]: Very important point, which potentially can dominate the economic and environmental analysis. Data might be obtained under a trustworthy cooperation between the sensor provider and the customer. Estimation has been done by TAIPRO and one particular customer.

1.4.2.2. Environmental data

The environmental data concerns directly the production plant manager. These data are rather difficult to obtain from the customer as they are important for the environmental effects, but are correlated with the sensor system only indirectly and do not have much influence on the sensor system implementation. Most of the time estimations or assumptions have to be done on the different criteria/inputs. That should be the logic to be followed with the web tool.

The different criteria to be identified are:

- Electricity consumption machine, operational times [kWh]
- Electricity consumption machine, downtimes [kWh]
- Electricity consumption overhead, infrastructure, at all times [kWh]
- Grease consumption with and without sensors [kg/a]

These data requirements are probably the most difficult information to be obtained from the customer. This is a severe risk for the overall LCA to go approach for the sensors sector, as this might result in a tendency, to undertake the economic analysis only and to neglect the environmental aspects. The initial idea has been different, namely that the economic analysis is a by-product of the environmental analysis.
As a mitigation strategy data has to be sourced, this can help to be used as default values. Such data from scientific literature is referenced in Chapter 2.4.
One specific data entry has been ruled out from further consideration, which is "Raw material specification". The upstream processes are relevant from a life cycle perspective, but as the focus is on the benefit of a sensor system controlled process line versus a process line not controlled by such a sensor system, the upstream processes are not affected (or: are the same for both scenarios) and therefore can be ruled out from further consideration.

1.4.2.3. Cost data

There are two different kind of cost data inputs required: one type of information is available for the "standard" market (eg: cost of electricity, cost of grease,...) and others are strongly dependent on a particular customer and his internal cost structure:

Available generic market data is the following:

- Electricity price [Euro/kWh]

- Grease costs [Euro/kg]
- Raw materials costs (steel) [Euro/kg]

Statistical data, such as the EuroStat energy statistics are a suitable source for typical energy prices depending on company size (i.e. energy consumption per year) and country. These are however average prices and might differ further on a regional level within a country, and individual energy supply contracts might fix again other prices.

The data strongly dependent on a particular customer are:

- Machine-hour rate [Euro/h]:
  - energy costs excluded, when possible; for the scenario without sensor system only,
  - hypothetical machine-hour rate for the scenario with sensor system will be calculated based on stated running times.
- Personnel costs for machine operation with and without sensor system [Euro/a].
- Machine maintenance costs with and without sensor system (costs of sensor system itself and its operation to be stated separately below) [Euro/a].
- Spare parts storage costs with and without sensor system [Euro/a].
- Price premium for steel products in case of sensor controlled production line [Euro/kg], this can be considered also a distinct higher quality of steel (or whatever the process line output is).

Concerning the data depending on an individual customer, obviously this information can be sourced only in close collaboration with the customer. It is a risk, that the customer might hold back this kind of information, which will hinder the sensor system provider to quantify the whole potential of the sensor system application. As a mitigation strategy, exemplary additional case studies for relevant production lines can be sourced or established in the course of the SME mentoring. This would help a sensor system provider to make some educated guess for these data entries and also to check plausibility in case the customer provides some own data.

Relevancy of the economic analysis for the case study SME

Reflecting on this economic analysis is considered a new opportunity for a sensor company like TAIPRO to add value to its services and systems and for an even better understanding of the needs and motivations of its clients. Besides selling sensor systems the access to the web tool and related services might become part of an extended business model for a company like TAIPRO as well.

Therefore, we feel that once we will be involved on different production sites we will be able to analyse in detail the production line with the customer by helping him to show the cost and environmental savings on his site.

1.4.2.4. Sensor system data

With respect to the sensor system data a sensor company has all the necessary information readily available, and this is also the case for Taipro. The different elements already known at TAIPRO are:

- Sensor system acquisition and installation costs [Euro] on a production plant
- Depreciation period for sensor system and installation [years] (Return On Investment)
- Maintenance and running costs sensor system [Euro/a]
- Number of sensor needed
- Abridged BOM of sensor nodes (chipsets, memory, PCB spec, housing, battery spec)
- Additional infrastructure components to make the system work (cabling, card / RFID / handheld readers, computers, internet backbone required)
- Grid electricity consumption of the sensor system [kWh/a]

It is important to note that some of the above mentioned criteria are inputs from the LCA to go web tool point of view but are also a very interesting negotiation input for Taipro (and thus for any sensor companies).

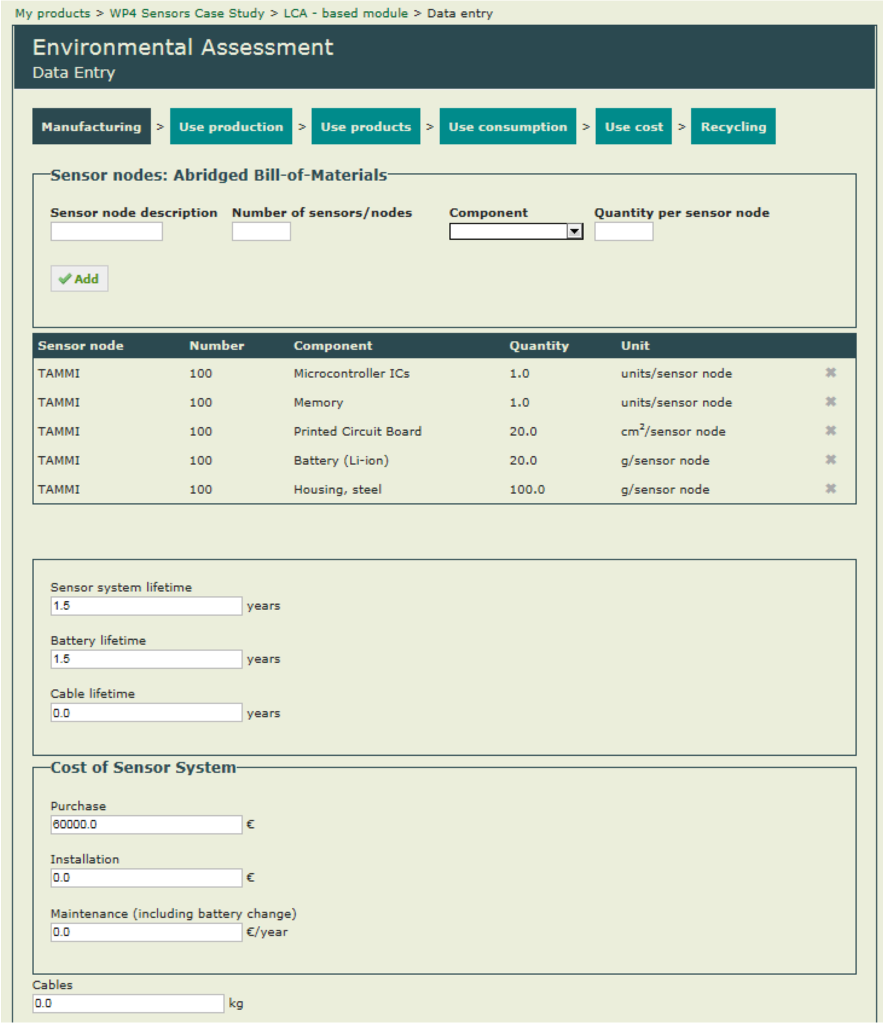
1.4.2.5. Data entries

The data entries for the case study are depicted in the following screenshots from the beta version of the web tool. Confidential data is replaced by dummy data, so entries should not be taken for real, but as a sound approximation yielding appropriate results.

The manufacturing phase basically requires data entries for an abridged bill-of-materials for the sensor nodes. Under sensor system lifetime not the actual technical lifetime is entered, but the depreciation time of 1.5 years to yield a correct economic analysis for the beginning of the system operation. For the environmental assessment, which is also based on this entry, this is a bit misleading, as rather the technical lifetime should be considered here.

Recommendation for the final version:

- Distinction between *technical lifetime* and *depreciation period*



Sensor node	Number	Component	Quantity	Unit
TAMMI	100	Microcontroller ICs	1.0	units/sensor node
TAMMI	100	Memory	1.0	units/sensor node
TAMMI	100	Printed Circuit Board	20.0	cm²/sensor node
TAMMI	100	Battery (Li-ion)	20.0	g/sensor node
TAMMI	100	Housing, steel	100.0	g/sensor node

Figure 16: Data entries sensors case study - Manufacturing

Data entries for the production scenario of the cold rolling mill are shown in Figure 16 and 17.

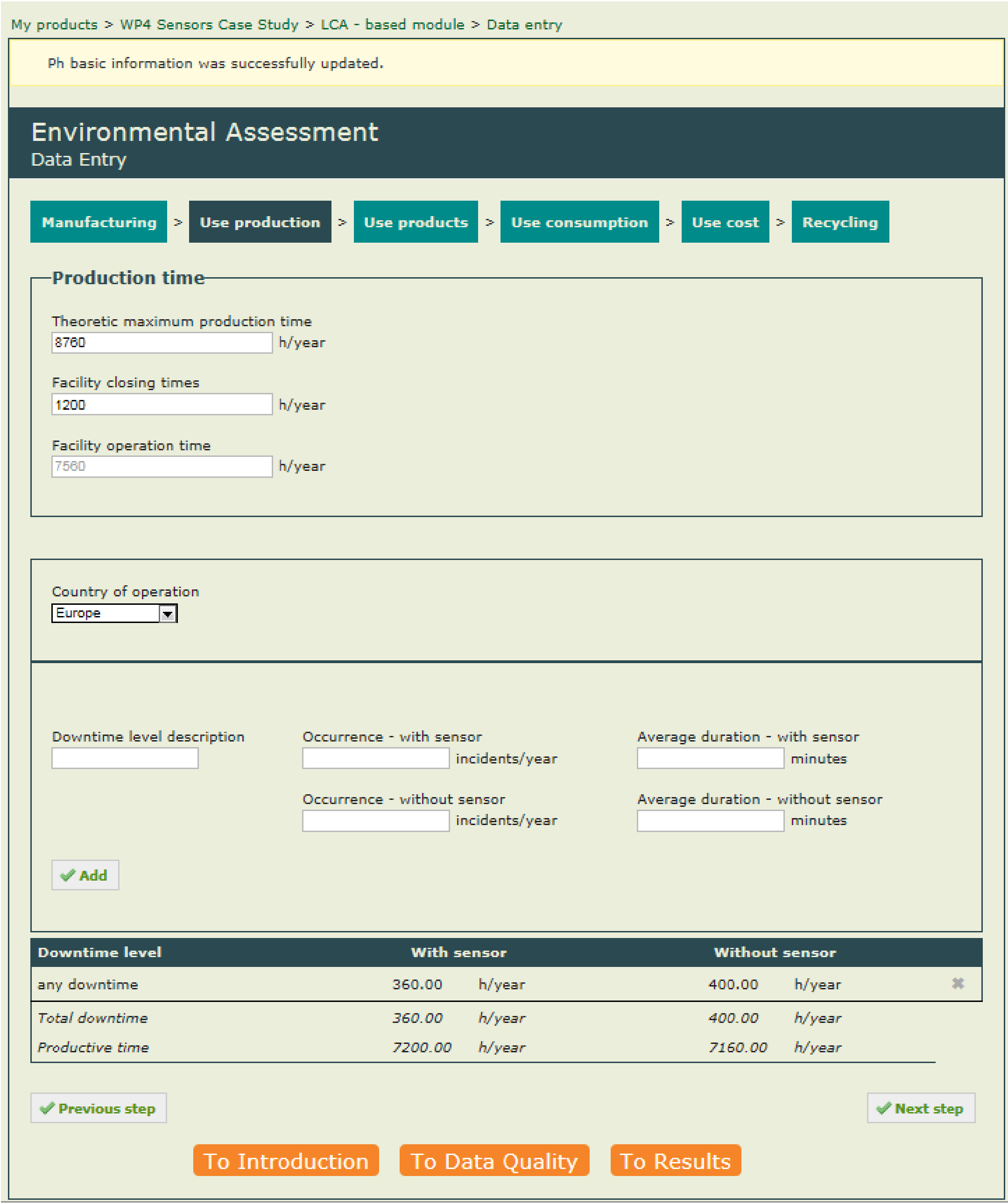


Figure 17. Data entries sensors case study – Use production

Data entries for the production output of the process line have to be entered in the “Use product” phase (Figure 18), but as this data is confidential, no real values are shown below.

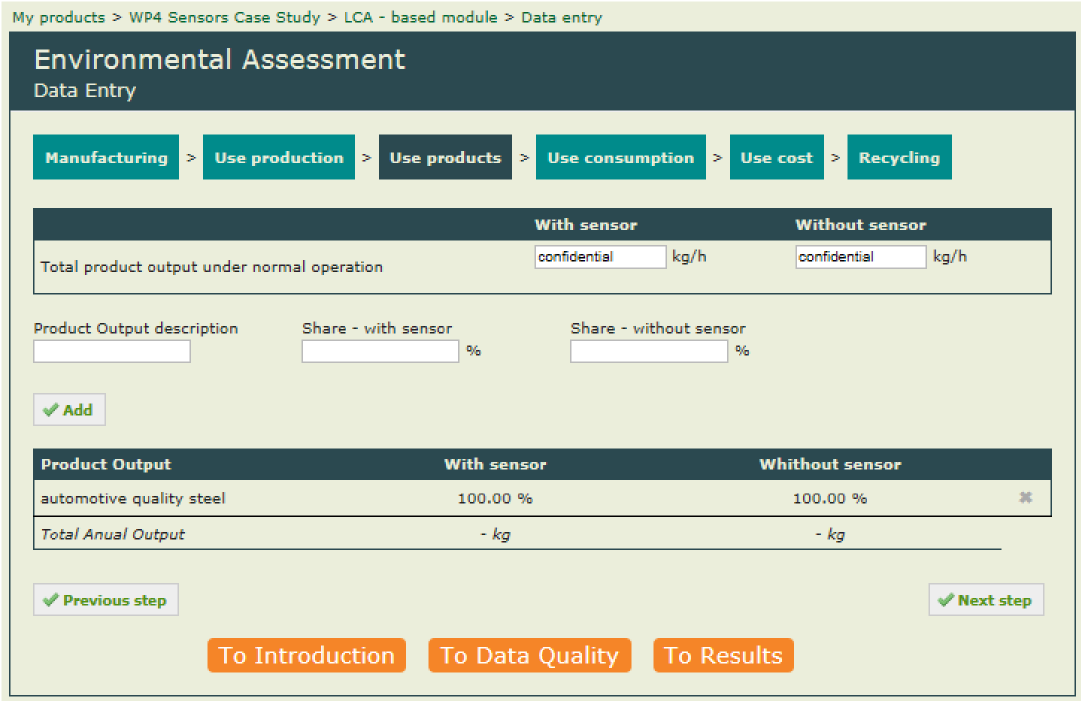


Figure 18. Data entries sensors case study – Use products

Similarly, data on energy, consumables and utilities usage are confidential. The screen shot for "Use consumption" in Figure 19 therefore has to be seen rather as an illustration of the tool's features and less a documentation of case study data as such.

According to a recent Fraunhofer study [Fleiter 2013] default data on energy consumption for cold rolling steel mill is 700 MJ/t fossil fuels and 25 kWh/t electricity [VDEh 2010, p. 73; Fleiter 2013]. For comparison, data for a hot rolling mill is 1.232 MJ/t and 125 kWh/t respectively [Fleiter 2013].

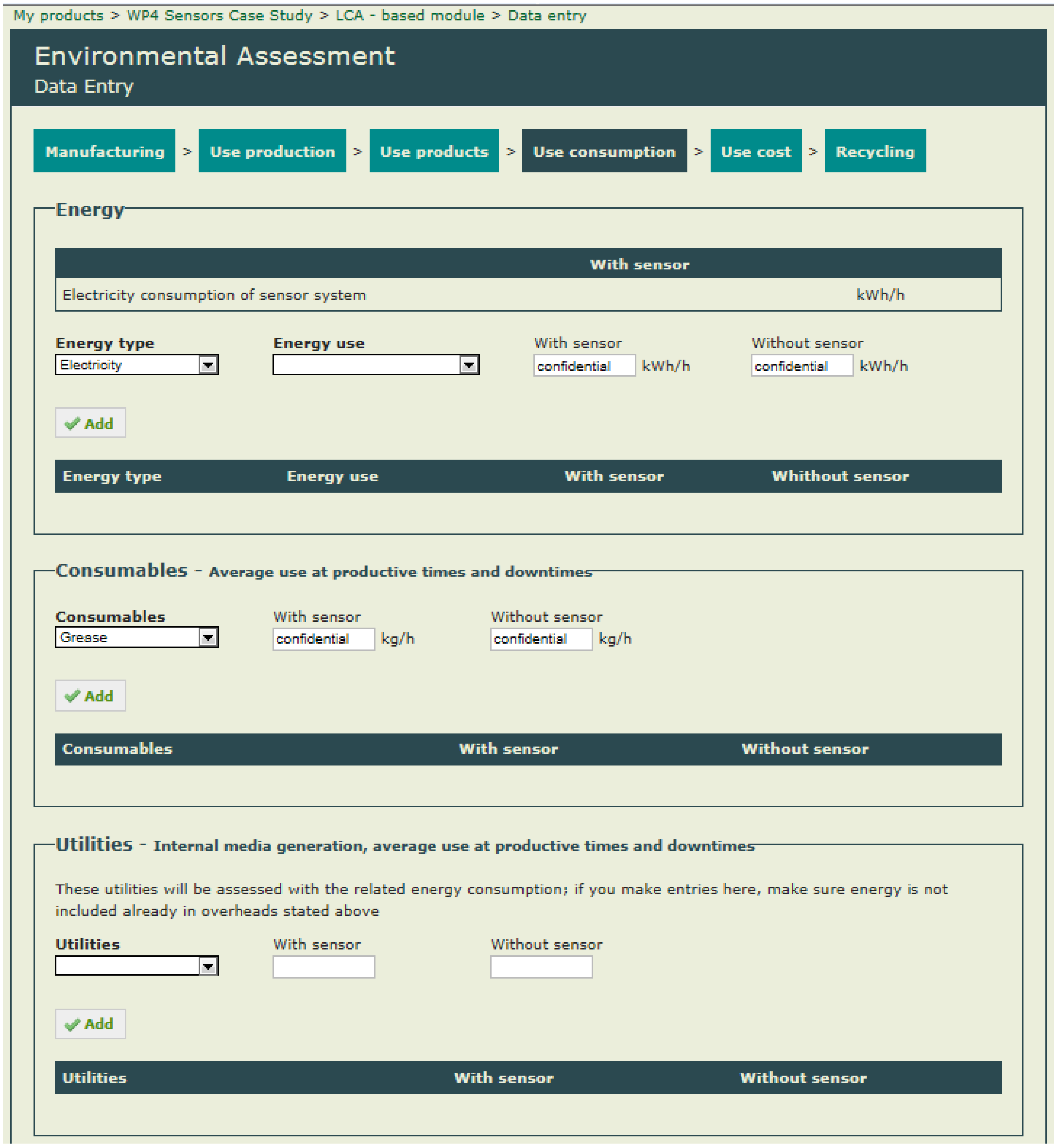
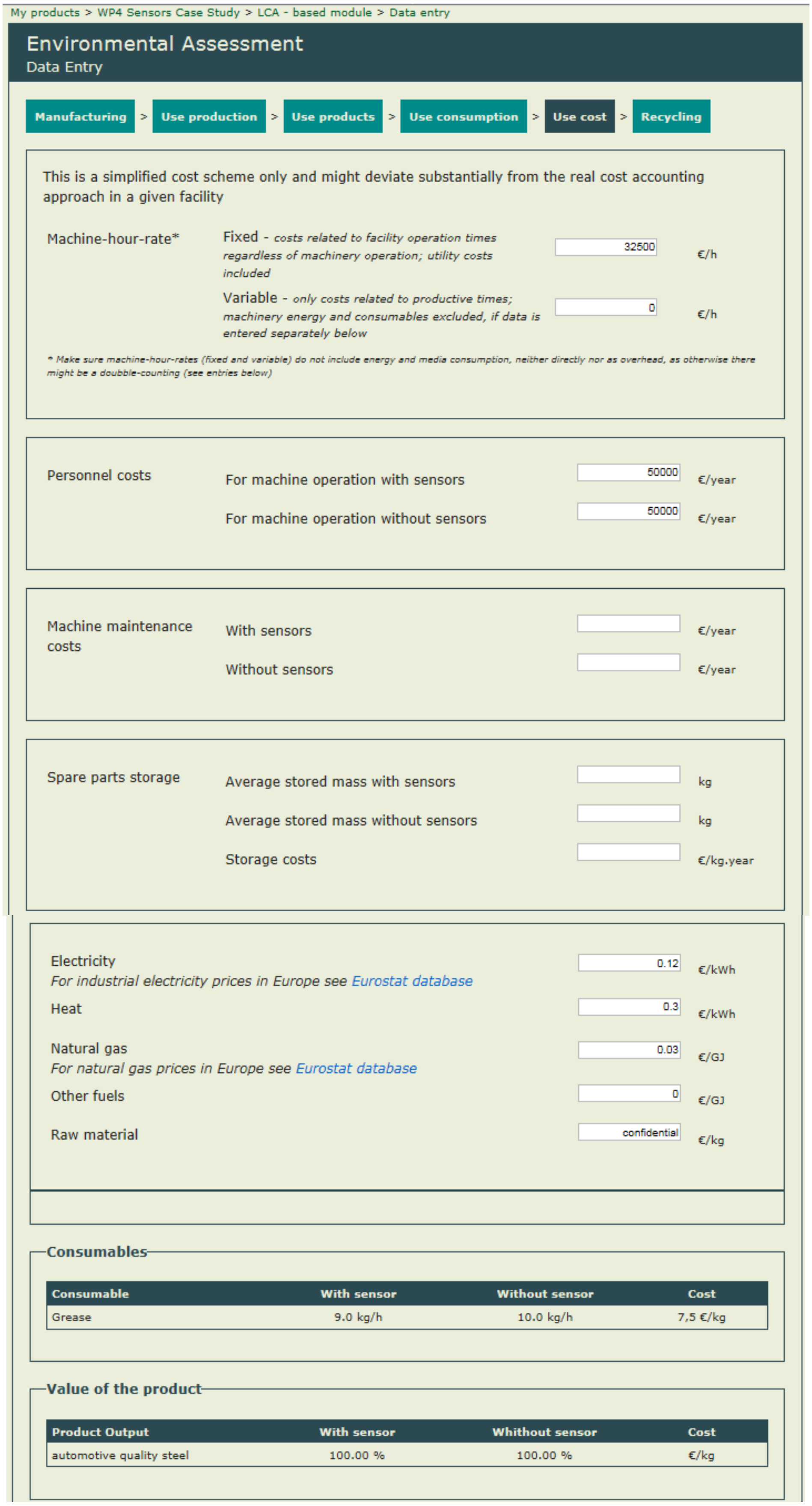


Figure 19. Data entries sensors case study – Use consumption

The screenshots with cost data entries are shown in Figure 20. For confidentiality reasons some entries are left blank, others are approximated. Typically for such an assessment not the full range of data entry options are required, which makes the handling of the data entries easier than it seems from first glance.



My products > WP4 Sensors Case Study > LCA - based module > Data entry

Environmental Assessment

Data Entry

Manufacturing > Use production > Use products > Use consumption > Use cost > Recycling

This is a simplified cost scheme only and might deviate substantially from the real cost accounting approach in a given facility

Machine-hour-rate*			
	Fixed - *costs related to facility operation times regardless of machinery operation; utility costs included*	32500	€/h
	Variable - *only costs related to productive times; machinery energy and consumables excluded, if data is entered separately below*	0	€/h

** Make sure machine-hour-rates (fixed and variable) do not include energy and media consumption, neither directly nor as overhead, as otherwise there might be a doubble-counting (see entries below)*

Personnel costs	For machine operation with sensors	50000	€/year
	For machine operation without sensors	50000	€/year

Machine maintenance costs	With sensors		€/year
	Without sensors		€/year

Spare parts storage	Average stored mass with sensors		kg
	Average stored mass without sensors		kg
	Storage costs		€/kg.year

Electricity *For industrial electricity prices in Europe see Eurostat database*	0.12	€/kWh
Heat	0.3	€/kWh
Natural gas *For natural gas prices in Europe see Eurostat database*	0.03	€/GJ
Other fuels	0	€/GJ
Raw material	confidential	€/kg

Consumables

Consumable	With sensor	Without sensor	Cost
Grease	9.0 kg/h	10.0 kg/h	7,5 €/kg

Value of the product

Product Output	With sensor	Whithout sensor	Cost
automotive quality steel	100.00 %	100.00 %	€/kg

Figure 20. Data entries sensors case study – Use costs

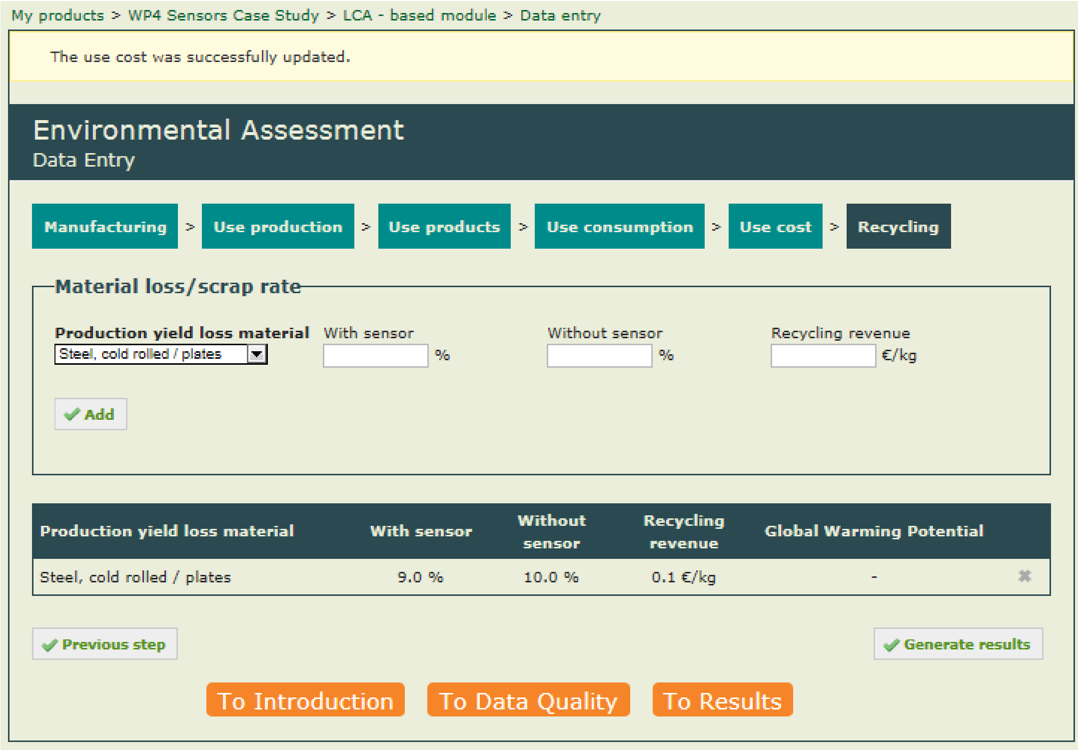


Figure 21. Data entries sensors case study – Recycling

Data for yield loss can be entered conveniently in the "Recycling" spreadsheet (Figure 21).

In case certain values are not exactly known, but ranges are stated as for the yield loss estimates, the user has to make discrete assumptions (average or conservative estimates) as the tool cannot calculate with uncertainty ranges. This is done on purpose to limit the complexity and thus user-friendliness of the tool.

Data quality follows a self-assessment, based on criteria implemented in WP2. Logically, data quality for the sensor life cycle is high, as this is directly under control of the user. All other phases require typically substantial assumptions, which inevitably lower the DQI level to indicative or illustrative (Figure 22).

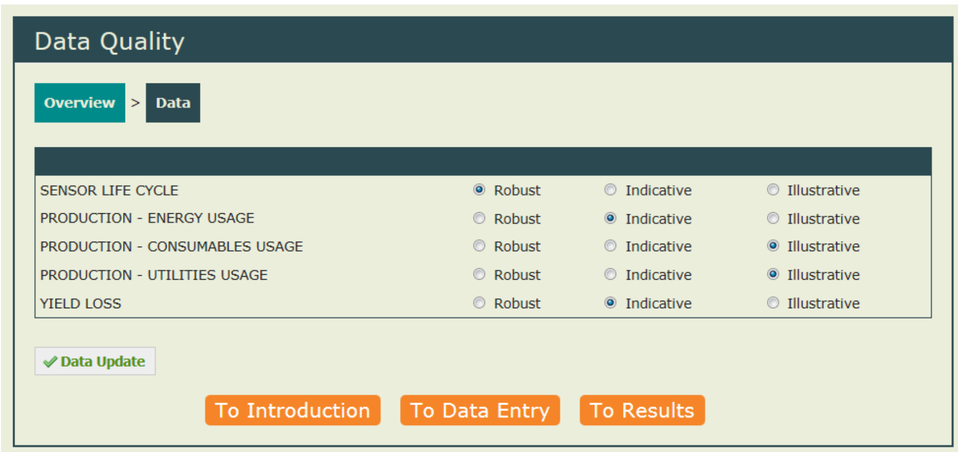


Figure 22. Data entries sensors case study – Data Quality Indicators

1.4.2.6. Feedback on tool evaluation criteria

To highlight the status of the main achievements we use the evaluation criteria established in D4.1 paragraph 2.4.4 and resumed in the table below.

Table 4. Evaluation criteria.

Evaluation criteria	Status
Simplification of the data collection • Identify the minimum amount of necessary data to run the LCA to go tools. • Identify the "maximum" of data that can be handled as a variable by an SME, which still results in a feasible amount of data entries	Achieved
Validation of the data • Ability to provide a clue (before end user agreement) that the tool is efficient	To be confirmed by test
End user agreement on the data	At TAIPRO level only for confidential reason
Versatility of the LCA to go tools • Ability to answer to a wide range of steel production plant • Ability to become transferrable to other "similar" continuous production plants (ex: paper production).	Still open and to be tested *(beyond the scope of the case study, to be explored in the mentoring programme, if suitable SMEs will be acquired for the mentoring)*
Forecasted improvement to be realised through implementation of the sensor solution. • Assessment of changed parameters against business-as-usual	Only some educated guess feasible (only in retrospective after a couple of months or years robust field data might become available)
Enhancement of customer-client-communication • As this is a "soft factor", a descriptive evaluation, anyway based on anecdotal evidence only, will be provided	Looks OK, indeed new contacts for using grease pumps on different markets thanks to SKF (active in all industrial maintenance companies) and DETRY's company (manufacturer of delicatessen & salt meat)

1.4.2.7. Recommendations

The case study experiences lead to recommendations on two levels. The first level are the recommendations for the tools under development, i.e. a feedback on the beta version with the intention to improve the tool for final release, and the second level addresses future evolution recommended for the tool and the LCA to go approach.

1.4.2.7.1. LCA to go web tool

The different recommendations identified are the followings:

- To allow a large variation range for each input, so the web tool has to be robust enough to sustain large variation of input data:
  - Actually, we observe that a lot of information is difficult to obtain from the customer. Therefore, it is very important "to play" with the inputs in order to be able large scale analysis of a typical production line.
  - Additionally, different production lines can have different inputs (depending of the production plan size) and therefore it is necessary to have a tool able to accommodate a large variation of production lines.
- The web tool has to involve the two test cases (smart grease guns and TAMMI). Normally it will not cause too many problems because the inputs needed are the same. Again the robustness of the software is a key because from case study to another, order of magnitude of input values can be different.
- The web tool should be validated in the course of the mentoring programme against experiences from sensor companies and energy-intensive industries, but also against third-party environmental assessments of similar processes, where such data is available and accessible.
- An outcome of the mentoring programme should be also further clarification on the system boundary issue (coverage of up- and downstream processes) for various application scenarios in energy intensive industries. Similarly, only practical implementation and discussion of this implementation can tell, whether provided guidance is unambiguously or if further clarification for the user is required.

1.4.2.7.2. Recommendations for future web tool evolution

Beyond the requirements for the LCA to go tool and its application as defined by the scope of LCA to go some further needs for future development and revision of the tool have been identified by TAIPRO. This largely corresponds with the evolution of potential further use cases targeted with TAIPRO's sensor systems, which could be (non-exhaustive list):

- Wind turbine monitoring.
- Cement production.

- Follow up of any continuous rotating equipment.
- Temperature monitoring in industrial fridges, oven, trucks (perishable goods).
- Shock/vibration monitoring on equipment, goods during transport.

The monitoring of wind turbines is technically a very relevant field for further tool evolution, but also as the sector renewable energy is already touched by LCA to go, although considering photovoltaic by now only.

Monitoring of cement production, continuous rotating equipment and industrial ovens does not match exactly the current scope of the LCA to go tool for the sensors sector, but is pretty close to it. Further extension of the tool in this direction seems to be feasible (but requires also the sourcing of some suitable background data), and ideally a to be mentored SME is interested in such application cases, so extension of the tool can be discussed immediately as part of the mentoring programme.

Further aspects of interest identified in the course of the case study are:

- To be able to quickly modify a calculation for other sensor cases by giving guidance (could be a services from a partner of LCA consortium) to update the input file

- To be able to give a sort of accreditation to the information given.

- To be linked directly to the selling of the equipment. It means that when any sensor is sold with a simulation, we can warranty a result to the customer (this is a very challenging recommendation and requires further exploration before being implemented).

1.5. TTA Case study on Photovoltaic Systems

As a preliminary work, TTA investigated the possible interfaces of their engineering work flow and the LCA to go web tool. According to the practical experience of TTA, the web tool will only find application in particular design phases (see Figure 23):

- Step 2. Engineering Outline: LCA to go tool will characterize the main LCA results and demonstrate extra benefits with low impact choices.
- Step 3. Detailed Engineering: LCA to go tool will ensure that critical LCA aspects identified in previous step are fulfilled and with possibility to influence final selection of component provider.

Furthermore, the tool shall be applicable in case of system retrofitting and enable the user to understand the effect of newly introduced components such as storage or high efficiency PV modules. Another possible utilization will be the post-construction assessment, applying real measured performance data.

Considering the above stated, various information has to be asked for in the web tool's interface and have therefore to be analyzed in advance by a future user and implemented by the project's software developers. The most important parameters are as follows:

- Regional information – Electricity mix, performance influencing ambient conditions (irradiation, temperature)
- General system outline – inclusion of storage, PV technology foreseen, mounting structure and space restrictions
- Detailed system sizing – quantity of used modules, power to be generated, specification of electric components such as inverters and batteries
- Performance indicators – module efficiency, performance ratio
- Optional specification of supply chain

During a first meeting of all PV sector related partners (TTA, Fraunhofer and Simpple for the web tool), multiple points concerning the web tool were discussed and decisions have been made.

Furthermore, a Barcelona local PV system distribution NGO focused on the promotion of sustainable energy SEBA (www.seba.es) was interviewed to check for typical maintenance extents. In order to make sure that the software specifications developed by the related partners are realizable, all ideas developed by TTA and Fraunhofer were presented to a representative of Simpple. The results of the interview and discussion were as described below:

- Storage systems definitely have to be included in the assessment, typical technologies used are lead acid and lithium ion.
- Major maintenance tasks are: replacement of electric components at the end of their lifetime, cleaning and precautionary site visits; battery

maintenance impact (e.g. refill of distilled water) was assessed and found negligible.

- Comparison of identical systems showing impact of different module technologies shall be possible.
- Improvement suggestions shall be included, optimization parameters to be chosen by tool's user.
- Performance ratio is the main performance indicator to be used in the tool – its calculation or estimation is a user's task (e.g. experience or engineering software); the tool will only give minimum and maximum range.

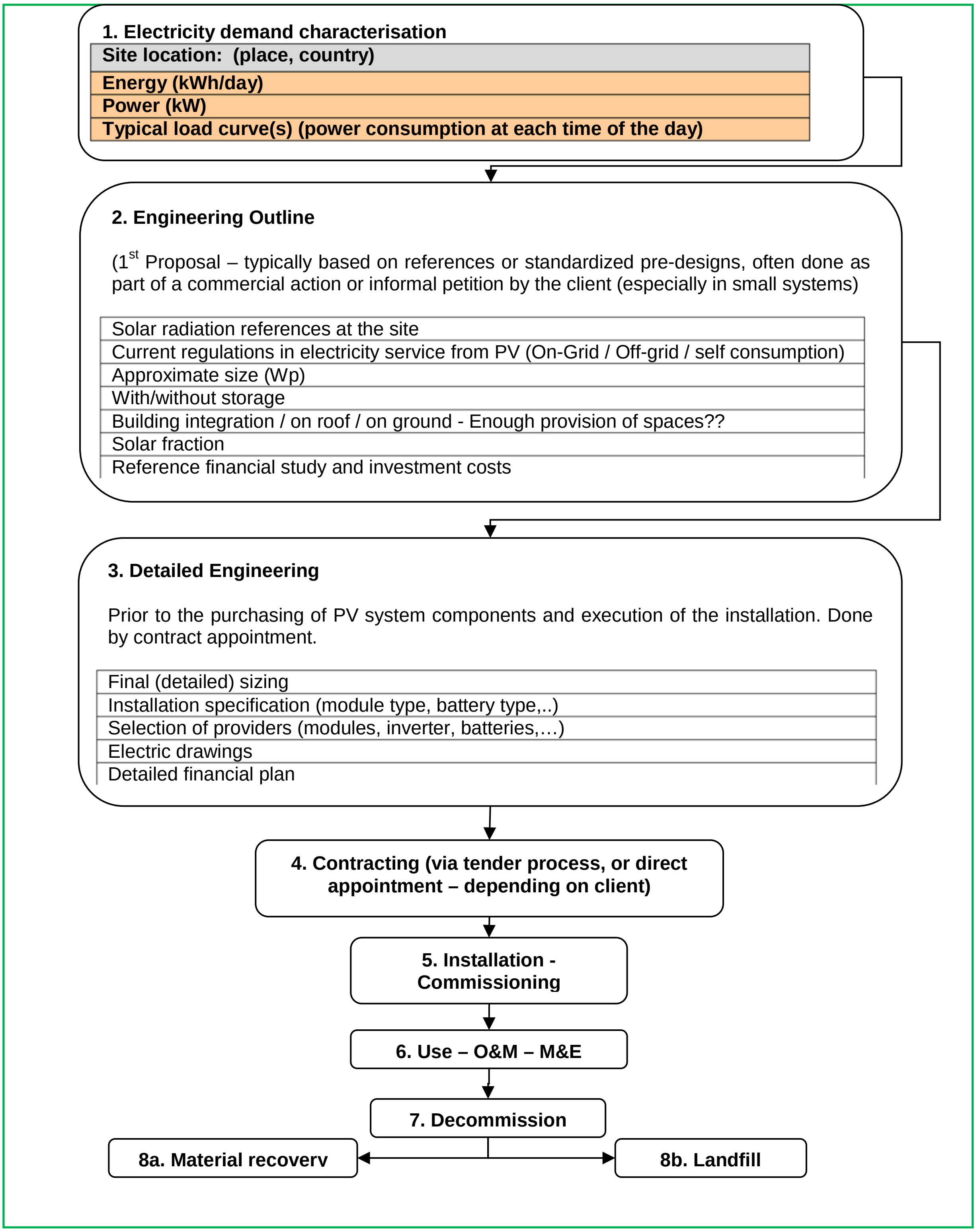


Figure 23. General workflow for a PV system design (source: TTA - www.tta.com.es)

Using the web tool specification derived from the above preparative work, a beta version was established and released for the use during the case studies. TTA also developed guidelines on how to calculate the performance ratio in order to enable the user to help himself at this point. Taking into account this background, the case studies lead to the following evaluation of the current web tool status:

Different case studies were selected as demonstrators for the PV case study: for the first system, the tool has been used to define an improved design (during the engineering outline) and one system has been assessed for the implementation of an Environmental Product Declaration (EPD).

In order to make sure, that the robustness and usability of the web tool is well assessed during evaluation, the case studies were selected in such a way that as many different configurations as possible are looked at. That includes the variation of location, technology used and type of installation (grid-connected or microgrid both including different storage options).

Following the identified improvements and recommendations are listed:

- The average temperature on the PV module surface is a requested input. This temperature cannot be known before installation, so during pre-design or design the temperature is an estimation. We used estimated values (i.e. 20 ºC above the average air temperature). For existing systems, the exact temperature can be known after some time of monitoring.

- The default value for the performance ratio (PR) should be lower than 0.7 when storage is included in the sytem. Attention should be paid on the values introduced for yearly generation and PR. These values should consider the PV system degradation (more information is provided in the manual for the calculation of the PR prepared for the e-learning course) as often the values are given for the first year. If the calculation is done based on the PR of the first year, this should be indicated in the tool.

- Type of mounting, in some cases (i.e. microgrids or others) the mountring structure is a pergola which has more material than a simple on ground structure. For the case study, the pergola type is considered as a ground mountring structure.

Figure 24. Pergola installed in Cabo Verde by TTA (source: TTA)

- With regard to the data to be introduced, the majority of the data is easy to get with some exceptions:
    - The main problem appears when information on the country of production for the Silicon feedstock or the Silicon wafers should be introduced (the country of production for the PV modules and the Silicon cells is also to be introduced but the information is not difficult to get). PV module manufacturers have different PV cells providers and the cell providers have different Silicon providers making difficult the tracking of the origin of them. It was not possible to introduce robust data regarding these two origins.
    - The lifetime of the batteries is hard to define, specially for lead-acid storage. It depends on the characteristics of the place and the cyclability; when the system is in its designing phase, the lifetime is estimated based on previous experience.
- The range of values is too narrow in some cases:
    - Battery units: Two battery banks of 24 units are used in one of the case studies, resulting in 48 batttery units. The tool is limited to 24 units and the values had to be adapted for the case study to obtain the same results (i.e. less units at more voltage).
    - Lithium-ion batteries were used in one of the case studies, the lifetime calculated by the manufacturer, based on temperature, cyclability and depth of charge was 19.5 years and the maximum possible lifetime to be introduced in the tool is 14 years.
    - Frequency of cleaning (mainteinance) is limited to a maximum of 6 times a year. For the case study in Chad the cleaning is expected to be once in the two weeks due to dust problems.

- In the results sheet, it is suggested including gensets/engines when the system is compared to the impacts of the electricity generated with other sources (i.e. lignite, hard coal, natural gas CCP, offshore wind power) as in rural electrification projects, the installation of PV systems often substitute diesel generators, and the results will support the decision of incrementing the PV capacity and reducing the capacity of the generators.

- In the results sheet, when the a comparison is done, it will be useful to have the possibility to compare more than two systems. Currently, the comparison is done for the separate components and presented in a graph. Add values of the total impact in the comparison will also be useful.

- A short description of the results will also be useful: When the table in the detailed results is showed, information on Carbon footprint of the system should be inclued; i.e. Embodied CO_2 (instead of CO_2) or Embodied Energy (instead of PE).

1.6. ELDOS Case study on Printed Circuit Boards

The case studies for Printed Circuit Boards sector covered issues presented in details at the D4.1 Report - Scientific Case Study Concepts. In the issue of software the main goal of case studies was answer on some methodological questions and the verification, improvement and simplification of algorithms for PCB sector created in WP2 based on case studies results and users opinions.

The analyses of new data from production process of PCBs gathered during case studies by the ELDOS Company enable to answer on following methodological questions:

- What is the shortest period of data collection acceptable in order to obtain reliable results from the sophisticated PCB module of the "LCA to go" tool?
- How big is influence of the production data from different periods of time on the PCB module algorithms and final result of KEPI calculation?
- Are all KEPIs included in the tool relevant? Can some of them be cut off without losing functionality?
- What is the highest possible error resulting from the PCB surface area being the only input information? Is it possible to apply such simplification for a complex product assessment?
- What is the transportation's share of a PCB's total carbon footprint – can it be neglected / cut off?

The sophisticated PCB module of the "LCA to go" tool enables PCB's manufacturers input real production data for the calculation of different KEPIs. It was stated that data of materials and media consumption from one year period are essential in order to obtain reliable results from the sophisticated PCB module of the "LCA to go" tool.
The data from 4th periods were analyzed. The data of materials consumption for 2011 and 2012 years were almost on the same level for similar level of PCB production. Half a year was too short period of data collection. The highest periodical fluctuation were observe for heat energy and water consumption as well as for some materials consumptions as Cu foils and prepregs used for multilayer PCBs production. Some examples of results used for answer on the question 1 and 2 are showed in Table 5 and Figures 25 – 28.

Table 5. The average consumption of materials during PCBs production in kg/m^2 of PCB from different periods.

Period	Laminate	Chemicals for ENIG coating	Chemicals for Sn coating	Chemicals for HAL coating	Other chemicals	Total materials consumption	Difference relative to reference level
2011	4.05	1.83	0.18	0.14	14.20	18.25	Reference level
2012	3.80	1.90	0.44	0.13	14.41	18.21	-0.2%
1st half 2012	3.30	1.53	0.05	0.12	11.45	14.76	-19.2%
2nd half 2012	4.63	2.49	0.03	0.15	18.49	23.12	+26,68%

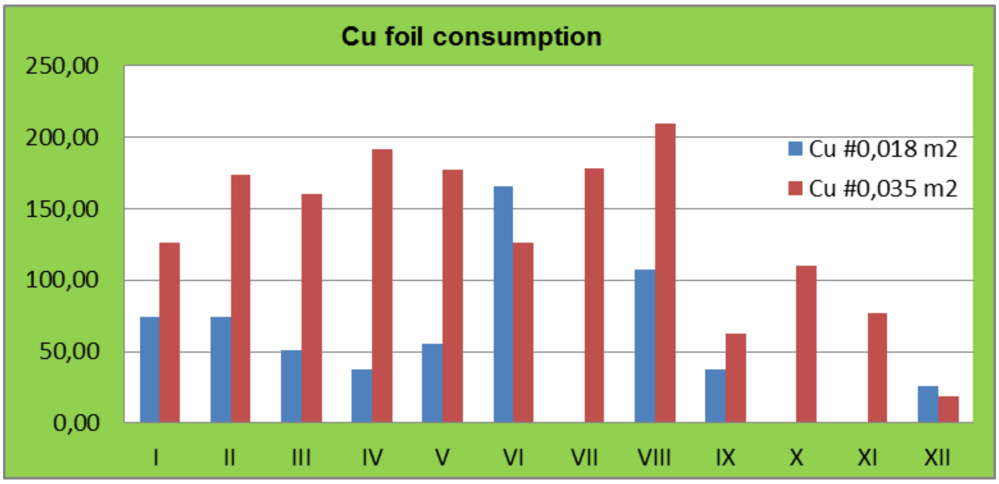


Figure 25. Cu foil consumption during one year period - 2012.

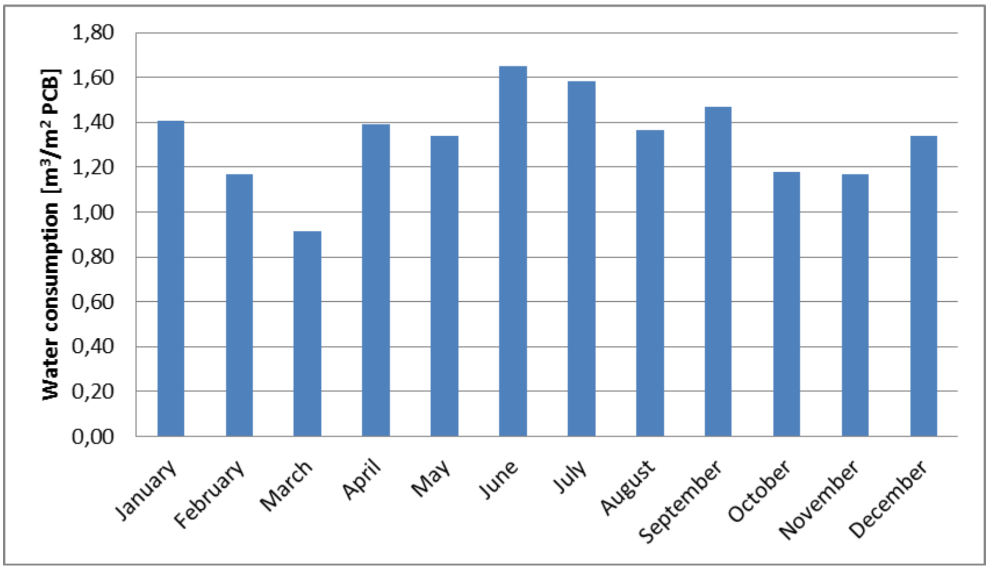


Figure 26. Water consumption during one year period - 2012.

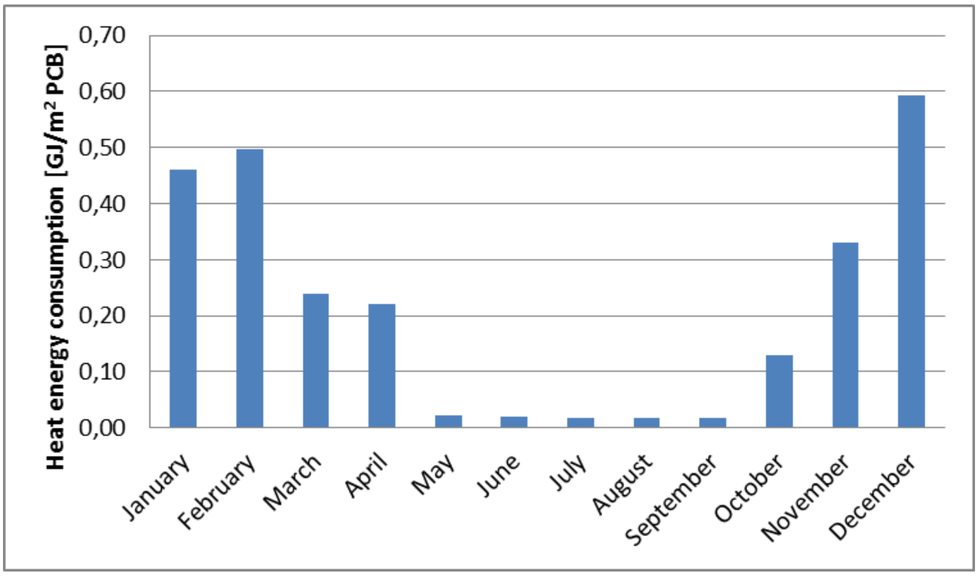


Figure 27. Heat energy consumption during one year period - 2012.

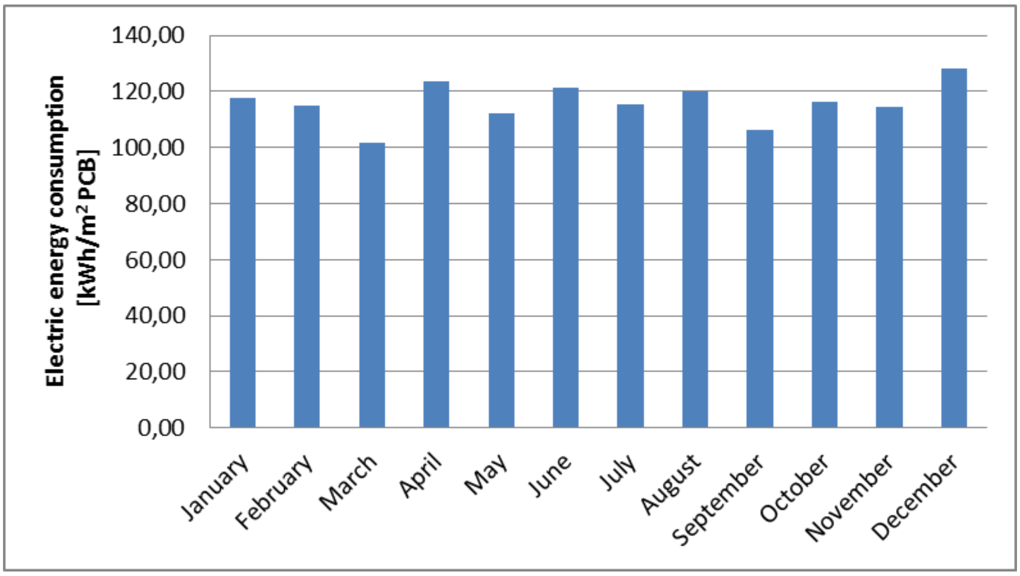


Figure 28. Electric energy consumption during one year period - 2012.

The algorithms implemented in the PCB modules of the "LCA to go" tool elaborated in the WP2 were based on production data collected during one year period. The case studies confirmed that such approach is correct, but the algorithms had to be adjusted in order to be more robust and adjust to the newest production data. The final results of calculation varied depends analyzed KEPIs. The differences were equal from 2% for energy consumption up to 68.7% for sludge and waste emission. The essential corrections were made. E.g. the factor related with water consumption for social needs was added to the algorithm elaborated in the task 2.3c. Moreover the factors related with coating production were taken out from previous factors in order to simplify the final algorithms for PCB.

The interviews with tool users showed that all calculated KEPIs included in the tool are relevant except economic information. The tool user said that costs of water and energy are very variable in some countries and can count them in an external program. Therefore this part of PCB module was cut off without losing functionality of the tool.

The analyses and interviews with represents of PCBs producers it showed also that in different PCB's companies the bill of materials (BOM) use in PCBs production processes could not be so precise or accuracy of data collection may not be as accurate as in the reference company. Therefore the window with input data in the sophisticated PCB module was changed as well as the algorithms were adjusted to new situation to prevent possibility of output errors caused by writing inaccurate data by the user.

The basic PCB module was designed for designers or producers of electronic equipment. For this target group, the results taken from the tool's PCB module are only valuable as input for the assessment of more complex products. Product designers usually are not familiar with PCB parameters – with exception of a PCB surface. Therefore the simplification of the tool in this issue was checked during case studies. It was stated that the error resulting from such simplification can be up to 700% (Fig. 29). This suggests that above mentioned simplification can be used only for sectors where influence of PCB is only a small part of whole product as e.g. industrial machine. For other cases more PCB's parameters have to be used for KEPIs calculation.

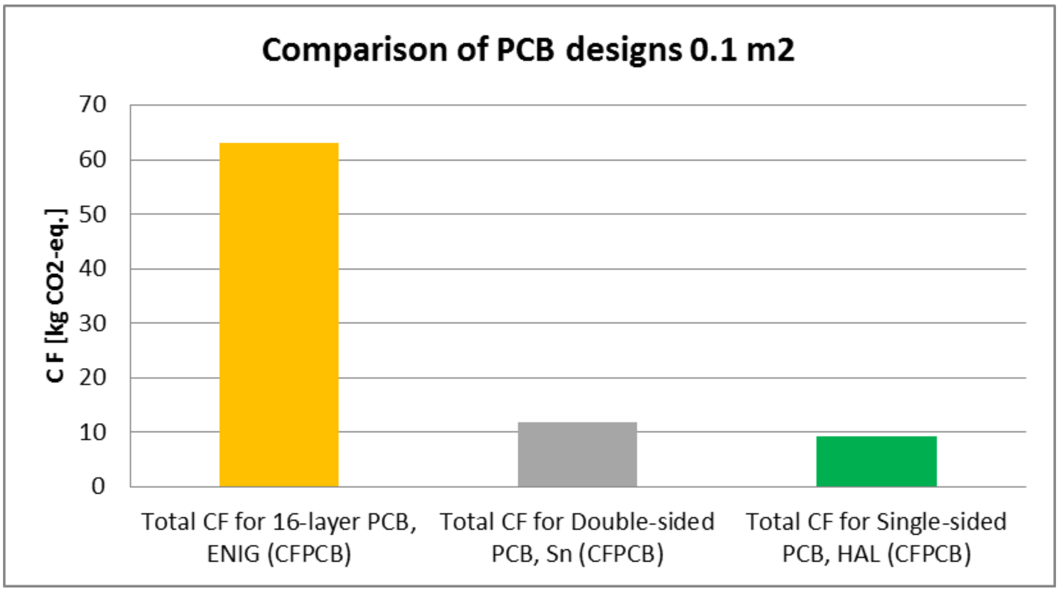


Figure 29. Total carbon footprint of typical PCB in different design version: surface 0.1m2, transport distance 10000 km by plane + 500 km by car.

It stated that the impact of transportation's in total carbon footprint of a PCB cannot be neglected because its share can be above 20% in some cases (Fig. 30 and 31).

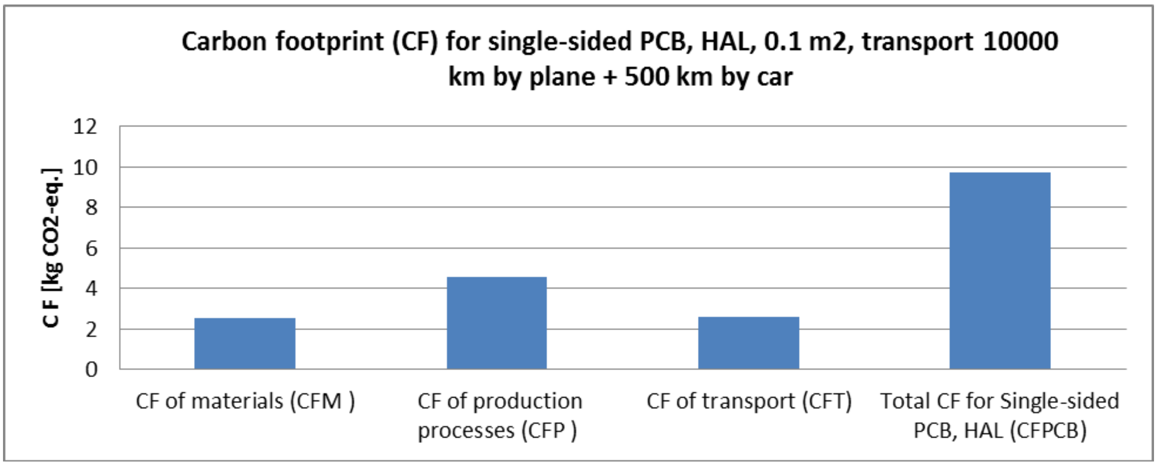


Figure 30. The transportation's share in total CF of a PCB.

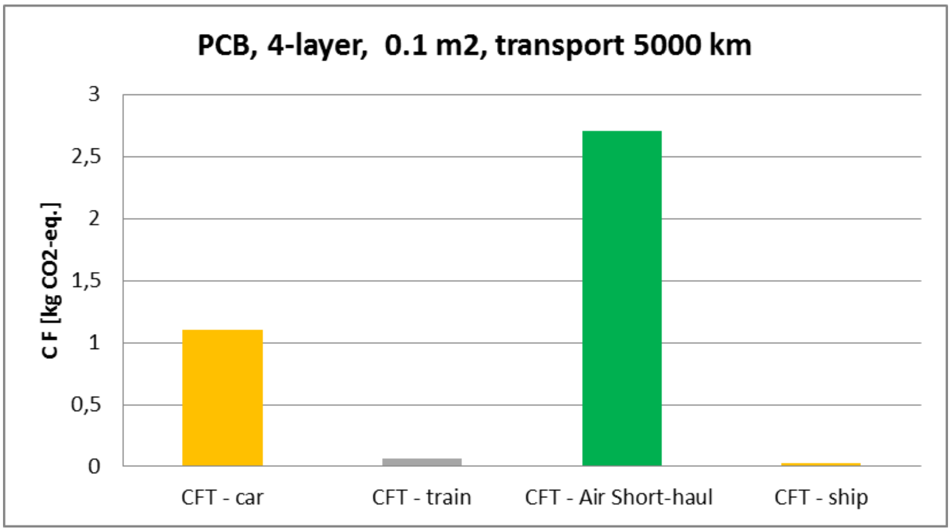


Figure 31. The transportation's share of a PCB's for different types of transport.

Based on the case studies results all algorithms and data bases for planned KEPIs calculation for PCB sector were improved. The algorithms and data bases for elastic PCBs were also added to PCB's tool. Finally elaborated a "user's manual" for the SIMPLE contained the assessment procedures step by step for both PCBs modules which have to be implemented in "LCA to go" tool.

Summary

The new data gathered during case studies in Eldos Company and users opinions were able to answer on all existing metrological questions presented in the D4.1 Report. The algorithms for PCBs modules created in WP2, based on case studies results were verified, improved and simplified. After analyses and interviews with represents of PCBs producers it was stated that BOM in different companies could not be so precise like in the reference company therefore the window with input data in sophisticated PCB module was changed as well as the algorithms were adjusted to prevent possibility of errors caused by the users. The improved and verified algorithms for PCBs modules contained "user's manual" were submitted to the SIMPLE for "LCA to go " tool preparation.

1.7. Future-shape Case Study on Smart Textiles

A streamlined LCA was conducted jointly by Future-Shape and Delft Technical University within a three-month period in spring 2012. The goal of the LCA was generating information on the prospective environmental impact of the SensFloor. The results are meant to support environmentally conscious decision-making in the ongoing product innovation process.

The scope of this study includes all phases of the product lifecycle (Cradle to grave) as far as information are accessible for the different environmental aspects. The system boundaries of this study encompassed the hardware of the SensFloor. As a simplified assumption the average European energy background system was chosen. The two scenarios were created to test the environmental viability of the SensFloor system during the use phase. For the purpose of the scenario analysis the energy consumption of the application context (room heating and lighting) was included in the system boundary of the LCA. When compiling the life cycle inventory (LCI) primary data was collected whenever possible from suppliers of half-products. If no primary data was available, data from literature and the eco-costs look-up tables of the Idemat2012 database was used [FS12]. The same inventory provided the data of the impact assessment. The results were calculated as Eco-costs, which is a LCA-based single indicator [FS13].

For the analysis a fast-track LCA approach, based on the single indicator 'Eco-costs", was used. The eco-costs allow for a rapid analysis of the environmental performance of materials, processes and energy use of a product. The approach takes advantage of LCA-based information about eco-costs of materials and processes that are available in form of look-up tables. The indicator describes the sum of all costs to offset the environmental burdens that occur throughout a product's life cycle "from cradle to cradle". Eco-costs represent virtual prevention costs of emissions as well as materials and energy consumption. The indicator covers the following impact categories: global warming, acidification, eutrophication, summer smog, fine dust, eco-toxicity, and resource depletion. Eco-costs are easily understandable by non-LCA experts 'by instinct' as they express a standardized monetary value (€). This is especially practical for SME [FS14, FS15].

Interpreting the LCA results lead to the identification of environmental improvement potentials. The recommendations were forwarded to the product developers of the SME as a basis for environmentally conscious redesign of the SensFloor. Preliminary technical approaches to improve the environmental performance were again checked by means of LCA. The results were published at the Joint international congress and exhibition Electronic Goes Green 2012 [FS11].

Two application scenarios were investigated:

A) Elderly home: Safety and energy management for an elderly person home for 20 years (SensFloor size 30m^2).

B) Lecture room: Presence monitoring system for a lecture room for 20 years (SensFloor size 4m^2).

In the first scenario (A), the sensing floor is placed in the house of an elderly person and is used for human fall detection (personal safety). An additional function is to control lighting, depending on room occupation. Also space heating is controlled, achieving estimated 30% energy savings for electricity (lighting) and gas (heating).

The second scenario (B) looks at building automation application. A room occupation monitoring system can save up to 36% of the annual electricity costs for lighting of a lecture room at a university. [16].

<u>The following assumptions were taken for both scenarios:</u>

- The system is operational 24/7 for 20 years.
- 6W operating power for all peripherals (transceiver, adapter and 3 meter of wire).
- No upgrades and maintenance during use phase (no introduction of new parts during use).
- EOL: down cycling to be used in ESD flooring.
- 3000km sea freight transport of parts to assembly.

Assumptions on the application context, Scenario A:

- Lighting: 1600kWh/a electricity (average NL)
- Room heating: 950 m^3/a natural gas (average NL)
- Energy savings potential of 30%

Assumptions on the application context, Scenario B:

- Lighting: 1440kWh electricity per year [16]
- No heating control
- Energy savings potential of 36%

Summary

For the analysis of two different SensFloor scenarios a fast-track LCA approach, based on the single indicator ‘Eco-costs”, was used, allowing for a rapid analysis of the environmental performance of materials, processes and energy use of a product. The approach takes advantage of LCA-based information about eco-costs of materials and processes that are available in form of look-up tables. The indicator describes the sum of all costs to offset the environmental burdens that occur throughout a product’s life cycle "from cradle to cradle". Eco-costs represent virtual prevention costs of emissions as well as materials and energy consumption. Eco-costs are easily understandable by non-LCA experts ‘by instinct’ as they express a standardized monetary value (€).

Part 2. Scientific case study results from each sector

2.1. VALSAY Case Study on bio-based plastics

2.1.1. Checklist of methodological issues addressed by the final Beta version of the sectoral tool for bio-based plastics

In the Deliverable 4.1 of LCA to go project a checklist of different methodological questions to be addressed in the bio-based plastics software tool were summarized in a table. A review of the methodological question is described in Table 6.

Table 6. Summary of methodological questions to be addressed by the Valsay case study.

LCA stages	Specific aspect	Bottleneck	Proposal	Evaluation criteria	Implementation in the beta version
Goal and Scope	Functional Unit	Ensure comparability of the product-systems analysed since bio-based plastic products may provide a different service and weight may change	Possibility to choose between a series of units, other than weight: volume, surface area, days of use, etc.	Analyse if the selection of units can be easily managed by the SME	Users are informed in every screen of the tool about the functional unit selected for their reference. Users can enter the functional unit just as a text, so they can chose between different types of units (mass, area, etc.)
	System boundaries	For most bio-based plastic products, energy consumption is not required for use	Exclude use stage from system boundaries	Assess the influence of the exclusion of the use stage	The use stage has been omitted in the software tool. Usually plastic products are not energy-consuming products at the use stage. This has been confirmed with experts (Ventura, 2013a)
		- Few specific regulations on the end-of-life stage of bio-based plastics products - Lack of common practices for waste management - Lack of reliable inventory data related to the end-of-life for some of the bio-based plastic families selected (PHA and Solanyl) - Lack of consistent data about end-of-life treatments - Risk of misinterpretation of impact results	Exclude end-of-life stage from system boundaries to minimize uncertainties	Assess the influence of the exclusion of the end-of-life stage Check the data availability	As has been commented above, the exclusion of the end-of-life stage has been reconsidered since one of the main advantages of bio-based plastics is expected at the end-of-life stage due to the biodegradability properties of some of them. However, users must take into account that most of the bio-based (but non-biodegradable) plastics have exactly the same end-of-life characteristics as the oil-based counterparts. An exhaustive work has been done to include the end-of-life stage which integrated the most up-to-date data about the end-of-life of bio-based plastics (Hermann, 2011) (Khoo, 2012).
		Data uncertainties about the processes considered within system boundaries	Allow enter customizable data a) KEPI values for the bio-based plastics production b) Customizable transport distance c) Fully customizable converting stage d) Enable/disable gate-to-gate LCC	Check if the customizable data really meets the needs of the SME If there is room for improvement add new suggestions for customization	A great effort was made on customizable options, which are described below a) Customizable KEPI's: the use of customizable KEPI's is still under discussion with Simpple. Apparently is not an easy task for

LCA stages	Specific aspect	Bottleneck	Proposal	Evaluation criteria	Implementation in the beta version
					programming. b) Customizable transport distance: this has been achieved successfully with a specific which allow users to enter the mode of transport (ship, road, train, etc.), type (delivery van, lorry > 32t, etc.), distance and amount of product transported. Beyond transport for raw material acquisition and distribution to customers, users are also able to enter internal transports between converting plants (e.g.: production of PET bottles from pre-forms, where the injection of the pre-form takes place in one plant and the stretch blow moulding of the bottle takes place in other site). c) Fully customizable converting/processing stage: This objective has been successfully achieved. Users are able in the beta version to enter customized data about processing: -Drying process (temperature, time) -Converting processes (electricity consumption, cooling water, lubricating oil, scraps) -Finishing process (electricity consumption, glue, ink) Default values are available if required, although own data is recommended for accuracy. d) Enable/disable gate-to-gate LCC: this objective has been fully achieved by the creation of a specific Economical

LCA stages	Specific aspect	Bottleneck	Proposal	Evaluation criteria	Implementation in the beta version
					Assessment module, which allow the calculation of gate-to-gate costs (from raw material acquisition to delivery of the final product to customers). Therefore users do not need to enable/disable the economic assessment. If required, users just need to enter their own economic data (default data is not provided for the economic assessment module)
	Cut-off criteria	Pay attention to small/not relevant flows which may have significant impacts (toxic, radioactive and carcinogenic substances)	To follow the same criteria as the cut-off rules given in the PCRs for plastics from the EPD system: *"Life Cycle Inventory data for a minimum of 99% (as mass or energy) of total inflows to the core module shall be included"*	Assess if the suggested cut-off rule really meet the needs of the SME's Check if whether add or not more complexity to the use of the webtool	We finally changed the concept for setting cut-off rules. Instead of the PCR criteria we based on the experience of the SME's to obtain data for LCA modelling. For instance the use of additives for PVC compounding was considered as these are used in high percentage (around 20-30% of total mass). Other materials like masterbatches (concentrates of additives and colorants used for plastic product converting) were also included, even though the additive/colorant itself represents a very small percentage in mass, the base material for the masterbatch is relevant, and therefore should be covered by the tool. A similar thing occurs with lubricating oil for converting equipment, which was also included.
LCI	Data collection availability	Balance between specific and generic data	➢ Use of generic data for raw materials and common processes and products (transport, electricity) ➢ Use of specific data (measured on-site) for processes under the SMEs control:	Analyse the process for company data collection in order to find gaps and difficulties with the LCA to go webtool	A deep analysis was made in order to look for the simplest scheme for the SME's. Two types of generic data were considered: a) Generic values for KEPI's of materials, electricity and transport, which were estimated from the state-of-

LCA stages	Specific aspect	Bottleneck	Proposal	Evaluation criteria	Implementation in the beta version
					the art references and data sources. b) Default values for processing stage (drying, converting, finishing processes), although users are noticed to enter their own data for more accurate results.
		Lack of LCI datasets and databases	Use of common templates for data collection achieved by SMEs in order to simplify data collection at company level	Assess if the use of the templates for data collection are whether effective or not	The way for enter the data was carefully reviewed with ITENE's and Valsay's users which are not LCA users. As a result of that several changes were made specifically for: a) Compounding and masterbatches b) Distribution stage c) Reorganisation of the processing step for an organized data entering scheme
		Restrictions due to property rights and/or confidentiality agreements	Allow LCA to go users to enter KEPI's on the web tool when necessary	Check if this measure could lead to wrong results/misunderstandings	As commented above, the use of customizable KEPI's is still under discussion with Simpple.
	Data quality	Lack of data quality in the available data	➢ Use of common templates for data collection ➢ Look at the criteria of existing PCR's for plastics from the EPD system, as a reference for data quality ➢ Users can enter their own KEPIs for raw materials when generic data are not found	Assess if the use of the templates for data collection are whether effective or not	As above mentioned, the way for entering the data was one of the core issues for the development of the beta tool. First tests with the beta tool seem work properly. Further tests will be made during the raising seminars for tool refining,
		Strong dependency on data sources (primary or secondary data)		Check if the users can really fill in customizable data when secondary data is not available	Default data for converting processes has been fully implemented in the beta tool in order to minimize such risk. In any case users are only asked about data that can be easily collected in a production site (electricity consumption, water

LCA stages	Specific aspect	Bottleneck	Proposal	Evaluation criteria	Implementation in the beta version
					use, lubricating oil, scraps produced, amount of material processed, distances and weigh transported). No complex questions have been made in the software.
	Period of validity of the database	Optimisation potential and room for improvement of bio-based plastics resin manufacturing and processing, which increases data uncertainty	➢ Allow users to enter their own KEPIs to consider a new material or any optimization ➢ Databases shall be updated in a three-year basis	Check if the users can really fill in customizable data when secondary data is not available	As above mentioned use of customizable KEPI's are still under discussion with Simpple. The period of validity and update of the KEPI's database is question for common discussion in the exploitation plan (WP7).
	Allocation	Most allocation problems arise from the upstream module where bio-based plastics is obtained among other co-products	Users will not have to manage with allocation issues since the LCA to go experts will take into account allocation issues both at upstream and core module when updating the internal database.	To be internally tested by ITENE	The co-product allocation issues were effectively considered by ITENE when the KEPI's database was developed. Users will not have access to that in order to minimize the risks of error by a wrong methodological choice. Economic allocation was considered since some of the co-products in the bio-based plastic production are produced in a big amount without having a commercial application. Therefore it was decided to apply the worst case which is to search for a bigger allocation of impacts to the commercial products.
		Allocation issues in the core module when plastic waste is used to produce electricity or heat			As above-mentioned, finally end-of-life was included for the bio-based plastics sector by using estimated data. Indeed, all the KEPI's for the end-of-life of oil-based plastics considered the credits due to the displacement of raw materials in case of recycling (Diaz, 2006) as well as the avoided burdens due to energy recovery both in landfill and incineration operations.

LCA stages	Specific aspect	Bottleneck	Proposal	Evaluation criteria	Implementation in the beta version
					In case of bio-based biodegradable plastics, it was considered the displacement of soil conditioners as a result of the production of compost, following the assumptions provided by Hermann (2011).
LCIA	Selection of impact categories	Select the most relevant impact categories for the LCA of bio-based plastics products	On the one hand, the selection takes into account the needs from SMEs and on the other hand it has been completed with other relevant impact categories defined from an ABC analysis on literature research. The final proposal of impact categories is: Global warming, Water footprint, Land use, CED (non-renewable resources), CED (renewable resources), Eutrophication, Acidification, POCP, Human toxicity	Check the areas of interest of the SMEs Does the company really understand what each impact category means?	Even though the scientific relevance of considering a wider group of impact categories, it seems that the more important concerns are related to carbon footprint. However it was decided to keep users the decision to select how many impact categories they want to check.
		Check the existing PCRs for bio-based plastics products to know if the results delivered by the LCA to go tool would serve to apply for ecolabelling schemes	The results of LCA to go tool can be very helpful to apply for an EPD since the impact categories are the main criteria of this ecolabelling scheme.	Check the integration of webtool results to apply for bio-based plastics ecollabelling schemes in which Valsay is interested	Current results provided by the tool can be used as a preliminary step for ecolabelling schemes. However fully integration with ecollabelling seems to be complex as the criteria often change. For instance, almost all the EPD PCR Basic Module CPC Division 36 Rubber And Plastics Products are covered. However this is only true if own data for processing in used in the LCA to go tool, since in accordance with this PCR , site specific data shall be used for the Core Module (converting stage).
	Biogenic carbon	One of the most influential aspects on LCIA of bio-based plastic products Potential source of uncertainties due to the existence of different ways to address biogenic carbon	➢ Consider biogenic carbon and storage at the raw material extraction stage ➢ Whenever possible biogenic and fossil carbon will be reported separately	To be internally tested by ITENE	Current methods for the treatment of biogenic carbon are still under development, and sometimes are unclear, especially at non-LCA expert level. In addition, to date (April 2013) there

LCA stages	Specific aspect	Bottleneck	Proposal	Evaluation criteria	Implementation in the beta version
					is not a standard method for the treatment of carbon storage in bio-based products (Pawelzik, 2013). Therefore, it was decided to keep as simplest as possible without distinguishing between biogenic and fossil carbon.
Interpretation of results	Life cycle results	Easy interpretation of LCA results for the SMEs users	➢ The tool should provide first assessment results within a few minutes, based on generic ecoprofiles ➢ Easy results analysis allowing the comparison between different alternatives ➢ Easy data import/export ➢ Easy internal and external results communication via templates ➢ Current legislation and standards in the tool development must be considered	To test the time required for the companies to obtain an assessment with the bio-based plastics webtool	The time required for an assessment with the bio-based plastics LCA to go tool has not been tested yet, since the tool is still under development (July 2013). However it was intensively discussed with Simpple the easiest way for presenting the results, Several suggestions were made by ITENE and Valsay, including for instance a) The automatic generation of customizable PDF reports. b) A cleared explanation of the significance analysis c) The number of alternatives to be compared. To date (July 2013) only a pair-wise comparison is allowed, although ITENE and Valsay suggested a comparison of at least 3 to 4 four alternatives.
	Comparability	Non ISO compliant LCA, but LCA studies should consider technical substitution potential of bio-based plastics for oil-based plastics	Make the comparison as close to the end product as possible	Discuss with Valsay how the results from the webtool can be used for internal and external communication	

2.1.2. Summary

The case study on bio-based plastics tried to give a reply on the current demands for SME's on environmental assessment within the bio-based plastic converting sector. A carefully review for simplicity was made. Consequently bio-based plastics tool users shall only enter just few data which are under their control like converting processes, raw material use and/or transport operations. Furthermore default data was also included for converting processes with the aim to help users when data is not available. Fully customizable processing, transport and distribution modules were also included in order to increase the versatility of the tool to customer demands

Moreover, the most important change has been the inclusion of the end-of-life as a part of the environmental assessment. Such decision was taken due to the expected advantages of the bio-based plastics during the end-of-life stage. Estimated KEPI's were considered in accordance to the state-of-the-art on the end-of-life of bio-based plastics. Pre-defined scenarios were built in accordance with selected references, although customizable end-of-life scenarios were also included.

In addition a full integration of gate-to-gate economic assessment has been achieved by the development of a separate gate-to-gate LCC module.

However, there are still some aspects for further work, like the use of customizable KEPI are which are currently under discussion with Simpple. On the other hand, the period of validity of the database and planned updates are still under discussion in WP7.

2.2. CDAMC Case Study on Industrial Machines

2.2.1. Scientific case study reports and evaluations

The detailed reports and results of the Kapp Grinding tool and Posalux EDM case studies are integrated in D4.4. The results all show that in the case of Industrial machines the Use phase is the predominant phase from a CED point of view.

In the case of the EDM case study the results showed that the total CED for the lifecycle of their product was 3,926,520 MJ and the Use phase accounted for 93% of the total CED. This particular product has an in use phase of 20 years. The second most significant phase was the materials phase at 4% of the total CED.

Methodological aspects

The process of applying the methodology worked quite well in the case of the EDM case study. The SME had most of the data required to hand or available in some format within their processes and systems. Their bills of materials helped with gathering raw data about the types of material used within their product and the weight of that material. Support was required to explain what Stand-by, Idle and in-production meant from an ISO/CD 14955 point of view compared to perhaps their own understanding of these terms within their organisation. The gathering of data for typical use scenarios is a process that will vary from SME to SME. In the case of the EDM product, the SME had to investigate typical use scenarios. They looked at one of their main customers and gathered information on their typical usage taking into consideration the normal working pattern e.g. the number of shifts per week, the typical in operation time per day, planned maintenance, typical OEE (Overall Equipment Effectiveness). By investigating this information it allowed them to fix a figure for the typical in operation time per day, which was calculated at 22.18 hours per day in production. The typical lifetime of their product is 20 years.

The results clearly indicated that any improvement strategies should focus on the Use phase and improvements to the electricity and compressed air consumption when the machine is in production.

The methodology clearly guides the user in the correct path to gather relevant data to result in an output that will highlight the most significant life cycle phases for their product.

In step 1 illustrative data can be used, however in step 2 it is important that robust data is collected otherwise the quality of the data can only be listed as indicative.

In the case of the EDM case study actual data from a user of their machining process was used to calculate the number of hours per day that the machine is actually available for production. Measurements were taken of the energy consumption of the machine the different phases such as stand-by, idle and in production. This is the level of data that is needed to ensure that the result is useful.

It was also a bit unclear for the companies what the indicator Cumulative Energy Demand (CED) means and what does it includes This should be clearly defined using an example within the webtool.

Evaluation criteria aspects

In deliverable 4.1 it was stated that the case studies would be evaluated through the following criteria:

- Robustness of the result,
    - Compare the results generated through the tool with the LCA-results from the case studies. Is there a difference in the environmental profile?

In this case it has not been possible to evaluate the robustness of the result against what would be achieved with the software as the software will not be available to test until October 2013. It is our intention to carry out this analysis with the case study SME's when the software is available. However for both case studies a rough LCA model has been carried out according to step 1 in the tool and compared to the results of the full LCA which can then be compared to the results of the tool.

- Simplification of the data collection,
    - Identify the minimum amount of data needed. What is the minimum amount of data needed for a robust result?

For both case studies different LCA models from rough to detailed have been carried out to ensure that the simplification of step 1 in the tool e.g. just 5 materials can be chosen for the materials of a machine tool, showing just minimal differences. Therefore it can be anticipated that the approach is feasible and gives robust results. On the other hand detailed information on the materials is needed for 98% of the materials in step 2.

The companies reported that on the one side the data required in the detailed assessment in stage 2 is very intensive as they have to do measurements for all main components but then on the other side results in quite good results for further analyses and improvement.

- Generalisation of the results,
    - Test under which conditions the tool is applicable to other machine tools, other than the ones under consideration in the case studies.

The case study SMEs whilst all under the umbrella of industrial machines were quite different processes. The same approach was adopted with all of them and the methodology worked well. However this will be checked when the software is available and under test by the SMEs to ensure that the tool will work for other processes that fall under the umbrella of industrial machines

- Potential to generate Improvement ideas,
    - Comparison of the detaileness of the LCA-results and the tool result. Are the results available in the same detail to generate the same improvement ideas?

The improvement strategies that were suggested to the SME case study companies such as focusing on improvements in compressed air consumption during the life cycle should also be the proposed improvement strategy that the software will make. This will be tested and evaluated when the software is available.

- Amount of ILCD datasets generated,
    - Count how much ILCD datasets are generated through the case studies.

The following datasets are planned for the areas of Grinding and EDM drilling.

- Profile grinding Steel_rough
- Profile grinding Steel_finishing
- Profile grinding Steel_average
- Profile grinding Aluminium_rough
- Profile grinding Aluminium_finishing
- Profile grinding Aluminium_average
- Profile grinding Machine (infrastructure)
- EDM Drilling Steel_thickness_1mm_&_hole_diameter_0.3mm
- EDM Drilling Steel_thickness_1mm_&_hole_diameter_0.1mm
- EDM Drilling Steel_thickness_1mm_&_hole_diameter_0.05mm
- EDM Drilling Steel_thickness_0.7mm_&_hole_diameter_0.3mm
- EDM Drilling Steel_thickness_0.7mm_&_hole_diameter_0.1mm
- EDM Drilling Steel_thickness_0.7mm_&_hole_diameter_0.05mm
- EDM Drilling Steel_average
- EDM Drilling Machine (infrastructure)

Our targeted ELCD datasets on machining processes should be compiled from average resource consumption of different machines. This is needed to secure a high level of quality of the datasets and to confidentiality reasons as data from a single company cannot be communicated. This data will be collected during the implementation of the LCA to go tools from 10/2014 - 06/2014

Summary

The case studies have proven very helpful for the SME's involved. The machine developers were very happy with the quality of the reports and the analysis that was carried out. The process was extremely helpful and guided their personnel through the various stages of gathering relevant data. The support documents including the excel templates used and the ISO documents helped them in carrying out the study. The process has introduced LCA to different areas of the organisation that were not aware of LCA at all prior to this study. Certain departments were aware of environmental aspects and carbon footprint but would not have known where to start to carry out an initial study. In the case of the EDM SME the results were surprising for them, due to the fact that the Use phase of their process is so significant e.g. their customers in Asia are already very concerned about the compressed air consumption of their product and the LCA to go study highlighted that this has a significant impact during the Use phase. Compressed air makes up 20% of the energy demand, therefore due to customer demands and the results of this study there is a real need for the SME to focus on the compressed air aspect of their product. The company also see this as a very valuable tool to be used internally to ensure that they have a better understanding of their product, there may be an option to use the information from a sales and marketing point of view however this has to be handled very carefully to ensure that doesn't result in a negative impact of their company if it is not handled appropriately. The company also sees the need for legislation and standards to control how companies use and promote and LCA data and customer demand for this information will also drive other machine tool companies to adopt LCA as a method of promoting the energy demand of their product.

In summary the case study SMEs found the process extremely useful, there was support and guidance needed to ensure that they were collecting the correct data. Supporting documents and links to relevant documents will be important in the software tool. This part of the process has been successful as we have worked with some good case study SMEs, they have been new to LCA but have found the process to be helpful and has given them another insight into their product. They see benefits in having done the study and they need to understand how they can best use the information gained for their businesses moving forward. The work has generated interest in the wider community as we have been asked to speak about the case studies work at other seminars and two research papers presenting the two case studies have been accepted. It is however important to note that it has not been possible to test the software however this will be done when the software is available in October 2013.

2.3. MicroPro Case study on electronics

2.3.1. Methodological aspects

Main methodological questions to be addressed in the course of the case study assessment are:

1. Inclusion of (component) lifetime
2. Definition of benchmarks
3. Modelling end of life
4. Bridging the gap between components data and the product assessment tool
5. (Re)design decisions derived from assessment results

2.3.1.1. Product Lifetime and Repair

Only if component lifetime is considered in the assessment, the benefits of longevity can be quantified. However, compared to other figures in this assessment which can be stated with a high level of confidence (e.g. housing weight, carbon footprint of CPU processing) a components lifetime can be stated much less precise. Even worse, lifetime will depend on external factors, such as the battery charging patterns of the user or thermal stress from the environment, operation in humid environments, mechanical stress, etc. Furthermore, technical lifetime of a component never is a discrete value, but follows a certain failure curve over time. Although there are reliability models and data (such as MTBF – mean-time before failure) for parts, components it is hardly possible to translate these into lifetime predictions for dedicated sub-assemblies, nor can MTBF directly related to failures in the field. For environmental data it is intended to neglect supplier differences. For reliability these differences might be even larger (good or bad design), but for a coherent approach, these supplier differences should not be addressed in the assessments. Nevertheless it is important to be aware of this.

The initial investigations in the course of the case study implementation unveiled a strong need to differentiate between technical lifetime and business model induced lifetime.

Only if component lifetime is considered in the assessment, the benefits of longevity can be quantified. However, compared to other figures in this assessment which can be stated with a high level of confidence (e.g. housing weight, carbon footprint of CPU processing) a components lifetime can be stated much less precise. Even worse, lifetime will depend on external factors, such as the battery charging patterns of the user or thermal stress from the environment, operation in humid environments, mechanical stress, etc. Furthermore, technical lifetime of a component never is a discrete value, but follows a certain failure curve over time. Although there are reliability models and data (such as MTBF – mean-time before failure) for parts, components it is hardly possible to translate these into lifetime predictions for dedicated sub-assemblies, nor can MTBF directly related to failures in the field. For environmental data it is intended to

neglect supplier differences. For reliability these differences might be even larger (good or bad design), but for a coherent approach, these supplier differences should not be addressed in the assessments. Nevertheless it is important to be aware of this.

Case Study Setting

MicroPro provided LCA to go with a list of the main components used in the iameco and their likely life. However, estimated lives are by definition anecdotal, as companies will not provide such data, and it is related to actual use. However, to establish the advantages of the reuse approach it is necessary to make assumptions about component failure, although it is probably not necessary to accurately estimate the life of particular components. It is more a question of determining the probability of "incidents" (component failures) and therefore the likelihood of the PC being scrapped with consequent CO2 and energy expenditure.

MicroPro suggested that LCA to go would need to calculate the likelihood of the entire computer being scrapped if any component fails. This could be around 70%, but is purely an assumption. That risk would be compounded every time another component fails. However, if we are assuming every component can be repaired in the iameco version, then the only reason we need to know when a component is likely to fail is to know when another component needs to be added. This setting is based on the assumption of rather high failure rates and that disposal of computers frequently is induced by hardware failures.

A differentiation has to be made to quantify the likely advantage of a computer designed for repairability and long lifetime: The probability of trashing in the event of component breakdown would be a certain percentage for PCs not designed for disassembly/reuse, but 0% if they were designed for disassembly and reuse and if the necessary service infrastructures are in place. The probability of trashing would double e.g. every two years as a result of increased component failure, if repairability is not enhanced. What the design for reuse and the reuse infrastructure is doing is reducing (or eliminating) the possibility of full system breakdown and trashing of machine. We would probably have to assume a number of repairs/upgrades over the extended life of the PC, based on the energy required to replace with used or new components (2 scenarios). The lifetime assumption could be very general, say an incident every two years, and the options are trash (or take-back, replace component with old or replace with new.

To check whether such an approach in general is based on appropriate and realistic assumptions, Fraunhofer explores below the feasibility of a technical lifetime model more in detail, based on some third party evidence.

Furthermore, the initial investigations in the course of the case study implementation unveiled a strong need to differentiate between technical lifetime and business model induced lifetime.

2.3.1.2. Technical lifetime

Technical Lifetime Model

For Hard Disk Drives the Annualised Failure Rate (AFR) is a typical technical parameter, which also makes it into the specification and product datasheets frequently. It is less frequently used for other components, but applicable as well.

Mean Time Between Failures (MTBF) and AFR are correlated as follows:

$$AFR = 1 - e^{\frac{-8760}{MTBF}}$$

This equation assumes that the component or device is powered on constantly, i.e. for 8760 hours per year. AFR then is the estimated fraction of all devices to suffer from a failure, i.e. the Annualised Failure Rate in % per year. As long as the AFR is small, which is the case for computer components, the formula can be simplified as follows and generalized to reflect actual power-on times:

$$AFR\left[\frac{1}{a}\right] = \frac{t_{on}\left[\frac{h}{a}\right]}{MTBF\,[h]}$$

Typical AFRs for computer components are in the range of 2% or less, even for HDDs which are usually known to be a weak point of computer products. Schematically this means a share of failed units over time as depicted in Figure 32.

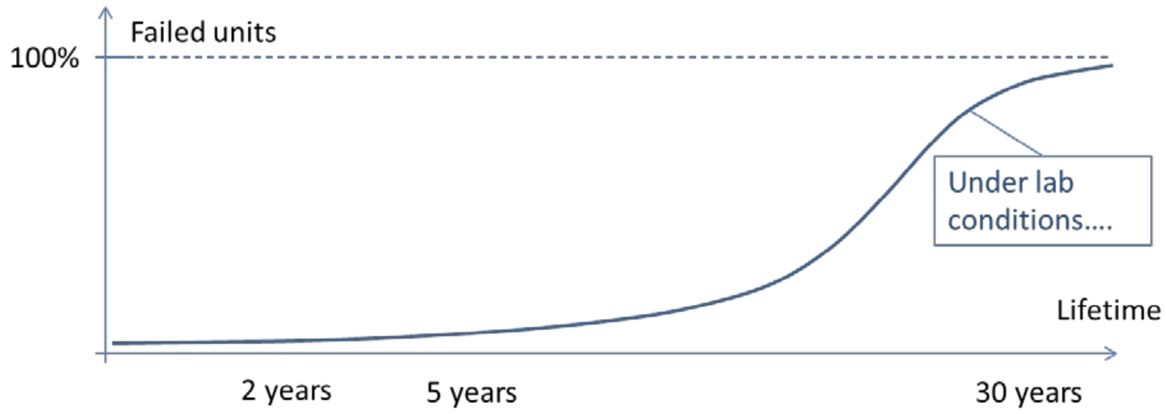


Figure 32. Failed units over time for one type of component (schematic illustration)

It has to be recognized, that component lifetime is not a fixed value, but rather a question of probability: An individual component might fail any time. Any lifetime statement has to be made with caution under these conditions. Furthermore, real life stress of any kind (heat, drop, stress, excessive power supply…) increases failure probability, and rarely in a reproducible manner.

Looking at the multitude of components and sub-assemblies in a laptop, each single component might have a pretty good life expectancy (Figure 33).

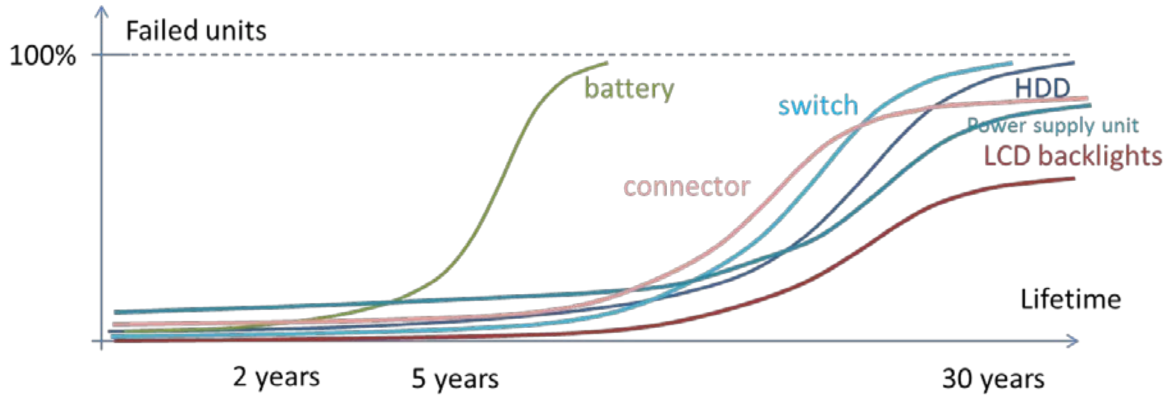


Figure 33. Failed units over time for major components (schematic illustration)

However, calculating the rate that ANY of the components might fail yields a rather high AFR for the whole unit, see schematic drawing in Figure 34.

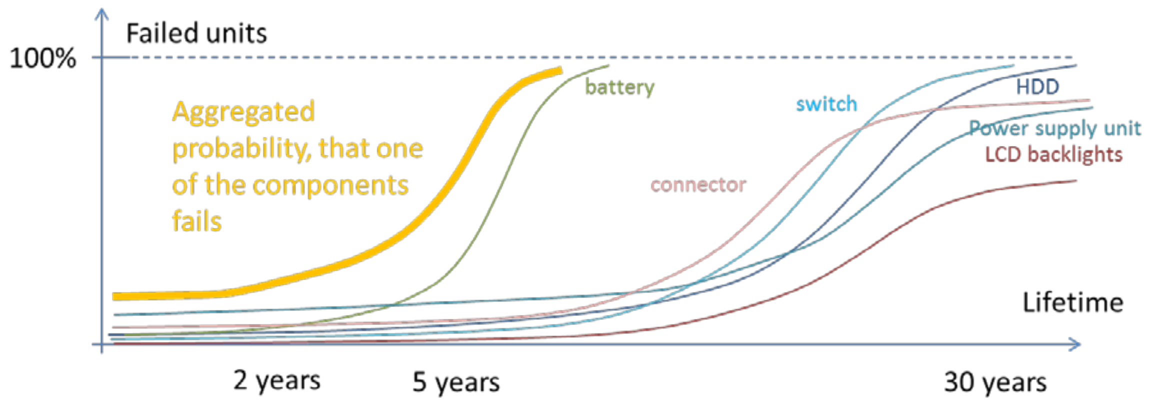


Figure 34. Aggregated failure rates (schematic illustration)

This graph also corresponds with field data, that the annual failure rate of company notebook computers in the US is roughly 20% (IDC, 2009).

The fact that no single component can be identified as the main failure hot spot is confirmed by the regular survey by German's c't magazine, where consumers are asked, which components are replaced or repair in case of a failure (which does not necessarily mean, that this component failed, but for disposal this does not matter). Repair includes also damage, not only malfunction.

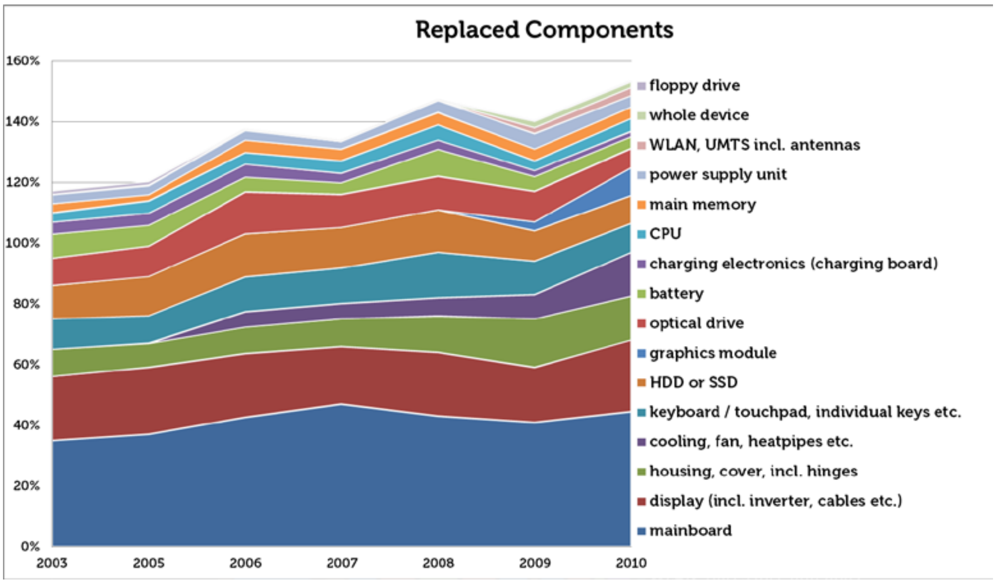


Figure 35. Replaced components of laptops (compilation based on data by c't)

For PCs the website hardware.fr reports an extensive return statistics, which allows to state failure rates of PC components, being returned within the first 6 to 12 months after the computer has been sold, thus in average not covering a full year [Prieur 2012]:

- Mainboard: 2.01%
- Power supply: 1.58%
- Memory: 0.78%
- Graphics card: 1.77%
- HDD: 1.74%
- SSD: 2.93%

Failure does not necessarily mean an end of life for the whole device: The next factor which comes into play is the likeliness that a device repair will happen as soon as one of the components fails. If a key on the keyboard fails it is very likely, that the user goes for a repair. If the display or mainboard fails this is related to significant spare parts costs, and it is less likely that the user decides to get the device fixed and might purchase a new laptop instead. What further complicates this matter is the fact, that the repair likeliness is not a fixed factor but decreases over time: A broken display might be fixed for a 2 years old computer, but not for a 6 years old unit.

There is one survey back from 2008 that in case of a failure, only 8% discontinue the use of the device, 28% keep on using it without getting the failure fixed, remaining 64% get the repair done [test 2008]. This indicates that a strategy for better repair might only have an effect on these 8%, plus those who continue operating a device with a failure but might replace the device then later on when the failure is one among other reasons to go for a new one. This latter effect however is a highly speculative one. This figure of 8% is also in contradiction to MicroPro's default assumption proposal of a 70% likeliness to trash a device, if a component is broken.

It can be assumed, that *repair likeliness* is close to 100% within warranty period of 2 years[3] and goes down to 0% in the following years.

A simplified assumption as follows can be made:

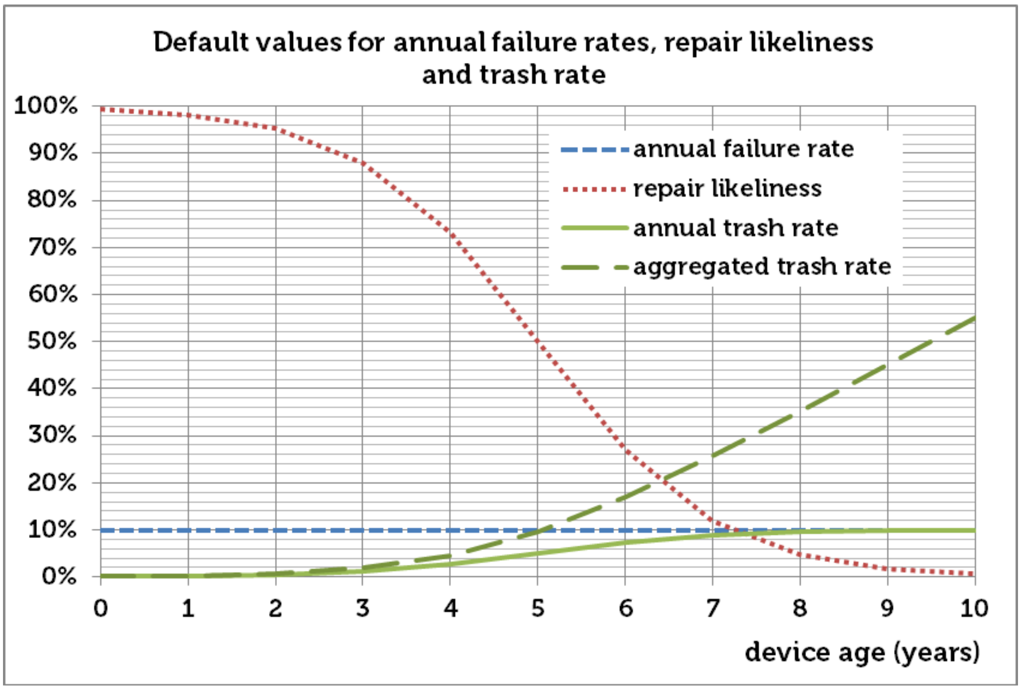
> Repair likeliness in average roughly 90% in the first 5 years, but then rapidly going down and meeting approximately a likeliness of 0% for a ten year old device, which is best approximated by an S-curve:

$$RL = 1 - (\frac{1}{1 + e^{5-t}})$$

This leads to the introduction of a rate, of how many laptops will reach end of life due to a component failure. For clarity, we call this the *Trash rate*. The Trash Rate TR for a given year related to the annualized failure rate and repair likeliness is defined as follows:

$$TR_a = AFR * RL_a$$

An adapted technical lifetime model based on a constant annual device failure rate of 10% (see data on device failure rates further below) yields an annual and an aggregated trash rate as depicted in Figure 36.



[3] Not covered is the case that unit which failed within the warranty period might be scrapped and exchanged by the manufacturer against a new device instead of being repaired.

Figure 36. Default values for failure rates, repair likeliness and trash rate

Logically, the annual device trash rate cannot exceed the annual failure rate of 10%, but aggregated the total trash rate exceeds 50% after ten years.

Precisely, a match between components, failure rates of these and repair likeliness depending on the component, which failed, would be required. A simplification however seems justified as according to the existing evidence the effect of repairability is only a minor one: Given this realistic technical lifetime mode, device lifetime in average is 9 – 10 years, which does not correspond with observed field lifetimes.

Field lifetime

According to background data used in the EPEAT Environmental Benefits Calculator device lifetimes (business to business products) for the initial user are 51 months for LCD monitor and desktop PC (FEC, 2009).

According to a survey by IDC (IDC, 2010) among 300 US companies the lifetime of laptops in average is 29 months. A second life is not included in these figures. The same source states, that per year 19.6% of all laptops used in these companies need repair.

The most comprehensive report on laptop failure rates is an analysis of Square Trade, an assurance company for IT products (Square Trade, 2009). According to their statistics failure rates are as listed in Table 7, which are significantly lower than those reported by IDC, but include mainly consumers, which are likely to use the devices less frequently than business users, thus resulting also in lower malfunction rates. A failure rate of 31 % after 36 months indicates a significantly longer technical lifetime of laptops than the observed device lifetime (given also the circumstance, that a malfunction does not mean the devices is disposed off at this point of time).

Table 7. Failure rates of laptops (SquareTrade, 2009)

	Months since item purchase		
	12 months	24 months	36 months
Malfunction rate	4.7% Premium laptops: 4.2% Entry-level laptops: 4.7% Netbooks: 5.8%	12.7%	20.4%
Accident rate	2.5%	7.0%	10.6%
Total failure rate	7.2%	19.7%	31.0%

The average age of computers, which includes PCs and laptops, used by consumers in Germany is between 2.5 and 3 years, consumers being asked for the age of their computer, the best equipped one in case more than one computer is in operation in a household [ACTA 2012]. If this is the current age, lifetime can be assumed to be significantly longer. Older than 5 years, however, is stated by roughly 15% of those, who stated an age of their computer, which indicates (under an almost constant household penetration with respect to computers) that in average computers are not likely to reach much more than 5 years lifetime in average. If it would be well beyond 6 or 7 years, a stock in use would pile up, which should correspond to a much higher percentage stated by the consumers. It should however be noticed, that almost half the respondents, who stated there is a computer in their household, also stated there is more than one. So frequently there is at least a second computer not covered by the above lifetime considerations, but this second computer frequently might be used only as a reserve. A representative 2009 survey published by Intel indicates other use patterns: According to their survey 32,9 % of the computers are maximum 1 year old, another 28 % are not older than 2 years. This indicates roughly a replacement cycle of 3 years [Intel 2009], again assuming that most sales are replacement sales. The difference between the 2009 and 2012 data might be due to the increasing sales of tablets lately. The Fachhochschule Nordwestschweiz [Stocker 2013] analysed the age of laptop computers recycled by Swico and identified an average age of laptops of **9 years** when they reach recycling. Definitely, there is a significant delay between the point of time when a laptop is not used anymore (regularly) and the time it is handed over to recycling by the user, but there is no further study available investigating the "use lifetime" as such. Given the above data and the expectation that the lifetime of PCs is likely to be longer than for laptops default "use lifetimes" for consumers are proposed to be 48 months for laptops and 60 months for PCs.

For a rack server Stutz et al [Stutz 2012] state in an LCA study 4 years lifetime, which is "consistent with general business customer use models". Note, that other manufacturers base LCA calculations on different assumptions, such as Fujitsu calculating with an average lifetime of 5 years [Böttner 2011].

Table 8. Default average electronics use lifetimes

	consumer use	business use
Laptops	48 months	29 months
PCs, Integrated PCs	60 months	51 months
Servers	n/a	48 months

Given these data sources it is evident, that the technical lifetime model developed above cannot address the dominating reasons for an end of a computers' lifetime. Hardware failures might be one reason, but obviously not the only one. Therefore it is not appropriate to calculate product lifetimes on the basis of technical lifetimes only.

To take into account the failures throughout the use lifetime the trash rate has to be calculated according to the equations developed above (now, on a monthly basis with monthly failure rate MFR, which is $1/12^{th}$ of AFR, and t in months):

$$TR_{lifetime} = \sum_{t=1}^{lifetime} (\frac{AFR}{12} * (1 - \frac{1}{1 + e^{t_{RL50} - \frac{t}{12}}})$$

t_{RL50} is the point, where repair likeliness is 50%. In our model this is 5 years: A device of this age is assumed to be repaired in 50% of all cases and trashed in the other 50% of cases. Following the S-curve this goes down to 12% for a 7 year old device.

Default settings and values for a benchmark product are as follows:

AFR: 0.1

t: see Table 2

t_{RL50}: 5 years

The trash rate will be used like a yield loss rate of the use phase. Example: For a "use lifetime" of 5 years under default settings the trash rate is 0.071, which means, for a target use lifetime of 5 years 1,071 devices have to be produced as additional 0.071 devices need to be produced[4] to replace trashed ones.

An adjustment of the default settings for the product under study can be justified in the following cases and the following extend:

AFR: In case of an extremely robust design or of extremely long living components an adaptation of the Annual Failure Rate is justified, but it should be kept in mind, that the 10% default AFR already considers robust B2B products, and that failures can be related to numerous components, misuse and accidents, and system aspects, which make it challenging to bring down the AFR significantly, and rarely to set it at values as low as 5% or less. Availability of real field data from minimum the first year of use allows to change default settings or well justified design measures, which are clearly better than the typical market average.

t: For extended use lifetime see justifications below.

t_{RL50}: Any major measures to enhance the repair likeliness (e.g. design for repair, free or low-cost replacement service or spare parts provision etc.) might justify to shift in the model the point of 50% repair likeliness by 1 or 2 years, but it should be recognised, that repair friendliness is not the dominating aspect, why a computer might become obsolete from the perspective of the user. Consequently a t_{RL50} of more than 7 years can hardly be justified.

[4] Differentiation still to be made, whether the „new" device is made from used components and whether trashed devices can be cannibalized for reusable components

2.3.1.3. Business model induced lifetime

The baseline considers typical product lifetimes (first life) as found in published statistical data and listed Table 8.

Any measure implemented to extend the product lifetime now allows to calculate with an assumed prolonged lifetime. Given the fact that it is typically not the hardware lifetime, which limits the computer lifetime other business related factors only count as valid basis for assuming a longer lifetime. Such justifications are:

- Implemented, user-friendly take back and refurbishment program (potentially along with suitable design measures for repair and upgrade)
- Implemented, user-friendly upgrade service
- Software configurations (open source software, such as Linux), which are affected less by software induced obsolescence
- Extended warranty (longer than default lifetimes)
- Strong evidence from the field, that products are used longer in average than the default lifetimes

Be aware, that also other factors influence computer lifetimes: Just as an example, there are indications that the current shift towards tablet computers might prolong the replacement cycles of PCs and laptops, just as the "need" for latest technology is rather served by the tablet computers used in parallel to a laptop or PC. Consequently, computer lifetime is a "moving target" and all lifetime statements are subject to major uncertainties.

The possibility of establishing a permanent relationship with clients through a lease model of sales, or a long-term warranty, is intended to have the effect of extending the product life through promoting the repair, upgrading and reuse of the product and its components, rather than scrapping in the case of component failure. This business model would require locally based service arrangements which would allow clients to either return their product so that it could be repaired, upgraded or replaced, and where the failing components could be replaced, and the products upgraded or in the worst instance cannibalised and re-assembled, thereby extending the product life. It is of course also likely that some components will not be reusable and will be disposed through normal recycling channels.

In the data model these business model induced lifetime extensions have to be justified and explained in relation to the default use lifetimes listed in Table 8.

2.3.1.4. Definition of benchmarks

Any benefits of eco-design and business strategies for longevity will be quantifiable only in comparison to conventional product concepts (benchmarks). The definition of these benchmarks can increase significantly the assessment burden for an SME as a product has to be assessed, which is not developed by the SME itself.

Throughout the concept development for the case study, two options have been proposed:

Option 1: Definition of a certain set of benchmark products, but given the multitude of possible configurations, this approach would result in an extensive database of conventional product configurations, with the risk of being out of date pretty soon, and/or a mismatch between such conventional product configurations and the dedicated configuration of the new, eco-designed product.

Option 2: The SME defines the benchmark product as a derivate of its eco-designed product, i.e. taking the entries for the eco-designed product as a starting point and to adapt only selected parameters, which to his best knowledge would represent a competitor's product (e.g., by adapting lifetimes, recycling quotas, energy consumption in the various modes, or exchanging SSD by HDD).

Now, having investigated further methodological issues and complexity the option to be implemented has to be redefined as follows:

A basic consideration is that default values have to be defined anyway to fill those gaps, where the SME lack knowledge or insights. This leads to a benchmark, where technical settings should be made as for the product under study (this will yield consequently no difference), and default entries for other aspects as listed in below.

Table 9. Default (benchmark) value for products.

Data entry	Default (benchmark) value	Source of default data
Product lifetime ("use lifetime")	Same as in **Table 2.** differentiated per type of product and consumer vs. business use	See above
Annual Failure Rate	0.10	See above
Repair likeliness at 50% (age of device)	5 years	See above
Time per mode		
PC – Power off	45%	Energy Star 6.0 draft
PC – Power sleep	5%	Energy Star 6.0 draft
PC – Power long idle	15%	Energy Star 6.0 draft
PC – Power short idle	35%	Energy Star 6.0 draft

Laptop – Power off	25%	Energy Star 6.0 draft
Laptop – Power sleep	35%	Energy Star 6.0 draft
Laptop – Power long idle	10%	Energy Star 6.0 draft
Laptop – Power short idle	30%	Energy Star 6.0 draft
Power consumption per mode		
Desktop PC. class A – Power off	0.91 W	EU EnergyStar database. Sept 2013
Desktop PC. class A – Power sleep	1.76 W	EU EnergyStar database. Sept 2013
Desktop PC. class A – Power long idle	21.98 W	EU EnergyStar database. Sept 2013
Desktop PC. class A – Short idle	21.98 W	Same as long idle according to Energy Star memo
Desktop PC. class B – Power off	1.18 W	EU EnergyStar database. Sept 2013
Desktop PC. class B – Power sleep	2.29 W	EU EnergyStar database. Sept 2013
Desktop PC. class B – Power long idle	33.11 W	EU EnergyStar database. Sept 2013
Desktop PC. class B – Power short idle	33.11 W	Same as long idle according to Energy Star memo
Desktop PC. class C – Power off	1.08 W	EU EnergyStar database. Sept 2013
Desktop PC. class C – Power sleep	2.00 W	EU EnergyStar database. Sept 2013
Desktop PC. class C – Power long idle	34.76 W	EU EnergyStar database. Sept 2013
Desktop PC. class C – Power short idle	34.76 W	Same as long idle according to Energy Star memo
Desktop PC. class D – Power off	0.93 W	EU EnergyStar database. Sept 2013
Desktop PC. class D – Power sleep	2.22 W	EU EnergyStar database. Sept 2013
Desktop PC. class D – Power long idle	38.68 W	EU EnergyStar database. Sept 2013
Desktop PC. class D – Power short idle	38.68 W	Same as long idle according to Energy Star memo
Integrated PC. class A – Power off	1.01 W	EU EnergyStar database. Sept 2013
Integrated PC. class A – Power sleep	2.41 W	EU EnergyStar database. Sept 2013
Integrated PC. class A – Power long idle	23.30 W	EU EnergyStar database. Sept 2013
Integrated PC. class A – Short idle	41.95 W	1.8times long idle according to Energy Star memo
Integrated PC. class B – Power off	0.83 W	EU EnergyStar database. Sept 2013
Integrated PC. class B – Power sleep	2.33 W	EU EnergyStar database. Sept 2013
Integrated PC. class B – Power long idle	33.22 W	EU EnergyStar database. Sept 2013

Integrated PC. class B – Power short idle	59.80 W	1.8times long idle according to Energy Star memo
Integrated PC. class C – Power off	0.79 W	EU EnergyStar database. Sept 2013
Integrated PC. class C – Power sleep	2.23 W	EU EnergyStar database. Sept 2013
Integrated PC. class C – Power long idle	37.62 W	EU EnergyStar database. Sept 2013
Integrated PC. class C – Power short idle	67.72 W	1.8times long idle according to Energy Star memo
Integrated PC. class D – Power off	0.79 W	EU EnergyStar database. Sept 2013
Integrated PC. class D – Power sleep	2.29 W	EU EnergyStar database. Sept 2013
Integrated PC. class D – Power long idle	44.17 W	EU EnergyStar database. Sept 2013
Integrated PC. class D – Power short idle	79.51 W	1.8times long idle according to Energy Star memo
Workstation – Power off	0.87 W	EU EnergyStar database. Sept 2013
Workstation – Power sleep	3.95 W	EU EnergyStar database. Sept 2013
Workstation – Power long idle	70.22 W	EU EnergyStar database. Sept 2013
Workstation – Power short idle	70.22 W	Not available. considered similar to desktop PCs
Laptop. class A – Power off	0.65 W	EU EnergyStar database. Sept 2013
Laptop. class A – Power sleep	1.16 W	EU EnergyStar database. Sept 2013
Laptop. class A – Power short idle	15.53 W	1.5times long idle according to Energy Star memo
Laptop. class A – Power long idle	10.36 W	EU EnergyStar database. Sept 2013
Laptop. class B – Power off	0.64 W	EU EnergyStar database. Sept 2013
Laptop. class B – Power sleep	1.32 W	EU EnergyStar database. Sept 2013
Laptop. class B – Power short idle	21.69 W	1.5times long idle according to Energy Star memo
Laptop. class B – Power long idle	14.46 W	EU EnergyStar database. Sept 2013
Laptop. class C – Power off	0.77 W	EU EnergyStar database. Sept 2013
Laptop. class C – Power sleep	1.65 W	EU EnergyStar database. Sept 2013
Laptop. class C – Power short idle	39.32 W	1.5times long idle according to Energy Star memo
Laptop. class C – Power long idle	26.21 W	EU EnergyStar database. Sept 2013
Material recycling (recycling quotas)		

See end-of-life modelling below		

The EU Energy Star database as of September 2013 comprises roughly 9000 Notebook computers, 70 integrated PCs (class A), 320 integrated PCs (class B), 130 integrated PCs (class C), 160 integrated PCs (class D), 430 desktop PCs (class A), 2100 desktop PCs (class B), 600 desktop PCs (class C), 1500 desktop PCs (class D) and 26 workstation PCs. For thin clients and small scale servers the Energy Star database does not comprise enough registered products for a sound quantification of average power consumption data. Assuming a broad coverage of the notebook market by Energy Star, arithmetic average data on power off, sleep and idle are taken as default data for the benchmark. As the current Energy Star database still refers to the Energy Star 5 specification, only (long) idle data is provided in the Energy Star database. In the course of the revision of the Energy Star specification, the difference between long and short idle has been investigated: "The difference between Short and Long Idle was analyzed and Short Idle was calculated to be 1.5 times Long Idle for Notebooks and 1.8 times Long Idle for Integrated Desktops (for Desktops, the Short and Long Idle values were assessed to be the same)." [Energy Star memo]

2.3.1.5. Modelling end of life

Typically, as a worst case scenario for IT LCAs just the processing and disposal of the products is taken into account, rarely the resulting recycling credits as any recycling quotas for a dedicated product hardly can be stated. For the target application in LCA to go to quantify the advantages of a service oriented take back model and good recyclability (DfR), such a distinction has to be made and default settings should not be zero recycling as this would yield a large advantage for DfR measures. From the perspective of a DfR product this would yield rather a best case calculation, not a worst case.

Establishing quotas on recycling credits for carbon footprint calculations has to consider

- **Collection rates** (how much WEEE is collected)
- **Treatment efficiency** (how much of an input material is properly channelled into the appropriate output fraction)
- **Material recycling efficiency** (how much of an input material leaves the process as a separated material, suitable to replace virgin material partly or completely)

Default settings for current recycling practice can build on official statistical data from EuroStat [2012]. Although data reported under the European WEEE directive is subject to major inconsistencies and uncertainties, this is still the best source available. Collection rates are listed in Table 10. The collection rate is defined as the amount of collected WEEE per year compared to all EEE brought on the market, which yields roughly an appropriate quota: The amount of IT and telecommunications equipment brought on the market is roughly stable over time, see Figure 37.

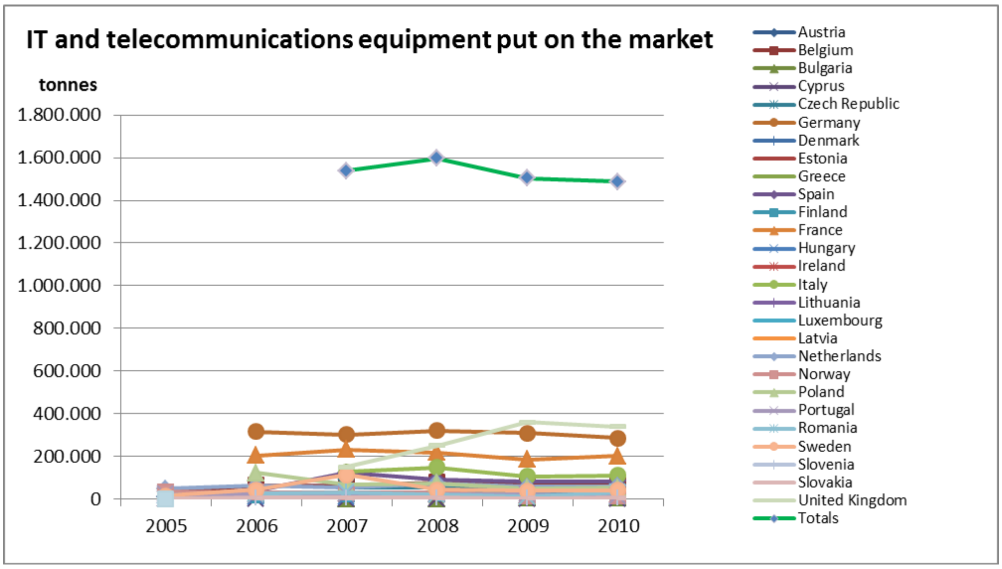


Figure 37. Amount of IT and telecommunications equipment put on the market (based on EuroStat data)

Table 10. Collection quotas for IT and telecommunication equipment in Europe [EuroStat 2012]

Collection quota		
EU (excl. Italy, Croatia, incl. Norway)	48%	
Belgium	28%	
Bulgaria	85%	
Czech Republic	35%	
Denmark	67%	
Germany	76%	
Estonia	85%	
Ireland	24%	
Greece	35%	
Spain	31%	
France	31%	
Italy	n.a.	EU average to be applied
Cyprus	28%	
Latvia	27%	
Lithuania	40%	
Luxembourg	20%	
Hungary	44%	
Netherlands	35%	
Austria	57%	
Poland	35%	
Portugal	45%	
Romania	20%	
Slovenia	92%	
Slovakia	59%	
Finland	39%	
Sweden	75%	
United Kingdom	43%	
Norway	103%	100% to be applied
Malta	13%	

It can be assumed, that devices are collected in those countries which are selected by the user of the tool also for the use phase (country specific electricity grid mix).

The treatment efficiency depends on the treatment process, the type of component and product design issues. Chancerel [2010] states a high discarding rate for precious metals from small WEEE, which is largely due to losses in pre-treatment processes. Different materials will yield different treatment efficiencies. Buchert [2012] estimates pre-treatment losses of

20% for cobalt (can be set synonymous with batteries), and

70% for silver and gold (largely found on PCBs, but also in connectors, contacts, that's why the loss rate for PCBs can be assumed to be lower, i.e. 30%).

The overall recovery quota in Europe regarding IT and telecommunications equipment is 85% according to EuroStat. It can be assumed that recovery is higher for bulk housing materials (steel, aluminium), and lower for miscellaneous smaller parts.

Among plastics ABS, HIPS and PP, which combined are slightly more than 50% of shredder residues from WEEE treatment, can be recycled for new EEE products. Capacity of such plastics recyclers however is much lower than related WEEE generation, so downcycling and thermal recovery can be assumed as state of the art. Plastics from Office and IT equipment contain roughly 50% ABS, but no significant amounts of HIPS and PP [Wäger 2010]. Despite the recycling potential, actually the amount of recycled plastics in Europe compared to the amount of plastics introduced to the market is only a very small fraction of 1 to maximum 10% (based on [Tange 2012]). However, as plastics from WEEE are actually separated and are sold as fractions, it is likely that a larger share is recycled outside Europe. According to EMPA and MBA Polymers data, recycling of plastics from WEEE can save roughly 1,2 kg CO_2-eq. per kg plastics material, balancing the credit of replacing virgin polymer against the impacts of the recovery process as such [Slijkhuis 2011].

There is no known large scale recycling of LCD Displays. These units, including LED backlights, glass and indium can be considered lost. The aluminium frame of the LCD module might be separated after a shredding process, but is only a minor material fraction compared to the metal content of other computer parts.

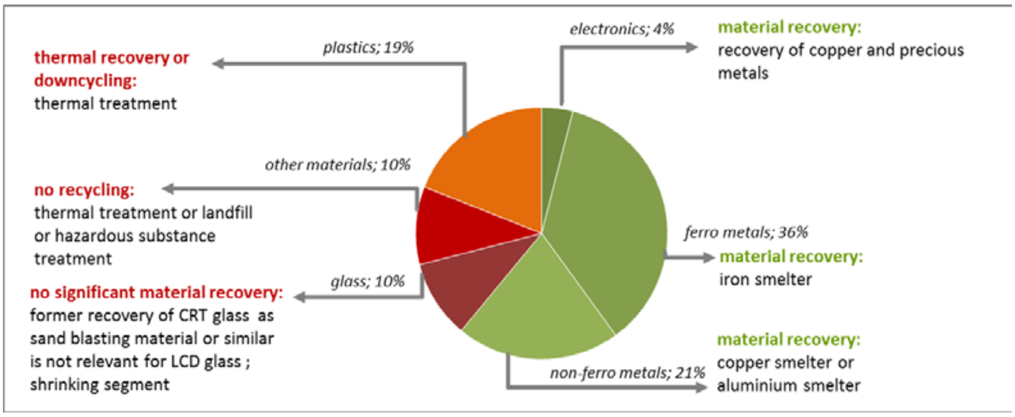


Figure 38. Material Composition of EEE and typical end-of-life routes

Given the above considerations the approximated treatment efficiency for the main relevant fractions is listed in Table 11.

Table 11. Approximated treatment efficiencies for computer products

Treatment efficiency	
Metal housing	90%
Plastics housing	85%
Wood housing	0%
Cables	80%
PCBs (including CPUs, memory)	70%
Batteries	80%
Displays	lost
Rest	lost

Critical metal recovery rates are again stated by Buchert [2012]. According to his analysis and further insights into recycling technologies (see also [UNU 2007], metal recovery rates from laptops and computers can be considered 95% for

- Cobalt
- Aluminium
- Steel and other bulk ferro metal parts

and 99% for

- Silver, Gold, Platinum Group Metals
- Copper

All other metals can be considered lost (i.e. 0% material recycling efficiency) as no appropriate recycling technology is in place. This includes explicitly Indium, Magnesium, Tantalum, Rare Earth Elements, and Silicon. Some other metals are (also) contained only in small amounts and might be recycled depending on the facility, but as the carbon footprint of these is low, the overall relevancy is low as well, e.g. Zinc and Tin. Also if a metal is channelled to the wrong smelter process it is typically lost or recycled on a very low level, such as aluminium and magnesium in a copper or precious metal smelter where these metals are transferred mainly to slags which are reused in the concrete industry as a substitute for gravel [Brusselaers 2006], but not as a virgin metal substitute.

Based on the carbon footprint share of primary mining and related processing of those metals, which can be recovered, compared to the total carbon footprint of certain sub-assemblies and components the carbon footprint gain at end of life can be calculated as follows:

$$CFC = CQ_{country\ i} * \sum_{j=1}^{n} (TE_{component\ j} * RR * CFS_{recovered\ materials})$$

with

CFC: Carbon footprint credit

$CQ_{country\ i}$: Collection quota per country (values from Table 3)
$TE_{component\ j}$: Treatment efficiency per component (values from Table 3)
RR: Recovery rate, default 95 %
$CFS_{recovered\ material}$: Carbon footprint share of potentially recovered material of component production per component

Based on the carbon footprint datasets developed in the methodological background research (WP 2 of LCA to go) carbon footprint shares of the relevant materials and related components can be stated as listed in Table 12.

Table 12. Carbon footprint share of potentially recovered material

Creditable Recycling Carbon Footprint Share of Production related Carbon Footprint		
Metal housing • Steel • aluminium		 74% 95%
Plastics housing	... %	
Cables (i.e. copper content)	85 %	
PCBs	... %	
CPUs	... %	
memory	... %	
Batteries	10 %	

2.3.1.6. Bridging the gap between components data and the product assessment tool

The LCA to go project addresses as relevant components:

- Semiconductors
- Printed Circuit Boards
- Passive Components

With respect to the end product level these 3 sub-sectors have to be addressed differently, as discussions with MicroPro and the environmental screening of those components (see WP2) unveil, see Table 13.

Table 13. Suitability of component models for the electronics product model

Data category	Environmental relevancy	Availability of relevant specification data for end-product assembling SME
Semiconductors	high	Outer dimensions known, including some technical specs, but not die size, technology node, number of mask / metal layers or bond material; high level aggregation required
Printed Circuit Boards	high	Board size known, board finish identifiable by visual inspection, but typically number of layers in multi-layer boards is not known; typical boards should be pre-defined
Passive Components	low	Specification of individual components on pre-assembled boards not known

Semiconductors and Printed Circuit Boards are both highly relevant, but Passive Components are not on the level of individual units. Passive Components therefore can be covered on a general level as an overhead on top of printed circuit board data.

For printed circuit boards benchmark designs can be established from literature and technical insights. Typical boards are listed in Table 14 below.

Table 14. Types of default printed circuit boards in computer-like devices

Application	Number of layers	Surface finish	Typical size	Carbon footprint (CO_2-eq./board)
PC, mainboard	6	Nickel-Gold	ATX (305 mm x 244 mm): 744 cm²	19.27
PC, memory module	6	Nickel-Gold	DIMM (130 mm x 25 mm): 32.5 cm²	0.84
PC, graphics card	4	Nickel-Gold	(6.6"): 118 cm²	2.19
PC, HDD board	4	Nickel-Gold	3.5" HDD: 42 cm²	0.78
PC, power supply unit board	Included in PSU dataset			
Laptop, mainboard	8	Nickel-Gold	270 cm²	8.96
Laptop, memory module	6	Nickel-Gold	SO DIMM: 20.3 cm²	0.53
Laptop, WLAN module	4	Nickel-Gold	Mini PCIe card: 15 cm²	0.28
Laptop, HDD board	4	Nickel-Gold	2.5" HDD: 58 cm²	1.08

Laptop, other rigid boards (e.g. power button PCB, USB connector PCB, touchpad PCB)	2	HAL	20 cm²	0.23
Laptop, power supply unit board	Included in PSU dataset			
Tablets (7" range), mainboard	8	Nickel-Gold	50 cm²	1.66
Tablets (10" range), mainboard	8	Nickel-Gold	80 cm²	2.66
Servers, mainboard	10	HAL	E-ATX (boards for 2 CPUs; 305 mm x 330 mm): 1007 cm²	39.87

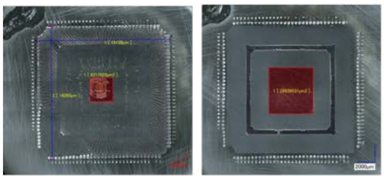
With respect to semiconductors the gap between the sectoral tool developed by UMC and data structure in the electronics tool is particularly challenging as the end-product assembler is not aware of die sizes, but can judge on the package type. UMC stated an average carbon footprint for their range of computing ICs of 1.4 kg CO2-eq. / cm² die area, referencing die size for simplification[5]

The relationship between packaged chip size and unpackaged die can be approximated based on a paper by Lu from 1996, according to UMC. The size of packaged IC is larger than the unpackaged die. The share of the unpackaged compared to the package is as follows, according to these sources:

- Flip Chip: 92.5% (FC package including underfill area)
- Wire bonded ICs: 72%
- QFP: 5.3%

Fraunhofer IZM verified this data through examination of some exemplary ICs (grinding and measuring chip dimensions, see Figure 39).

[5] but be aware that the actual IC model considers not only the die size, but also other technology factors, such as technology node, mask layers, metal layers, distinct IC type



- CPU
  - same as for 3,5" HDD
  - Package size: 14 x 14 mm²
  - 2 stacked ICs
  - Die area: 0,082 cm² + 0,289 cm² = 0,371 cm² (18,9% of package size)

- Memory
  - same as for 3,5" HDD
  - Package size: 10 x 22 mm²
  - Die area: 0,147 cm² (6.7% of package size)

- Motor controller
  - different from 3,5" HDD
  - Package size: 6 x 14 mm²
  - Die area: 0,095 cm² (11.3% of package size)

Figure 39. Exemplary analysis of chip to package ratio for ICs on a 2.5" HDD

The analysis of several such IC packages typically found in computer and telecommunications products by Fraunhofer IZM is listed in the table below. Under these conditions a direct correlation of package type and size with the contained die area is rarely feasible, which is also confirmed by Kahhat et al. [2011]: "The area of chip packaging does not correlate with contained silicon wafer. Any model relating the package and wafer area would need to encode additional information such as the type of chip." However, even the chip type is not sufficient as information.

Table 15. Die size to package size ratio for exemplary ICs

Package type		die size to package size
FC-BGA	logic	44.2%
QFP128	logic	18.9%
TSSOP56	logic	11.3%
SPBGA423	logic	12.7%
PBGA120	logic	40.7%
BGA120	logic	29.5%
BGA117	logic	45.2%
TSOP54	memory	6.7%
FBGA60	memory	35.7%
VFBGA63	memory	37.3%
FBGA	memory	73.3%

Kahhat et al. [2011] analysed laptop mainboards of 5 different models, 4 from 2008 one from 2001. Despite the found mismatch between package size and die size they found out, that the total die size on laptop mainboards is in a very stable range between 2.55 and 2.83 cm² for 2008 models (compared to 4.83 cm² for a 2001 model).

Taking the average of 2.64 cm² as a baseline, which obviously excludes the CPU (as no die is larger than 0.18 cm² in Kahhat's depicted data) and DRAM memory (memory card slots not populated in the shown analysed mainboards), and UMC's stated value of in average 1.4 kg CO_2-eq./cm² for computing products and an back-end overhead of 1/3, the **carbon footprint of all packaged ICs on computer mainboards is 5 kg CO_2-eq.**, excluding CPU and DRAM memory, including e.g. WLAN and a graphics IC (baseline).

Based on this analysis a sound benchmark can be defined. The user can model the own product with only minor adaptations of individual components, e.g.

- adding a graphics card
- define DRAM memory
- define CPU

(see also analytical data for the memory and CPU models in D2.6), but not a full determination of chip sizes.

2.3.1.7. (Re)design decisions derived from assessment results

The fact, that the case study assessment unveiled, that the actual component lifetime is less relevant for total product lifetime than other factors also sheds a new and important light on redesign decisions. Whereas business models and consumer education to extend usability of the iameco v3 and D4R laptop respectively is dominant, actual use of particularly long living components is less an issue. A list of priorities, which can be derived from the current status of assessment findings, is as follows (ranked from high to low):

(1) **Use of reused components for new product** (as the use of reused components is the only way to make sure that use lifetime of components is really prolonged)

(2) **Business model in place for refurbishment of used computers** (incentivize takeback, refurbish / upgrade, and attractive resale conditions)

(3) **Reuse of components at end of life** (same as no. 1, but with the uncertainty, whether takeback and reuse will really work in a mid-term future)

(4) **Particularly customer-friendly service model**, e.g. component and software upgrade, good service infrastructure at no or moderate service costs for the customer, to avoid discontinued use of technically working units by the customer

(5) **Good system design with respect to thermal management** (no major heat dissipation to heat sensitive components), **and robustness** (mobile products)

(6) **Design for (Material) Recycling** by facilitating disassembly and material separation, avoidance of composites

(7) **Design for Repairability** (access to components, compatibility of components)

(8) **Use of components specified for a particularly long-lifetime** (as technical lifetime of individual components is less frequently an issue)

There are some inter linkages between these measures, as e.g. Design for Reparability will also support a business model for refurbishment. Vice versa system design for robustness is likely to hamper material separation. These correlations are depicted in the matrix below.

2.3.2. Evaluation criteria aspects

(1) Input data and simplification of the data collection, ease of use

The time required to source relevant environmental data (e.g. energy consumption in the use phase) and to enter the specification in the LCA to go tool is low to moderate. MicroPro confirmed that all relevant data is easily accessible for them.

(2) Simplification of the electronics tool

All KEPIs defined for the sector are considered relevant and it is not recommended to cut off any of them to simplify the tool. The main problem rather persists with the communication aspect of the findings. Material-wise resource savings is a sound and valid outcome of the screening assessment, but it is hardly possible to communicate the meaning of saving a certain amount of a certain resource. It is important for the communication to provide explanations in a layman language why a certain substance is a critical raw material.

(3) Eco design ideas developed and hypothetical improvement potential

The extensive discussion of the methodology with MicroPro yielded a substantially changed product strategy: Whereas initially it was anticipated, that frequent repair is required among conventional products, and that a focus on components with long lifetime might improve the environmental assessment results drastically (i.e. a *design focus*), the discussion and complementing research in the course of the case study unveiled, that major improvements require rather a changed *business focus* and measures to influence the user to use IT devices longer by enhancing usability.

The design approach of using highly reliable components is a point not to miss, but this measure alone saves at maximum few per cent points carbon emissions over the lifetime. Larger savings in the range of 20-50% can be achieved only through the use of reused components and a robust service system in place for servicing and upgrading computers in use.

2.3.3. Summary

The case study on computer-like devices addressed highly relevant methodological questions, which were raised by MicroPro due to their current product and business strategy. As the assessment tool as such will be developed consecutively and the electronics sector is last with having the beta version readily available, the case study reflected on the methodological issues as such and the alpha version, but no full quantitative assessment results are provided in this report.

The main finding of this case study with MicroPro is the review of lifetime considerations in the methodology and the ranking of most effective measures to red that allows designers and manufactures to establish best options both for design of specific equipment, for sourcing of materials both new and used, and for designing of industrial and service networks for this product.

2.4. TAIPRO Case study on Sensors

Methodological aspects identified and analyzed in the course of the case study are the evaluation criteria:

- Data availability, and
- Sensitivity of data entries

and as a general aspect:

- Establishing exemplarily generic case studies for other energy-intensive industries

2.4.1. Data availability

An overview on data availability as experienced in the case studies is summarized in Table 15.

Data entries are marked as follows:

(green)	Data readily available from the client, through own data access or well justified estimates or third-party data; data entries non-critical
(yellow)	Data is readily available (typically) from the client, but is considered confidential, so might not be accessible for the sensor system provider in all cases
(orange)	Data might be available, but related data gathering is a lengthy process and can severely affect the usability of the overall approach; user should be prepared to acquire external data or to make assumptions
(red)	Data is not available, so it should be checked by the user through e.g. a sensitivity analysis, whether this aspect is relevant or can be neglected in a specific case

Table 16. Sensors case study – data availability

	Case study		
	Smart grease pump	Multisensor platform	Lubrication monitoring
WP4, Task 4.4, Case Study Data Needs			
Production and productivity of the monitored production line			
1. Raw material specification (type of steel, sheet thickness or else)	lengthy data gathering process		
2. Maximum operational time per year of the production line [h/a]	available but confidential		
3. Downtimes before installation of sensor system [h or % of max. operational time]	available but confidential		
4. Estimated downtimes after installation of sensor system [h or % of max. operational time]	no data available	reduction of 10% is expected	no data available
6. Production output at normal operational times [kg/h]	available but confidential		
7. Yield losses without sensor system [%]	15 to 5%		
8. Estimated yield losses with sensor system [%]	no data available	13.5 to 4.5% is expected	no data available
Environmental data			
9. Electricity consumption machine,	available but confidential		

operational times [kWh]			
10. Electricity consumption machine, downtimes [kWh]	lengthy data gathering process		
11. Electricity consumption overhead, infrastructure, at all times [kWh]	lengthy data gathering process		
12. Other types of energy consumed?	Fuel of any types: gasoline, Natural gas…		
13. Grease consumption with and without sensors [kg/a]	7.5 € /Kg		
14. Any other auxiliaries affected by sensor usage? (electroplating chemicals…)	N2 and H2 for the oven(s), chemicals fluid for: galvanic bath, painting, cleaning…		
Cost data			
15. Electricity price [Euro/kWh]	0,12€/KWH (to be crosschecked)		
16. Other energy costs	0.3€/KWH (for natural gas - to be corss checked)		
17. Grease costs [Euro/kg]	lengthy data gathering process		
18. Other auxiliaries cost	65€/h (but crosscheck to be done if it is operational hour or not)		
19. Machine-hour rate [Euro/h] (energy costs excluded, if possible; for the scenario without sensor system only, hypothetical machine-hour rate for the scenario with sensor system will be calculated based on stated running times)	available but confidential		
20. Personnel costs for machine operation with and without sensor system [Euro/a]	available but confidential		
21. Machine maintenance costs with and without sensor system (costs of sensor system itself and its operation to be stated separately below) [Euro/a]	Electroplating line: increase performance and productivity for minimum 20h/an per line (Benefit for less maintenance and more productivity)		
22. Spare parts storage costs with and without sensor system [Euro/a]	lengthy data gathering process		
22. Spare parts cost	lengthy data gathering process		
23. Raw materials costs (steel) [Euro/kg]	lengthy data gathering process		
24. Price premium for steel products in case of sensor controlled production line [∆Euro/kg]	lengthy data gathering process		
Sensor system data (please keep this information confidential)			
25. Sensor system acquisition and installation costs [Euro] on a production plant	35k€ (installation done by our customer)	400€ - 800€ per point to be monitored (around 100 points by production plant)	350€ per line to be monitored (50 points for the beginning) (remark: customer as to buy an additionnal software services including an informatic platform for which I do not know the cost.
26. Depreciation period for sensor system and installation [years] (Return On Investment (as discussed during conf call dated from 9th of July	no data available	18 months	18 months
27. Maintenance and running costs sensor system [Euro/a]	3500 - 4500€ (to be confirmed after deployment of the solution)	<0€ (estimation :it will replace a big part of the actual maintenance- Today, operators make a "walk" to "sense" if everything looks OK)	<0€ (estimation :it will replace a big part of the actual maintenance- Today, operators make a "walk" to "sense" if everything looks OK)
28. Number of sensor nodes employed	not applicable	100 (estimation before deployment of the solution)	50 (estimation before deployment of the solution)

29. Abridged BOM of sensor nodes (chipsets, memory, PCB spec, housing, battery spec)	provided separately		
30. Additional infrastructure components to make the system work (cabling, card / RFID / handheld readers, computers, internet backbone required)	Only 1 standard computer	Coupled with other informatic platform solutions (No detail available + but already available on site ~approx 80% to 90% available)	Coupled with other informatic platform solutions (No detail available + but already available on site ~approx99% available)
31. Grid electricity consumption of the sensor system [kWh/a]	8 KWh/year (for the global solution)	2.8KWh/Year/sensor	3.5 KWh/Year/sensor (espected value)

Based on this analysis, most critical data requirements are:

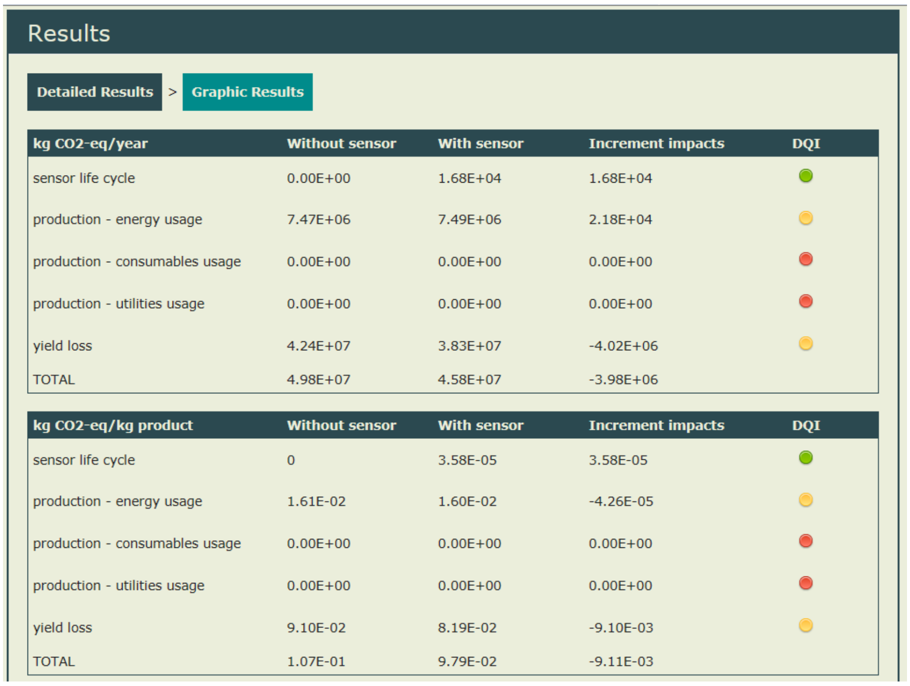
- Electricity consumption: machine downtimes and overheads
- Consumables costs
- Spare parts storage related costs (but this effect might be minor one anyhow)
- Cost data related to raw materials and product output

For these critical data requirements a sensitivity analysis is performed to assess how sensitive the overall findings are to an uncertainty of these data entries.

2.4.2. Case Study Results

2.4.2.1. Environmental Assessment

The scenario with the sensor system implemented in the cold rolling steel mill for condition monitoring of motors and drives yields absolute greenhouse gas emission savings of close to 4.000 t CO_2-eq. / year, which is mainly due to the anticipated yield loss reduction (see screenshot in Figure 40). Other factors increase, such as the sensor life cycle and the effect of energy usage in production. In communication with a client the latter needs further explanation, as it seems to be a negative effect. The reason actually is the higher productivity, i.e. longer running times of the process line, which is exactly the intended effect of condition monitoring. This effect becomes clearer when looking at the results with reference to the functional unit in the second results table: Total greenhouse gas emissions with the sensor system are 0.107 kg CO_2-eq./kg steel for the gate-to-gate analysis, which is a reduction of 0.00911 kg CO_2-eq. compared to the status quo without the sensor system being implemented. Again, the main contribution stems from yield loss reduction (9.1 g CO_2-eq.). The effect of direct energy savings through higher productivity is 0.042 g CO_2-eq./kg steel. The impact of the sensor system production and its own energy consumption, based on a 1.5 years depreciation, is 0.036 g CO_2-eq./kg steel, thus nearly outweighs the energy efficiency effect, but the difference will be higher once the depreciation period has elapsed.



Results

Detailed Results > Graphic Results

kg CO2-eq/year	Without sensor	With sensor	Increment impacts	DQI
sensor life cycle	0.00E+00	1.68E+04	1.68E+04	
production - energy usage	7.47E+06	7.49E+06	2.18E+04	
production - consumables usage	0.00E+00	0.00E+00	0.00E+00	
production - utilities usage	0.00E+00	0.00E+00	0.00E+00	
yield loss	4.24E+07	3.83E+07	-4.02E+06	
TOTAL	4.98E+07	4.58E+07	-3.98E+06	

kg CO2-eq/kg product	Without sensor	With sensor	Increment impacts	DQI
sensor life cycle	0	3.58E-05	3.58E-05	
production - energy usage	1.61E-02	1.60E-02	-4.26E-05	
production - consumables usage	0.00E+00	0.00E+00	0.00E+00	
production - utilities usage	0.00E+00	0.00E+00	0.00E+00	
yield loss	9.10E-02	8.19E-02	-9.10E-03	
TOTAL	1.07E-01	9.79E-02	-9.11E-03	

Figure 40. Results sensors case study – Detailed Environmental Results

The data quality is "indicative" only for the aspect with the highest impact, but this is due to the general approach, where effects have to be estimated before a system is implemented. Only after having operated the system for a while, statistical data can enhance data quality.

Graphically results are depicted in Figure 41, which unveils two visual problems: The effect of yield loss savings can be so overwhelming, that all other effects seem to be zero, even where this is not the case. Similarly, for the direct gate-to-gate comparison of both scenarios the overall effect is a minor one. Although it is know in advance, that condition monitoring will not revolutionize steel production, but might bring the incremental productivity enhancements, which lead to higher competitiveness, the optical impression from the graphs might be psychologically problematic. Focusing on the two graphs depicting the delta of both scenarios only is recommended, the comparison for both scenarios is complementary information then only.

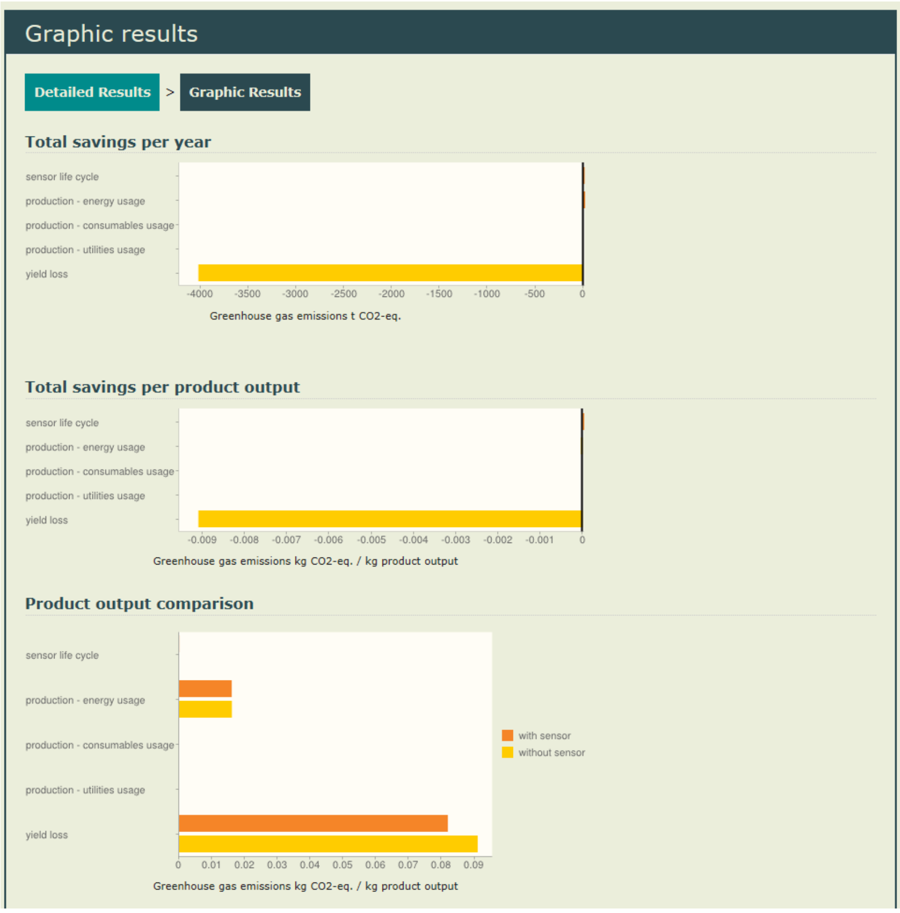


Figure 41. Results sensors case study – Graphic Environmental Results

Stating the values next to the bars can help to avoid the impression of a zero impact in some of the categories. Another alternative for software enhancements could be to depict two charts with and without yield losses, but this increases complexity and redundancy of information displayed.

2.4.2.2. Economic Assessment

The detailed results of the economic analysis largely run in parallel to the environmental results (Figure 42). Yield loss reduction is the most important cost savings factor.

Euro/year	Without sensor	With sensor	Increment impacts
sensor life cycle	0.00E+00	0.00E+00	0.00E+00
production costs	2.49E+08	2.49E+08	-4.57E+04
yield loss	2.47E+07	2.23E+07	-2.34E+06
value creation	-2.51E+08	-2.52E+08	-9.36E+05
TOTAL	2.21E+07	1.88E+07	-3.32E+06

Euro/kg	Without sensor	With sensor	Increment impacts
sensor life cycle	0.00E+00	0.00E+00	0.00E+00
production costs	5.34E-01	5.31E-01	-3.07E-03
yield loss	5.30E-02	4.77E-02	-5.30E-03
value creation	-5.40E-01	-5.39E-01	1.00E-03
TOTAL	4.75E-02	4.01E-02	-7.37E-03

Figure 42. Results sensors case study – Detailed Economic Results

As the categories are sorted differently than for the environmental analysis, which means sensor life cycle, production costs, yield loss and value creation are the cost categories depicted, the bar charts cannot be directly compared with the environmental analysis.

Only the difference between both scenarios on a product output basis is depicted as a bar chart (Figure 43).

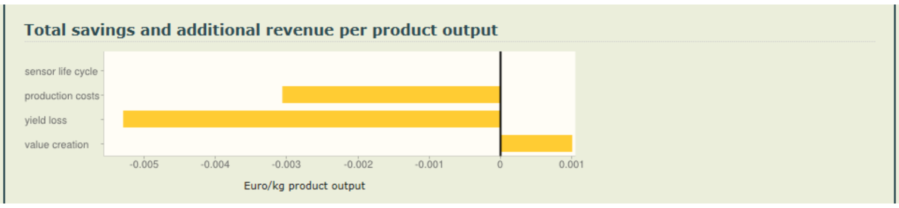


Figure 43. Results sensors case study – Graphic Economic Results

The overall cost savings effect is in the sub-cent range, but this can be the decisive cost savings in the steel business. Production costs go down by 0.3 Euro-cents per kg, yield loss savings reduce costs further by 0.5 Euro-cents per kg steel output.

2.4.3. Sensitivity analysis

The sensitivity analysis is based on the case study of the cold rolling steel mill (~60 to 65 tons of steel per hour).

Yield losses reduction can be identified right from the overall results as the most dominating impact of the sensor system installation.

Yield loss without sensor system is assumed to be the stated arithmetic average of the stated span, i.e. 10%, whereas yield loss with sensor system is varied between 4.5 and 10% (see Figure 44). The overall result is highly sensitive to the yield loss. A yield loss reduction from 10% to 4.5% can be considered an extreme case, but even much smaller yield loss reductions easily dominate the overall result. Consequently, due care should be paid to the yield loss entries and the prognoses yield loss reduction. As a conservative assessment of a condition monitoring system it is recommended always to provide also a calculation without yield loss reduction.

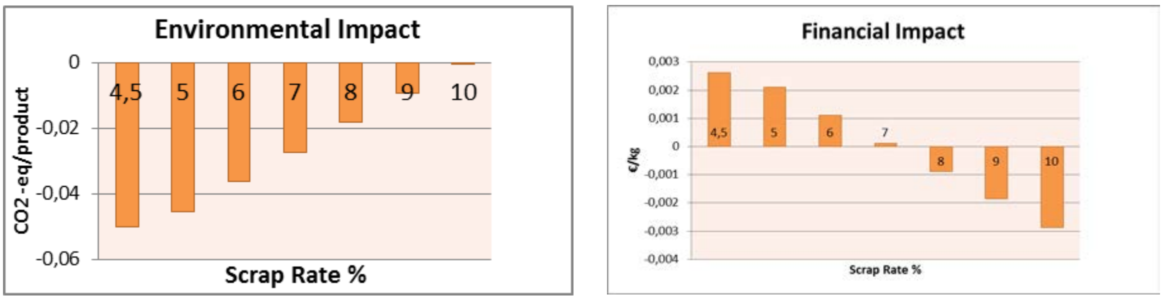


Figure 44. Sensitivity Analysis – Yield loss

Not to be dominated by the yield loss effect all following sensitivity analyses are conducted on the basis of an unchanged yield loss of 10% under both scenarios, with and without sensor system.

At the outset of a sensor system project the number of points, which need monitoring is a variable as definitely not all motors and drives need monitoring. To get the balance right is a question of overall system engineering. Varying the number of sensor nodes from 50 to 500 is depicted in Figure 45. Whereas there is a clear positive environmental effect in the initial planned range of 100 sensor nodes, this effect is reversed in the sensitivity analysis at 400 sensor nodes and above. This sensitivity analysis however neglects the fact, that increased monitoring also means process related improvements, but this correlation is highly unknown and thus cannot be reflected in the sensitivity analysis. Furthermore it should be kept in mind that as soon as any yield reduction is achieved there will be a definite trade-off even for a high number of sensor nodes. Also both analysis are based on a depreciation period of 1.5 years (see above), although for the environmental analysis the technical lifetime is the more relevant calculation basis. The sensitivity analysis therefore results in a higher sensitivity than it should be.

The economic analysis shows only a low sensitivity with respect to the number of sensor nodes.

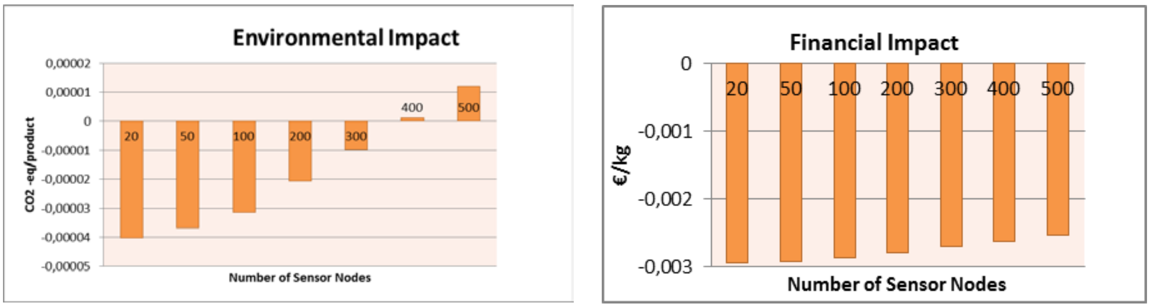


Figure 45. Sensitivity Analysis – Number of Sensor Nodes

Reductions in downtimes depend on practical experience gained once the monitoring system is operational for a certain time. Varying the downtimes from 0 to 50% reduction is considered an appropriate range. The change with respect to environmental and economic impacts is huge, and thus needs thorough modelling in the course of any calculation.

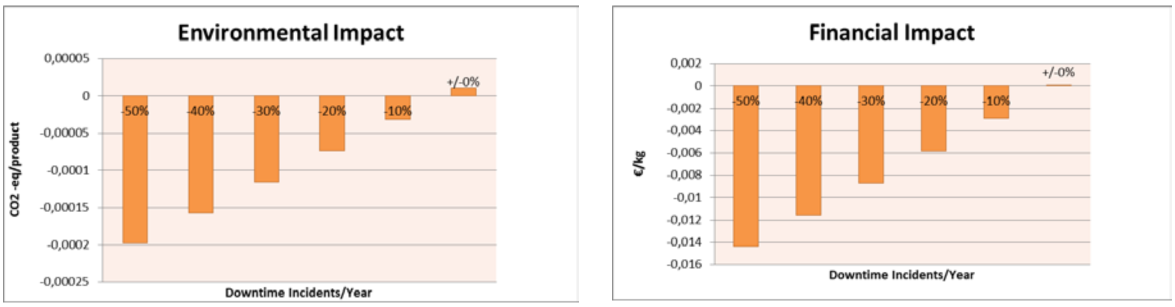


Figure 46. Sensitivity Analysis – Downtime reductions

Process line energy consumption at downtimes typically is not known to externals nor can it be extracted from third-party literature. An estimate requires a good knowledge of the process and whether certain sub-processes (e.g.: oven, electroplating) have to run also during downtimes (e.g. to guarantee stable process conditions). Furthermore, energy consumption during downtimes depends also on the machineries capability to facilitate a staged shut-off regime. Energy consumption at downtimes will be a fraction of energy consumption under full line load. The sensitivity analysis is based on the range from zero power consumption (complete shut-off) to same-as-operational power consumption. The logical effect is, a non-optimal power management regime yields a higher positive effect of better process line monitoring.

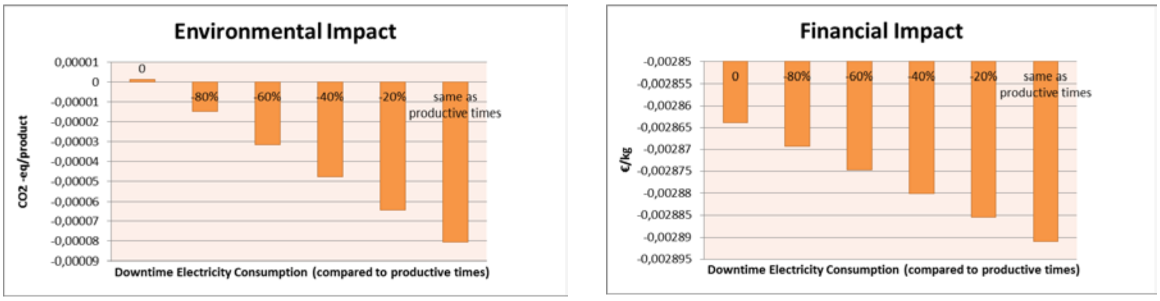


Figure 47. Sensitivity Analysis – Energy Consumption at Downtimes

Electricity prices vary among company sizes and countries. Although energy-intensive processes will be found in companies at the lower end of the electricity price range there is still a remarkable span to consider. The sensitivity analysis is based on an electricity price between 6 and 15 Euro-Cent/kWh. Logically, electricity prices do not have an impact on environmental impacts on the micro-economic level, but the economic analysis is significantly affected (Figure 48).

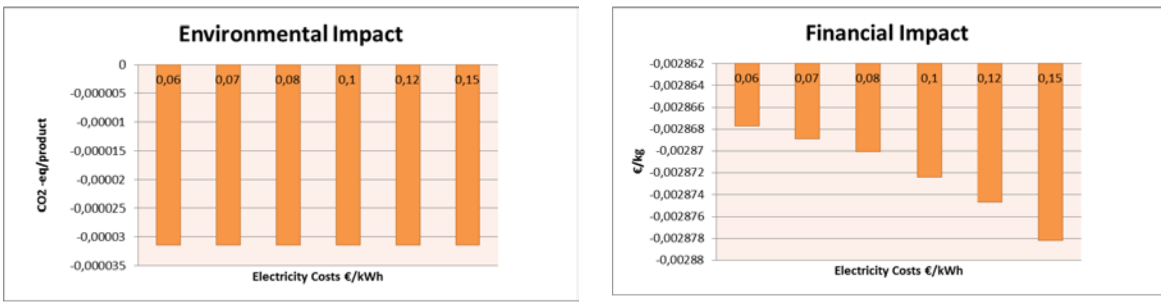


Figure 48. Sensitivity Analysis – Electricity Prices

Similarly to the reductions in downtimes the reduced consumption of auxiliaries in a sensor-controlled system can be prognoses, but only practice will tell, whether the related savings can be realised in the end. Furthermore the types of auxiliaries to be dosed more precisely can span a very broad range. The case study is on a smart grease pump, but actually any auxiliary or process fluid can be controlled in a similar way. The amount of grease used is reduced in the sensitivity analysis by up to 50% (Figure 49).

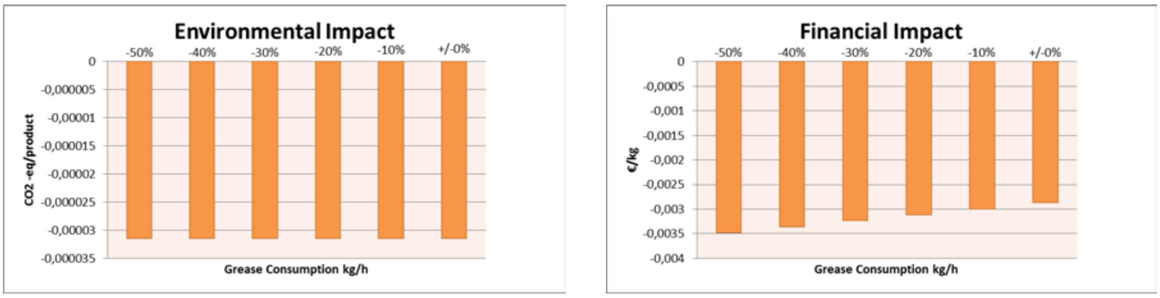


Figure 49. Sensitivity Analysis – Auxiliaries consumption

2.4.4. Generic Data for other energy intensive industries: Example paper machine

According to the identified risk of lacking appropriate environmental data from the customer, data on typical energy consumption for paper machines as an example of another energy intensive industry is compiled here based on a recent Fraunhofer study [Fleiter 2013] to be used as default data. Data is provided on a basis per ton and can be up-scaled to the known our anticipated process line output.

Table 17: Sensors case study – Energy data for paper machines

	Fossil fuels	Electricity	source
Paper: Paper machine (excluding calendaring)	4.950 MJ/t	80-140 kWh/t (drives, former, press, dryer, sizer, reel) Plus overhead 20-30 kWh/t for compressed air; 40-60 kWh/t for paper machine ventilation; 15-40 kWh/t for lubrication and hydraulic pumps	[Fleiter 2013], [IPPC 2010]
Paper: Calendars	n.a.	100-120 kWh/t	[IPPC 2010]

Large paper machine output is in the range of 70 t/h at an investment of 100 – 500 million Euro. Typical annual production time is 8.300 h/a [Fleiter 2013]. As "electric power consumption in many systems in a mill is quite constant and fairly independent of production levels" [IPPC 2010] machine energy consumption at downtimes can be considered similar to production times. As an assumption, 20% lower energy consumption at downtimes might be justified. Yield losses, i.e. paper waste in paper mills varies depending on paper quality. IPPC cites paper waste values corresponding to yield losses of 0.2% for wood-free paper and board, 0.7% for tissue, and 5% for specialty papers. Some environmental reports indicate a higher internal recycling of paper waste of 9%, so this figure remains to be a critical data entry, given also the sensitivity for yield loss data identified above.

Table 18: Sensors case study – Generic data for a paper machine

	Generic Paper Machine, status-quo without sensor system implemented	Comment / source
Production and productivity of the monitored production line		
1. Raw material specification	Pulp, ready for paper production	
2. Maximum operational time per year of the production line [h/a]	8.760 h/a	
3. Downtimes before installation of sensor system [h or % of max. operational time]	460 h/a	based on production time stated by [Fleiter 2013], but might be an optimistic scenario
6. Production output at normal operational times [kg/h]	70 t/h	
7. Yield losses [%]	Wood-free paper and board: 0.2% Tissue: 0.7% Specialty paper: 5%	[IPPC 2010]
	Paper: 9%	based on environmental reports, internal circulation
Environmental data		
9. Electricity consumption machine, operational times [kWh]	7000 kWh/h	
10. Electricity consumption machine, downtimes [kWh]	5600 kWh/h	
11. Electricity consumption overhead, infrastructure, at all times [kWh]	7000 kWh/h	
12. Other types of energy consumed?	Fossil fuels: 350.000 MJ/h	
13. Grease / lubrication oil consumption	0.1 kg / t paper produced	Environmental report Schwedt (includes pulp production)
Cost data		
15. Electricity price [Euro/kWh]	See EuroStat data	
16. Other energy costs	See EuroStat data	
19. Machine-hour rate [Euro/h]	8000,- Euro/h	
20. Personnel costs [Euro/a]	n.a.	
21. Machine maintenance costs [Euro/a]	n.a.	
22. Spare parts storage costs [Euro/a]	n.a.	
23. Raw materials costs (paper) [Euro/kg]	1.14 Euro/kg	DeStatis: pulp and similar

Table 3 summarises recommended default data entries for a paper machine. Data has been partly extrapolated based on an output of 70 t/h. Based on these default values the user can model a paper machine with the LCA to go tool by entering and adapting related data. Effect of sensor system implementation has to be modelled based on own estimates as no data is available, which kind of sensor system might have which effect on the paper machine.

Summary

The case study implementation for the sensor sector was subject to a lengthy process of discussing the project with TAIPRO's client from the steel business under critical economic circumstances. The assessment of the case study cold rolling steel mill nevertheless was feasible as an engineering implementation

planning, just as foreseen by the application scenario defined for the sensors sector.
The main challenge turned out to be data acquisition on the process line, where the sensor system shall be installed. Whereas data availability is good or at least an educated guess is feasible for many of the data entries, particularly cost data is a sensitive issue. To circumvent this this challenge, the development of some generic default scenarios for some key industries is advisable and has been established for paper machines. Further default scenarios might be established in the course of the mentoring program, given that relevant sensor system providers can be acquired.
The sensor sector is one of the few, for which a fully operational beta version of the LCA to go tool was readily available for road-testing in the case study and yielded sound results with respect to quantified savings potentials.
Given the specifics of the sensor sector to base assessments on predicting future implementation effects a high level of uncertainty is inevitable for this sector. Given the specifics of the sensor sector to base assessments on predicting future implementation effects a high level of uncertainty is inevitable for this sector. A sensitivity analysis has been undertaken to address and verify the likely impact of uncertainty. Given the high relevancy of the yield loss prognosis all other factors are of minor importance – unless a scenario is likely, where the yield loss is not affected at all by the sensor system under study.

The concept of the Data Quality Indicators (DQIs) has been implemented successfully in the tool and could be applied within the case study.

2.5. TTA Case study on Photovoltaic Systems

2.5.1. Methodological aspects

Methodological questions asked in D4.1 were:

1. How much “extra” time should be spent to get the data for the tool?
2. Would you like to include any other KEPI, representing other criteria or impact categories?
3. Which are the aspects of the tool that you would use the most?
4. Would you use the results for marketing aspects?
5. Would you modify your PV system design if there is place for improvement?

The case studies showed that

1. Depending on the quality of the data to be obtained, more or less “extra time” has been spent on the tool. During the pre-design phase (i.e. for the engineering outline) not more than 1 extra hour has been spent on the tool.
   When more robustness in the data was required (i.e. for EPD or during the detailed engineering where different manufacturers are compared by comparing the origin of their components, detailed temperatures, lifetimes of components or accurate performance ratio values), more time was to be spent. Providers and manufacturers are to be contacted and the PR manual is to be followed.

2. So far, embodied energy and carbon footprint are the most representative KEPIs for the sector.

3. In the results sheet, it is suggested including gensets/engines when the system is compared to different energy sources (i.e. lignite, hard coal, natural gas CCP, offshore wind power) as in rural electrification projects, the installation of PV systems often substitute diesel generators, and the results will support the decision of incrementing the PV capacity and reducing the capacity of the generators.
4. The most useful aspects of the tool will be the possibility to compare systems, in order to select the most appropriate technology. And the detailed results for marketing issues.

5. The results can be used for marketing proposes by showing the environmental benefits of the PV systems.

6. The final system design will depend on the client. If a design has place for improvement, as far as the client agrees, the PV system design will be modified.

2.5.2. Evaluation criteria aspects

In order to make sure, that the robustness and usability of the web tool is well assessed during evaluation, the case studies were selected in such a way that as many different configurations as possible are looked at. That includes the variation of location, technology used and type of installation (grid-connected or micro grid including storage).

As described in D4.1, the tool can be used in two ways: first, during development of the final design, mainly for improvement of environmental performance and second, for assessment of the approved system design. The assessment of the approved system includes an evaluation of the effect, that supporting systems such as the storage do have on the system and enables the user to check the influence of the production country of modules on the total impact.

The case studies showed that the different possibilities could be assessed by the tool.

The first PV system assessed was already installed and working. It is a 2.76kWp grid-connected with storage (for self-consumption) PV system installed in Spain (Europe). The environmental results for this system were evaluated by introducing robust data into the tool. Fraunhofer has been in charge of its verification for the generation of an Environmental Product Declaration (EPD).

The second PV systems assessed is a Microgrid of 42kWp to be installed in Chad. This system is in its designing phase. The tool enabled the comparison of different tecnologies and the selection of the most environmentally friendly option (considering the pre-conditions set by the client) included in the engineering outline. Currently the team is working on the detailed engineering. Within this phase different manufacturers will be compared by introducing data on the origin of their components.

The system in Spain has and the Micro grid in Chad will have monitoring system to enable the monitoring of the results. Data such as the performance ratio, temperature and efficiency will be assessed in order to compare them with the data introduced in the tool during designing phase or first year of operation.

Summary

As shown in Deliverable D4.4. *Pilot Products, Projects and Declarations* and in the previous section of this deliverable, the tool enabled both to make an improved design and to implement an Environmental Product Declaration (EPD).

Different configurations were assessed with the tool. Although minor modifications are required almost all the aspects were possible to assessed: PV systems with storage (lithium-ion and lead-acid), small installations (2,76kWp) and medium sized installations (40kWp), and systems in different countries such as Spain in Europe or Chad in Africa.

One system was assessed in its designing phase, enabling the improvement of the design by selecting the best option of PV modules after doing the assessment with the LCA to go tool.

A working PV system was assessed with the tool to implement the EPD verified by Fraunhofer.

2.6. ELDOS Case study on Printed Circuit Boards

The case studies in Printed Circuit Boards carried out according scientific case study concepts showed in D4.1 Report. The main goal was further validation and improvement of the methodological approach and algorithms developed for the PCB modules of the "LCA to go" tool. Therefore the ELDOS Company was continued gathering related data from real PCBs production processes (water, energy and materials consumption etc.) for different types of PCBs. And next these data were used for comparisons the KEPIs of chosen PCBs, generated by the alpha-version of the "LCA to go" tool, with KEPIs calculated based on measured data from production processes. The conclusions from these comparisons were utilized for improvement of the algorithms and databases for both modules (basic and sophisticated) of PCB's tool as well as for the development of recommendations for the assessment procedure and areas of applications of PCB's tool. Furthermore, ILCD datasets extracted from the results of case studies were identified.

Scientific case study reports and evaluations

In order to take into consideration all relevant aspects connected with PCB sector, two groups of case studies were executed. The first one includes the most typical PCBs on the market to check correctness of "LCA to go" tool for PCB sector. The second group deals with three different examples of PCBs for real products. These examples were taken from the sensor and smart-textile sectors of the "LCA to go" project. There, the PCB is a part of the final product and the results of the PCB's tool are an input for these sectors for further calculation. The detailed description of analyzed PCBs and environmental reports are integrated in D4.4 report. Below were presented the main conclusions from case studies.

Methodological aspects

The answers on main methodological questions for PCB sector were presented in the chapter 1.6. They were showed that data from production processes from whole year have to be used for validation and improvement of accuracy of the PCB tool results – therefore such methodology was applied.

All calculated by PCB's tool KEPIs like: water, energy consumption during production processes, sludge and waste emission, carbon foot print and the issue of quantity of possible materials recycling from PCB's were considered in those case studies. It was calculated the KEPIs for main types of PCBs using the alpha-version of the "LCA to go" tool and multiply by level of annual production of the PCBs and next the results were compared with measured KEPIs gathered from whole 2012 year in the PCB factory. The very precise information about levels of annual production of different types of PCBs with different coatings was used for those calculations.

The results of comparison calculation varied depends analyzed KEPIs. The differences were equal from 2% for energy consumption, above 30% for water consumption up to 68.67% for sludge and waste emission.

Water consumption issue

It was observed significant differences between the "LCA to go" tool output and real production data for water consumption (e.g. above 38% for 4-layer PCB). Again was carried out analyses of all processes taken part in production processes for different types of PCBs (The methodology was presented in details in D2.3 Report) and it was stated that the reason of errors was fact that social water consumption in a factory hasn't been taken into account during the development of the algorithm for water consumption calculation. The necessary amendments were made in the algorithm, which significantly increased the accuracy of the tool (Fig. 50).

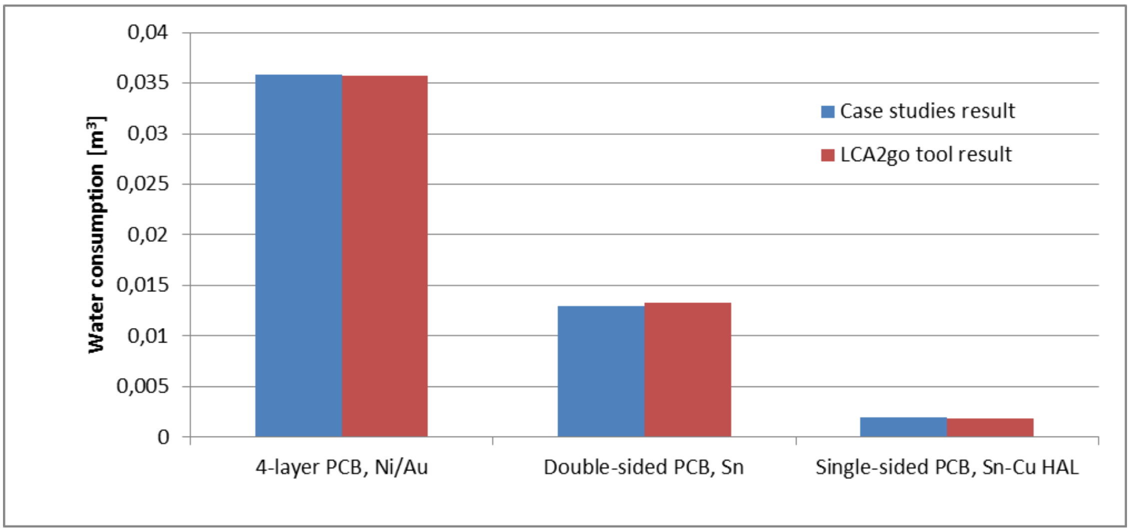


Figure 50. Results of the tool accuracy investigation for water consumption – PCB surface 0.01 m^2.

Based on case studies results it was stated that the elaborated tool could be useful for calculation of annual consumption of water and electricity what can help PCB's company during annual budget planning process.

Energy consumption and carbon footprint issues

The results of comparison analyse were very good for energy consumption during production processes (accuracy about 2%). This mean that elaborated approach was correct and the algorithm not require modification. The good results of energy consumption influence on correctness of PCB's total carbon footprint (T_{CF}) calculate by "LCA to go" tool. The T_{CF} of PCB in our tool is a sum of carbon footprint of materials for PCBs production, carbon footprint of processes during PCBs production related with energy consumption, carbon footprint of GHG emission during PCBs production as well as carbon footprint of transport (type and distance) connected with the place of PCB manufacture. The more information about other factors influence on carbon footprint issue of PCB was presented in chapter 1.6. For example it was stated that the impact of transportation's in total carbon footprint of a PCB cannot be neglected because its share can be above 20% in some cases. Regards the carbon footprint of materials for PCBs production it was checked that there may be significant errors in collecting data concerned materials consumption or some companies do not keep accurate statistics. Therefore to prevent errors caused by tool user the sophisticated module of PCB tool was modified and the possibility of input user data related with materials consumption was canceled.

Sludge and waste emission

It was observed the significant difference (68.67%) between annual sludge and waste emission in the factory and the annual value of sludge and waste emission calculated using the "LCA to go" tool. It was checked based on historical data from PCB factory that sludge and waste emission was different in different years. This KEPI was also closely related with the production portfolio for given year (number of manufactured single-sided, double-sided or multilayer PCBs as well as types of manufactured coatings on PCB). This confirmed earlier knowledge that sludge and waste emission is connected with level of production and materials consumption during PCB's manufacture processes as well as chemicals consumption needed for sewage treatment in sewage treatment plant.

Therefore, to improved our tool, the correction factor was used to change the indicators related with sludge and waste emission during PCB production processes in data basis for this KEPI in the tool. The algorithm uses for calculation was simplified as well – see below:

Sludge and waste emission algorithm for chosen PCB:

The algorithm of sludge and waste emission (E_{SW}) calculation depends from PCB settings and is as follow:

$$E_{SW} = (A \cdot (Ln \cdot I_{TSW} + I_{CTW})) \cdot n$$

Where:
E_{SW} - *sludge and waste emission [kg],*
A – area of PCB [m²],
Ln - number of layers,
I_{TSW} - *Indicator of sludge and waste emission for chosen type of PCB during production of PCB,*
I_{CTW} - *Indicator of sludge and waste emission related to chosen type of finish coating,*
n - number of PCBs.

The results of next verification calculations using new algorithm and data basis has shown that the error is below 1%, what met the evaluation criteria.

Materials recycling from PCB's issue

Analyze of issue of possible materials may be recovered from the PCB during recycling showed that exists relation between PCB's design and "LCA to go" tool results which causes some errors. However, it was stated that utilized in tool algorithm which uses the most typical PCB design is enough. It was decided only to add for environmental report, generating by the tool, comment: "For the calculation possible materials for recycling the following PCB design was used: circuits - 35% of surface, Cu layer thickness 35 µm". The information from this comment should enable users recalculate results if they recognize that it is unnecessary – the analyze PCB's design is significantly different that used in algorithm.

Elastic PCB's issue

During case studies the elastic PCB's issue was investigated. It was stated that major difference is the substrate material (laminate for rigid PCB, "Kapton" for elastic PCB). Other materials and almost all production steps are the same as for rigid PCBs. The number of layers usually is no more than 4 for elastic PCBs as well as HASL coating is not used - only chemical coatings like Ni/Au, Sn and Ag. The appropriate modifications of the PCB's tool's algorithms were made to adapt them to flexible PCBs.

Evaluation criteria and other issues

The following evaluation criteria and issues were considered during case studies and based on them the tool improvement were realized.

Accuracy of the PCB tool results.

The results of KEPIs calculated by the tool were compared with the LCA-results from the case studies. The tool's algorithms were modified if the differences were higher than 20%.

Simplification of the PCB tool.

It was checked does all calculated by the tool for PCB sector KEPIs are relevant. Based on users opinions only economic information was cut off to simplify the tool. Other KEPIs were qualified as essential for internal or external communication.
It was checked that transport of PCBs plays a significant role in some cases and this part of carbon footprint calculation shouldn't be deleted. Very often the PCBs are manufacture in the Far East and next they are shipment to different counties in Europe using different types of transport. The case studies showed that transport part may be as high as 20% in the total CF (See chapter 1.6). Based on these results the algorithms weren't changed according the case studies evaluation criteria presented at the D4.1 Report ("Modify algorithms if transport share in the total carbon footprint will be below 5%").

Impact of the PCB surface

It was evaluated the impact and the error resulting from the PCB surface area being the only input data as a way to simplify the procedure of PCBs assessment by the tool. It was stated yet that the error resulting from such simplification can be up to 700% (see Chapter 1.6). Based on this result stated that more PCB's parameters (surface, type of PCB, number of layers, type of coating) have to be used for KEPIs calculation to prevent significant errors.

Tool improvement ideas

The case studies enabled to check different ideas for tool algorithms and data bases improvement as well as ideas for the PCB's eco-profile improvement. The case studies showed also advantages of the elaborated PCB's tool for users.

The data bases were reorganized and uniform to simplify the beta version of the tool preparation. For most KEPIs used the same shape of data bases containing the part related to type of boards and the second part related with coating type on PCB. This improvement should help in web tool preparation and prevent mistakes during programming.

The calculation procedure in the sophisticate version of PCB's tool both for the software developer and the user has been reorganized to utilized as many elements of the Basic version of the PCB's tool. The details of this issue were discussed with SIMPLE, but the beta version wasn't finished yet, because it will be ready in October 2013 according the software development schedule.

The other tool and algorithm improvement were described above and in the Chapter 1.6

The case studies showed also ideas for the PCB's eco-profile improvement and advantages of the tool for users (PCB's producers or electronic equipment designer). The Table 19 is showing examples of possible eco-benefits related with different version of PCB's design manufactured in Europe (transport wasn't included). It is visible that the tool user by choosing more eco-friendly version of PCB design can save environment as well as he can save money.

Table 19. The comparison of KEPIs for two versions of PCB designs.

Key Environmental Performance Indicators (KEPI):	Results for 4-layer PCB, surface 0.036m^2, SnCu (HAL) coating.	Results for double-sided PCB, surface 0.036m^2, SnCu (HAL) coating.	Possible eco-benefits related with PCB design.
Water consumption	0.0123 [m^3]	0.0054 [m^3]	**56.10%**
E_{CM} (Energy consumed during materials production for PCB)	0.58 [kWh]	0.40 [kWh]	**31.03%**
E_{CP} (Energy consumed during production processes of the PCB)	0.99 [kWh]	0.65 [kWh]	**34.34%**
Total sludge and waste emitted	0.0284 [kg]	0.020 [kg]	**29.58%**
Carbon footprint (CF)	0.570 [kg CO2-eq.]	0.38 [kg CO2-eq.]	**33.33%**

The tool user can also check the influence of different life-cycle phases of PCB on her total CF as well as influence of a place of her manufacture. From Fig. 52 it is visible that the benefit for CF can be as high as 260%. This information also helps in improving the eco-profile of the designed PCB.

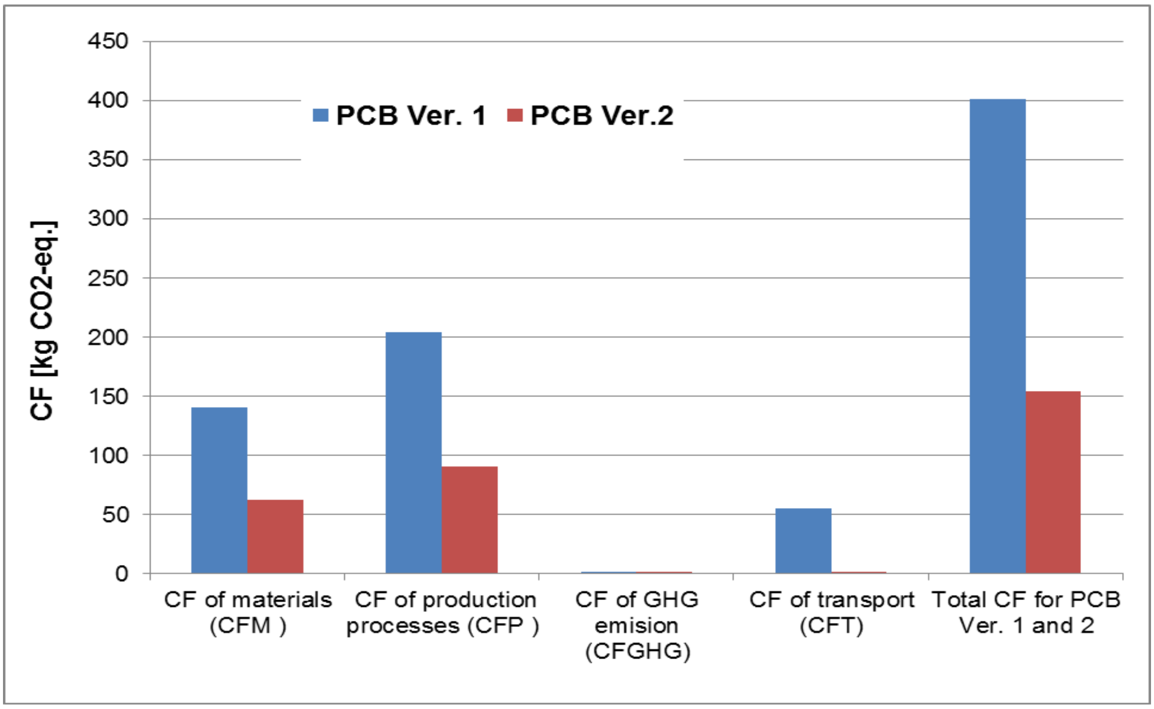


Figure 51. The Carbon footprint (CF) for two PCBs: Ver. 1: 4-layer PCB, coating ENIG, 1 m^2, manufacture place – China (transport 10000 km by plane + 1000 km by car); Ver. 2: 4-layer PCB, coating Sn, 1 m^2, manufacture place – Europe (transport 200 km by car).

ILCD datasets

The analyses of data during case studies enable to answer on methodological question: Which data from the case studies can be classified as ILCD datasets? The 20 ILCD datasets for the most typical PCBs designs were extracted during case studies. They covered materials use for PCBs production processes as well as electricity and heat consumption during production processes for 20 PCBs types. The ILCD datasets details were input to the D4.3 Report.

Summary

The case studies in Printed Circuit Boards carried out according scientific case study concepts showed in D4.1 Report. The simplified Life Cycle Assessments of different types of PCBs were carried out in the case studies in order to validate the methodological approach developed for the PCB's modules of the tool. New data from real PCBs production processes (water, energy and materials consumption etc.) were gathered from Eldos to check correctness of the algorithms and possibility of tool improvement and simplification.
The case studies enabled to check different ideas for tool algorithms and data bases improvement as well as ideas for the PCB's eco-profile improvement. The case studies showed advantages of the elaborated PCB's tool for users. It was showed that the tool user by choosing more eco-friendly version of PCB design can save environment as well as save money. The level of improvements for different KEPIs could be from tens to hundreds of percent.
The 20 ILCD datasets for the most typical PCBs designs were extracted during case studies and transferred to Fraunhofer for the D4.3 Report preparation.

2.7. Future-shape Case Study on Smart Textiles

The WP4 case study was continued with the LCA-based redesign of Future-Shape's SensFloor along the trajectory outlined in the D2.7. Special attention was given to reducing the power consumption and replacing the textile polyester material with cork.

LCA evaluation secures the success of the redesign in terms of environmental product performance. The whole process serves as a test bed for the new LCA to go tool, which will be tested against the previously applied LCA approach.

Figure 52 shows the distribution of eco-costs incurring throughout the product life cycle of the SensFloor. The results confirm the initial assumption that the use phase has the highest environmental relevance. This is due to the continuous power dissipation of the system over its lifetime. The difference between scenarios A and B results from the different size of the SensFloor.

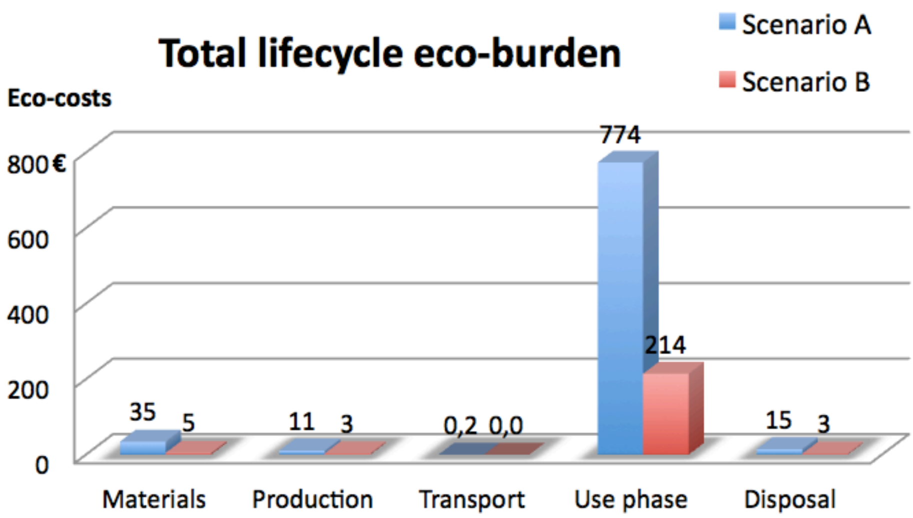


Figure 52. The relevance of life cycle stages (SensFloor size: A=30m^2; B=4m^2).

The distribution of eco-costs among the components of the SensFloor are summarised in Table 20. The polyester base-layer has the highest environmental impact, mostly due to the weight of the material. Other than expected the shielding Al-layer has rather low eco-costs because of its thinness. The environmental relevance of the textile-embedded modules appears to be moderate. However, the margin of error for these electronic components is high because of data unavailability. The relative eco-burden of peripheral electronic devices (transceiver SE8, etc.) is the higher the smaller the SensFloor area in the application.

Table 20. Relative environmental burden of the components of the SensFloor (in percent of total eco-costs) for the two application scenarios.

Component	$30m^2$ size	$4m^2$ size
Conductive textile (polyester part)	6.5 %	4.8 %
Conductive textile (Cu/Sn coating)	9.2 %	6.8 %
Base material (polyester fleece)	72.8 %	53.4 %
Shielding layer (Al-foil)	1.0 %	0.8 %
Microelectronic modules (4 per m^2)	4.9 %	3.6 %
Power supply	1.6 %	8.7 %
Transceiver SE8	3.2 %	17.8 %
Cables	0.8 %	4.2 %
Total eco-cost	**€ 60,20**	**€ 10,90**

As depicted in table 20, the polyester fleece of the SensFloor base material has a quite high percentage in eco-costs, due to its high weight ($450g/m^2$). Cork slab was tested as a substitution material for the 2.5 mm thick polyester fleece, being the component with the highest environmental relevance. The component serves as a surface levelling material and capacitive spacer, which requires specific dielectric properties. Various commercially available cork materials were compared. A 3 mm thick cork insulation slab was found to be technically and economically viable. A LCA-based comparison confirmed the environmental advantage of cork slab over polyester fleece (Table 21). Cork, being a bio-based material, has lower eco-costs and a lower Product Carbon Footprint (PCF) than polyester.

Table 21. Comparing the environmental burdens of polyester fleece and cork slab. Data source: [FS12]

	Polyester fleece		Cork slab	
	Eco-costs €/m^2	PCF kg_{CO2eq}/m^2	Eco-costs €/m^2	PCF kg_{CO2eq}/m^2
Raw material production	0.90	3.3	0.02	0.07
Manufacturing	0.01	1.0	0.18	0.8
Use	0	0	0	0
Waste incineration with electricity	0.13	0.7	-0.14	-0.8

Total	1.04	5	0.06	0.07

Summary

The polyester fleece of the SensFloor base material has a quite high percentage in eco-costs, due to its high weight (450g/m²). A LCA-based comparison confirmed the environmental advantage of cork slab over polyester fleece. Cork, being a bio-based material, has lower eco-costs and a lower Product Carbon Footprint (PCF) than polyester. Concerning the composite structure of the SensFloor underlay, the change from polyester as a base material to cork reduced the eco-cost from 1.04 €/m² to 0.06€/m².

Summary

The report comprised from 2 parts (the first software related aspects and the second one the scientific case study results) summarizes the achievements of the case study implementation, lessons learned, targets achieved and informs about needs for further web tool revisions where appropriate for each sector. It contains results from each case study realized according to the Scientific Case Study Concepts described in the deliverable D4.1 for each sector.

Bio-based plastics sector

The case study on bio-based plastics tried to give a reply on the current demands for SME's on environmental assessment within the bio-based plastic converting sector. Both bio-based and oil-based plastics were considered in the software layout which was comprised by several modules: raw materials, processing, distribution and the end-of-life module. A carefully review for simplicity of the tool was made. The bio-based plastics tool users shall only enter just few data which are under their control like converting processes, raw material use and/or transport operations. The use stage was directly omitted from the software since bio-based plastic products are not usually energy consuming. Furthermore default data was also included for converting processes with the aim to help users when data is not available. Fully customizable processing, transport and distribution modules were also included in order to increase the versatility of the tool to customer demands. The tool module for economic assessment was limited only to those costs which are under the control of the company.
Moreover, the most important change has been the inclusion of the end-of-life as a part of the environmental assessment. Such decision was taken due to the expected advantages of the bio-based plastics during the end-of-life stage. Estimated KEPI's were considered in accordance to the state-of-the-art on the end-of-life of bio-based plastics. Pre-defined scenarios were built in accordance with selected references, although customizable end-of-life scenarios were also included. As a result of all these changes a final beta version of the bio-based plastics software tool was elaborated.

Industrial machines sector

The industrial machinery case study exercise has been very successful from the point of view that the case study the machine developers were very happy with the quality of the reports and the analysis that was carried out. The process was extremely helpful and guided their personnel through the various stages of gathering relevant data. The support documents including the excel templates used and the ISO documents helped them in carrying out the study. The process has introduced LCA to different areas of the organisation that were not aware of LCA at all prior to this study. In the case of the EDM SME the results were surprising for them, due to the fact that the Use phase of their process is so significant e.g. their customers in Asia are already very concerned about the compressed air consumption of their product and the LCA to go study highlighted that this has a significant impact during the Use phase. The company

also see this as a very valuable tool to be used internally to ensure that they have a better understanding of their product, there may be an option to use the information from a sales and marketing point of view however this has to be handled very carefully to ensure that doesn't result in a negative impact of their company if it is not handled appropriately. The company also sees the need for legislation and standards to control how companies use and promote and LCA data and customer demand for this information will also drive other machine tool companies to adopt LCA as a method of promoting the energy demand of their product.
The exercise has also been helpful in testing the methodology that was developed and has allowed modifications and improvements to be made. It has not been possible to date to test the beta version of the software; however this will be carried out with the case study SME's when the beta version of the software is made available for testing in October 2013.

Electronics sector

The case study on computer-like devices addressed highly relevant methodological questions, which were raised by MicroPro due to their current product and business strategy. As the assessment tool as such will be developed consecutively and the electronics sector is last with having the beta version readily available, the case study reflected on the methodological issues as such and the alpha version, but no full quantitative assessment results are provided in this report.
The main finding of this case study with MicroPro is the review of lifetime considerations in the methodology and the ranking of most effective measures to red that allows designers and manufactures to establish best options both for design of specific equipment, for sourcing of materials both new and used, and for designing of industrial and service networks for this product.

Sensor sector

The case study implementation for the sensor sector was subject to a lengthy process of discussing the project with TAIPRO's client from the steel business under critical economic circumstances. The main challenge turned out to be data acquisition on the process line, where the sensor system shall be installed. Whereas data availability was good or at least an educated guess was feasible for many of the data entries, particularly cost data was a sensitive issue. To circumvent this this challenge, the development of some generic default scenarios for some key industries was advisable and has been established for paper machines.
It was stated that given the specifics of the sensor sector to base assessments on predicting future implementation effects a high level of uncertainty is inevitable for this sector. A sensitivity analysis has been undertaken to address and verify the likely impact of uncertainty. Given the high relevancy of the yield loss prognosis all other factors are of minor importance – unless a scenario is likely, where the yield loss is not affected at all by the sensor system under study.
The concept of the Data Quality Indicators (DQIs) has been implemented successfully in the tool and could be applied within the case study.

The sensor sector was one of the few, for which a fully operational beta version of the LCA to go tool was readily available for road-testing in the case study and yielded sound results with respect to quantified savings potentials.

Photovoltaic sector

The case study on photovoltaic systems was focus on the specifics of SMEs in this sector. During meetings of all PV sector related partners multiple points concerning the web tool were discussed and necessary corrections have been made. Next, a beta version of tool was established and released for the use during the case studies.
Different configurations of PV systems were assessed with the tool. Although minor modifications were required almost all the aspects were possible to assessed: PV systems with storage (lithium-ion and lead-acid), small installations (2,76kWp) and medium sized installations (40kWp), and systems in different countries such as Spain in Europe or Chad in Africa. One system was assessed in its designing phase, enabling the improvement of the design by selecting the best option of PV modules after doing the assessment with the LCA to go tool.
The case studies showed that the different possibilities could be assessed by the tool. The tool can be used in two ways: first, during development of the final design, mainly for improvement of environmental performance and second, for assessment of the approved system design. The assessment of the approved system includes an evaluation of the effect, that supporting systems such as the storage do have on the system and enables the user to check the influence of the production country of modules on the total impact.

Printed Circuit Boards sector

The case studies in Printed Circuit Boards carried out according scientific case study concepts showed in D4.1 Report. New data from real PCBs production processes (water, energy and materials consumption etc.) were gathered from Eldos to check correctness of the algorithms, possibility of tool improvement and simplification as well as to answer on some methodological questions.
The simplified LCA of different types of PCBs were carried out during the case studies in order to validate the methodological approach developed for the PCB's modules of the tool. Moreover, based on feedback from represents of PCBs producers it was stated that input data for the tool, in different companies, could not be so precise like in the reference company therefore the window with input data in sophisticated PCB module was changed as well as the algorithms were adjusted to prevent possibility of errors caused by the users.
The case studies enabled to check different ideas for tool algorithms and data bases improvement as well as ideas for the PCB's eco-profile improvement. The case studies showed advantages of the elaborated PCB's tool for users. It was showed that the tool user by choosing more eco-friendly version of PCB design can save environment as well as save money. The level of possible improvements for different KEPIs could be from tens to hundreds of percent.
The improved and verified algorithms for PCBs modules contained "user's manual" were submitted to the SIMPLE for Beta-version of the "LCA to go " tool preparation.

Smart Textiles sector

The Smart Textiles sector case study was continued with the LCA-based redesign of Future-Shape's SensFloor along the trajectory outlined in the D2.7. Special attention was given to reducing the power consumption and replacing the textile polyester material with cork.
For the analysis of two different SensFloor scenarios a fast-track LCA approach, based on the single indicator 'Eco-costs", was used, allowing for a rapid analysis of the environmental performance of materials, processes and energy use of a product. The polyester fleece of the SensFloor base material had a quite high percentage in eco-costs, due to its high weight (450g/m²). A LCA-based comparison confirmed the environmental advantage of cork slab over polyester fleece. Cork, being a bio-based material, has lower eco-costs and a lower Product Carbon Footprint (PCF) than polyester. Concerning the composite structure of the SensFloor underlay, the change from polyester as a base material to cork reduced the eco-cost from 1.04 €/m² to 0.06€/m².

The ILCD datasets and sub-datasets reported by individual sectors, extracted from the case studies results were transferred to Fraunhofer for the D4.3 Report preparation.

The results and conclusions presented in the report are the input for the beta version of the web tool and a basis for the dissemination activities in WP6.

Appendixes

Appendix 1 - References

References for bio-based plastics sector

(ACC, 2011) The Plastics Division of the American Chemistry Council (ACC), Revised final appendices, Cradle-to-gate life cycle inventory of nine plastic resins and four polyurethane precursors, prepared by Franklin Associates, A division of eastern research group, inc. August 2011

(Ashby, 2002). Mike Ashby and Kara Jonhson. Materials and Design: The Art and Science of Material Selection in Product Design. Second edition. Publisher: Butterworth-Heinemann from Elsevier. 2002. Page 249. Available at: http://books.google.es/books?id=IX4kgW1uYwcC&pg=PA249&lpg=PA249&dq=specific+heat+PHB+mirel&source=bl&ots=czxVKP4Tyr&sig=F-J6x8r7iBrp0Pmy9ocFJ4CQWwM&hl=es&sa=X&ei=oBmKUZuHCMfH7AaCv4DYCg&ved=0CEMQ6AEwAg#v=onepage&q=mirel&f=false

(Althaus et al., 2007) Althaus et al. (2007) Life Cycle Inventories of Chemicals. Final Report ecoinvent data v2.0 No. 8. EMPA, Swiss Centre for Life Cycle Inventories, Dübendorf, CH. Available at www.ecoinvent.org

(Bioplastics Magazine. 2012). PBS Production. The energy-saving. resource efficient production of PBS using the 2-reactor process. Bioplastics Magazine 5/12 Vol 7.

(Boustead, 1997) Boustead I. Eco-profiles of the European Plastics Industry. Polymer conversion. Report 10. Association of Plastics Manufacturers in Europe (APME) in collaboration with European Plastics Converters (EuPC) and supported by European Committee of Machinery Manufacturers for the Plastics and Rubber Industries (EUROMAP), Brussels.

(Boustead, 2005a). Eco-profiles of the European Plastics Industry – Methodology. Plastics Europe. 2005 Available at http://lca.plasticseurope.org

(Boustead, 2005b). Ethylene. Eco-Profiles of the European Plastics Industry; PlasticsEurope: Brussels, Belgium, March 2005

(Boustead, 2005c) Pipeline ethylene. Eco-Profiles of the European Plastics Industry; PlasticsEurope: Brussels, Belgium, March 2005

(Boustead, 2005d) Polyethylene (separate reports for High Density Polyethylene/HDPE, Low Density Polyethylene/LDPE and Linear Low Density Polyethylene/LLDPE). Eco-profiles of the European Plastics Industry; PlasticsEurope: Brussels, Belgium, March 2005

(BREF, 2003) Integrated Pollution Prevention and Control (IPPC): Reference Document on Best Available Techniques Mineral Oil and Gas Refineries, February 2003

British Standard Institution. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services

(BUWAL, 1996) BUWAL 250, Ökoinventare für Verpackungen, Umwelt-Materialien Nr. 250, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, 1996

(Cargill Dow LLC, 2007). Moldflow Material Testing Report MAT2238 NatureWorks PLA. Prepared for Cargill Dow LLC. by Moldflow Plastic Labs. July 2007. Available at http://www.natureworksllc.com/~/media/Technical_Resources/Properties_Documents/PropertiesDocument_7000DMoldFlowReport_pdf.pdf (accessed in April 2013)

(Chen and Patel, 2012) Chen G.. Patel M.K. Plastics derived from biological sources: present and future: a technical and environmental review. Chem. Rev. (2012) 112. 2082-2099.

(Coca-Cola Company, 2011) Coca-Cola Company. The Coca-Cola Company Announces Partnerships to Develop Commercial Solutions for Plastic Bottles Made Entirely From Plants. Corporate. December 15th 2011. Press release available at http://www.coca-colacompany.com/press-center/press-releases/the-coca-cola-company-announces-partnerships-to-develop-commercial-solutions-for-plastic-bottles-made-entirely-from-plants

(Coca-Cola Company, FAQ 2013) Coca-Cola Company. Frequently Asked Questions (FAQ). Available at http://www.coca-colacompany.com/stories/plantbottle-frequently-asked-questions, accessed on March 2013

(Conover, 2008) Conover CR. Gravure Package Printing Update from North America. August 2008.

(Davis, 2006) Davis G.. Song J.H. Ind Crop Prod 23: 147–161; 2006

(DfE, 2002) Design for the Environment, an EPA Partnership Program, Flexographic ink options: a cleaner technologies substitutes assessment, Volume A – CTSA, Chapter 6: Resource and Energy Conservation, 2002. Available at http://www.epa.gov/dfe/pubs/flexo/ctsa/index.html

(Diaz, 2006) Diaz R.. Warith M. Life-cycle assessment of municipal solid wastes: Development of the WASTED model Waste Management 26: 886–901; 2006

(Doka, 2007) Life Cycle Inventories of Waste Treatment Services. ecoinvent report No.13. Swiss Centre for Life Cycle Inventories. Dübendorf. 2007

(Dupont, 1995) Dupont. Molding guide. Rynite® PET. thermoplastic polyester resin. 1995. Available at http://www2.dupont.com/Plastics/en_US/assets/downloads/processing/228760D.pdf

(ECPI, 2013) European Council for Plasticizers and Intermediates. Information about phthalate plasticizers. Available at http://www.plasticisers.org/uploads/Factsheets/ECPI_Factsheet_EN_2013_FINAL.pdf

(ECPI, 2001) Prepared by ECOBILAN. Member company of PricewaterhouseCoopers for the European Council for Plasticisers and Intermediates (ECPI). a sector group of CEFIC. Eco-profile of high volume commodity phthalate esters (DEHP/DINP/DIDP). January 2001.

(Edwards, 2011) Dr. Chris Edwards, Jonna Meyhoff Fry, Life cycle assessment of supermarket carrier bags. Report: SC030148 published by Environment Agency. February 2011.

(ELCD, 2013) http://elcd.jrc.ec.europa.eu/ (accessed March 2013)

(Eni S.p.A., 2005a) Eni S.p.A. Divisione Refining & Marketing, Product datasheet for Agip OSO fluids Available at http://veredium.com/index/pds/PDS_Oso.pdf

(Eni S.p.A., 2005b) Eni S.p.A. Divisione Refining & Marketing, Product datasheet for Agip Blasia fluids Available at http://www.eni-q5.com/fileadmin/FILES/blasia.pdf

(EPA, 2008) EPA, United States Environmental Protection Agency, Office of Pollution Prevention and Toxics – Design for the Environment Program. Wire and Cable Insulation and Jacketing: Life cycle assessments for selected applications Chapter 2: Life-Cycle Inventory, Report nº EPA 744-R-08-001, June 2008

(EPD, 2013). PCR 2010:16 Plastics in primary forms 1.0 (valid until 2013-08-12): http://www.environdec.com/en/Product-Category-Rules/Detail/?Pcr=5864 (accessed January 2013)

(ES 2175821 T3 (2002)) Jongboon ROJ, Stuut PI, Rodenburg JA. Molduras biodegradables. Oficina Española de Patentes y Marcas de Nov. 16, 2002

(ETH-ESU, 1996) Environmental Consultancy for Business and Authorities (ESU-services). ETH-ESU 96 libraries. Switzerland

(European Bioplastics, 2011) Landfilling fact sheet 2011.

(European Bioplastics and IfBB, 2012) European Bioplastics and Institute for Bioplastics and Biocomposites (IfBB), Bioplastics production capacity 2011 and 2016 by type. October 2012. Available at: http://en.european-bioplastics.org/press/press-pictures/labelling-logos-charts/

(Eurostat, 2010) Eurostat, Statistics for domestic plastic packaging waste in 2010, for EU-27. Available at http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key_waste_streams/packaging_waste

(Eurostat, 2011) Eurostat, Statistics for municipal waste in 2010, for EU-27. Available at http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key_waste_streams/municipal_waste

(Freedonia, 2011) The Freedonia Group, Inc. Freedonia Focus Reports World Collection– World Bioplastics (Nov 2011)

(Frischknecht et al., 2007) Frischknecht R.. Tuchschmid M.. Faist Emmenegger M.. Bauer C. and Dones R. (2007a) Strommix und Stromnetz. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Vol. ecoinvent report No. 6-XVI. v2.0 (Ed. Dones R.). Paul Scherrer Institut Villigen. Swiss Centre for Life Cycle Inventories. Dübendorf. CH retrieved from: www.ecoinvent.org.

(Fuller, 2012) H.B. Fuller Company, Lindquist L. and Eklund W. Adhesives and key essentials for laminating biopolymer films into flexible packaging. 2012. Available at http://www.adhesives.org/docs/pdfs/biopolmer-film-lamination-hb-fuller-workshop.pdf?sfvrsn=0

(Gallardo, 2011) Gallardo M. Life Cycle Assessment of platform chemicals from fossil and lignocellulosic biomass scenarios LCA of phenolic compounds. solvent. soft and hard plastic precursors. Master Thesis in Industrial Ecology NTNU.

(Green Chemicals 2012). Green Chemicals Blog, Coca-Cola picks 2nd bio-EG supplier, 2012, Available at http://greenchemicalsblog.com/2012/10/01/coca-cola-picks-2nd-bio-eg-supplier/

(Groot, 2010) Groot WJ. Borén T. Life cycle assessment of the manufacture of lactide and PLA biopolymers from sugarcane in Thailand. Int J Life Cycle Assess (2010) 15:970-984

(Gueskens 2008) Gueskens M., from Rodenburg Biopolymers B.V, from a telephone communication with the authors of PRO-BIP 2009

(Häkkinen, 2010) Häkkinen T.. Vares S. J Clean Prod 18 (2010): 1458-1463

(HallStar, 2009) HallStar, Chlorinated Polyethylene; CM (CPE), 2009. Available at http://www.hallstar.com/pdf/HallFacts/ChlorinatedPolyethyleneCPE.pdf (Accessed in May 2013)

(Harding et al, 2007) Harding KG. Dennis JS. van Blottnitz H. Harrison STL. Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly--hydroxybutyric acid using life cycle analysis. Journal of Biotechnology 130 (2007): 57–66

(Habersatter et al., 1998) Habersatter K. et al. Ökoinventare für Verpackungen. BUWAL Schriftenreihe Umwelt Nr. 250. BUWAL. Bern

(Hermann, 2011) Hermann B.G.. Debeer L.. De Wilde B.. Blok K.. Patel M.K. Polym Degrad Stabil 96 (2011) 1159-1171

(Hischier, 2007) Hischier R. Life Cycle Inventories of Packaging and Graphical Papers. ecoinvent-Report No. 11. Swiss Centre for Life Cycle Inventories. Dübendorf. 2007. Part II. Plastics

(Ichikawa, 2012) Ichikawa Y. Mizukoshi T Bionolle (Polybutylenesuccinate) Adv Polym Sci: 245 (2012): 285–314. DOI: 10.1007/12_2011_145

(Ides, 2011) Ides prospector, material data information for generic biodegradable polymers, as obtained in 2011 from the Plastics web® www.ides.com

(Indorama Venture, 2011) Indorama Venture. Processing guidelines: Drying PET. May 2011. Available at http://www.indorama.net/polymerseurope/generaldoc.aspx (prior free registration is needed)

(IPCC, 2007) Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

(Interempresas, 2008) Interempresas.net "Erema imparte un symposium sobre cómo hacer flejes con PET reciclado". Available at http://www.interempresas.net/Plastico/Articulos/23447-Erema-imparte-un-simposium-sobre-como-hacer-flejes-con-PET-reciclado.html

(IPTS, 2005) IPTS. Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe. Report EUR 22103 EN

ISO/TS 14067:2013. Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication. ISBN 978 0 580 71382 8

(Jongboom 2005) Jongboom R., from Rodenburg Biopolymers B.V, Use and application of Solanyl®, 2005, Available at http://www.ienica.net/bioplastics/jongboom.pdf

(Kellenberger et al., 2007) Kellenberger D.. Althaus H.-J.. Jungbluth N.. Künniger T.. Lehmann M. and Thalmann P. (2007) Life Cycle Inventories of Building Products. Final report ecoinvent data V2.0 No. 7 EMPA Dübendorf. Swiss Centre for Life Cycle Inventories. Dübendorf. CH. On-line version under: www.ecoinvent.org.

(Khoo, 2010) Khoo HH. Tan RBH. Int J Life Cycle Assess 15 (2010): 338–345

(Kolstad et al., 2012). Kolstad. Assessment of anaerobic degradation of Ingeo polylactides under accelerated conditions

(LCA to go, 2012) Lead author: Antonio Dobon, Deliverable 2.1 Technical sector report on data models for bio-based plastics. LCA to go project, Boosting Life Cycle Assessment Use in European Small and Medium-sized Enterprises.

(Lee, 1996) Lee. S.Y Plastic bacteria? Progress and prospects for polyhydroxyalkanoate production in bacteria. Trends Biotechnol. 14 (1996). 431–438.

(Material data centre, 2011) Comparison data for Mater-Bi® NF01U. NF803 and YI01U/C from www.materialdatacenter.com. created on 2011-04-12.

(Matweb 2013a) Material property data for the category "Overview of materials for Polyethylene Terephthalate (PET), unreinforced". Available at http://www.matweb.com/search/DataSheet.aspx?MatGUID=a696bdcdff6f41dd98f8eec3599eaa20 (accessed on April 2013)

(Matweb, 2013b) Datasheets for PHB products available at www.matweb.com. Products found are: PHB 88/PHV 12; PHB 92/ PHV 8.

(Metabolix, 2013). Metabolix Inc. MirelTM processing guides. Available at http://www.metabolix.com/Products/Biopolymers/Resource-Center/Processing-Guides (accessed in April 2013)

(Mitsubishi Chemical, 2013) Mitsubishi Chemical. GS Pla® FD92WN Data Sheet.

(Moussa. 2012). Moussa HI. Polybutylene succinate life cycle assessment variations and variables 11/2012; In proceeding of: American Institute of Chemical Engineers (AIChE) 2012 Annual Meeting. At Pittsburgh. PA

(MSDS Solanyl® C 2010) Material Safety Data Sheet, Solanyl ® C2201- Extrusion/thermoforming grade. Ref: MSDS Solanyl C v2010.01, Revised: June 2010

(Myriant, 2013). Myriant Achieves Major Milestone: Successful Start-Up At Flagship Bio-Succinic Acid Plant in Lake Providence, LA. Press release. http://www.myriant.com/media/press-releases/myriant-achieves-successful-start-up-at-lake-providence-la-plant.cfm (accessed July 2013)

(NatureWorks LLC. 2013) Crystallizing and Drying Ingeo™ Biopolymer. Technical bulletin available at: http://www.natureworksllc.com/~/media/technical_resources/processing_guides/processingguide_crystallizing-and-drying_pdf.pdf (accessed May 2013)

(NatureWorks, 2013). NatureWorks LLC. Crystallizing and Drying Ingeo™ Biopolymer. Available at http://www.natureworksllc.com/~/media/Technical_Resources/Processing_Guides/ProcessingGuide_Crystallizing-and-Drying_pdf.pdf (accessed in April 2013)

(Nexant, 2012) Prospectus July 2012. Is bio-butanediol here to stay

(Nexant, 2013) PERP Program - 1.4-Butanediol/Tetrahydrofuran (BDO/THF) http://www.chemsystems.com/about/cs/news/items/PERP2012_3_BDO_THF.cfm

(Norden 2012) Norden, Nordic Council of Ministers, Food contact materials and articles: printing inks, Checklists for compliance in industry and trade and control by food inspection, Report TemaNord 2012:521, 2012. Available at http://dx.doi.org/10.6027/TN2012-521

(Novamont, 2010) Environmental Product Declaration (EPD) of Mater Bi® CF05S of Novamont (September 2010)

(Novamont, 2001) Environmental Product Declaration (EPD) of Mater-Bi® NF type: biodegradable plastic pellets for films Novamont (December 2001)

(Perugini, 2005) Perugini F. Mastellone M.L.. Arena U. A Life Cycle Assessment of Mechanical and Feedstock Recycling Options for Management of Plastic Packaging Wastes. Environmental Progress Vol.24. No.2 (2005)

(PE Europe GmbH, 2004) PE Europe GmbH. IKP. IPU and RANDA Group. Final Report - LCA of PVC and of principal competing materials commissioned by the European Commission. April 2004

(Petchprayul et al, 2012) Petchprayul S.. Malakul P.. Nithitanakul M.. Papong S.. Wenunun P.. Likitsupin W.. Chom-in T.. Trungkavashirakun R. and Sarobol E. Life cycle management of bioplastics for a sustainable future in Thailand: Sa-med island model. Chemical Engineering Transactions. 29 (2012). 265-270

(Petrie, 2007) Petrie EM, Laminating adhesives for flexible packaging, presented by Omnexus4Adhesives and sealants. 2007. Available at http://www.packagingconnections.com/downloads/download195.pdf

(PIRA, 2009) Pira International Ltd. The Future of Packaging: Long term scenarios to 2020. 2009.

(Plastics Engineering 2012). Plastics Engineering, Society of Plastics Engineers, 2012. Available at http://plasticsengineeringblog.com/2012/08/13/the-race-to-100-bio-pet/

(Plastics Europe, 2005a) Eco-profiles of the European Plastics Industry Polypropylene (PP). A report by I Boustead for Plastics Europe Data last calculated March 2005

(Plastics Europe, 2005b) Eco-profiles of the European Plastics Industry Low Density Polyethylene (LDPE). A report by I Boustead for Plastics Europe Data last calculated March 2005

(Plastics Europe, 2005c) Eco-profiles of the European Plastics Industry High Density Polyethylene (HDPE) A report by I Boustead for Plastics Europe Data last calculated March 2005

(Plastics Europe, 2005d) Eco-profiles of the European Plastics Industry Linear Low Density Polyethylene (LLDPE) A report by I Boustead for Plastics Europe Data last calculated March 2005

(Plastics Europe, 2006) Eco-profiles of the European Plastics Industry Polyvinylchloride (PVC) (suspension polymerisation) A report by Axel Ostermayer. Jürgen Giegrich for the European Council of Vinyl Manufacturers (ECVM) & Plastics Europe Data last calculated July 2006

(Plastics Europe, 2010a) Eco-profiles of the European Plastics Industry PET Injection stretch blow moulding. A report by TNO for Plastics Europe. Data last calculated February 2010 (Eco-profile expired according to http://www.plasticseurope.org/plasticssustainability/eco-profiles/browse-by-flowchart.aspx)

(Plastics Europe, 2010b) Eco-profiles of the European Plastics Industry Injection moulding of PVC. HDPE and PP A report by TNO for Plastics Europe. Data last calculated February 2010 (Eco-profile expired according to http://www.plasticseurope.org/plasticssustainability/eco-profiles/browse-by-flowchart.aspx)

(Plastics Europe, 2010c) Eco-profiles of the European Plastics Industry Pipe Extrusion A report by TNO for Plastics Europe. Data last calculated February 2010 (Eco-profile expired according to http://www.plasticseurope.org/plasticssustainability/eco-profiles/browse-by-flowchart.aspx)

(Plastics Europe, 2011) Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers Polyethylene Terephthalate (PET) (Bottle grade) Plastics Europe May 2011

(Plastics Technology. 2013) Knowledge Center Plastics Drying: http://www.ptonline.com/knowledgecenter/Plastics-Drying/Drying-Questions/PET-Drying (accessed April 2013)

(PPFA, 2008) PPFA, The Plastic Pipe and Fittings Association, Final Report: Life Cycle Inventory of the Production of Plastic and Metal Pipes for use in three piping applications. Prepared for PPFA by Franklin Associates, June 2008.

(PRO-BIP 2009) Shen L, Haufe J, Patel MK, Product overview and market projection of emerging bio-based plastics, PRO-BIP 2009, Final report, June 2009, revised in November 2009

(PVC, 2013) PVC Europe. http://www.pvc.org/en/p/pvc-additives. (accessed on May 2013)

(Rebsdat, 2005) Rebsdat S, Mayer D: Ethylene Oxide – Ethylene Glycol. In Ullmann's Encyclopedia of Industrial Chemistry, WILEY-VCH Verlag, Weinheim, 2005

(Regulation (EC) No 715/2007) Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information. Official Journal of the European Union. 29/06/2007

(Relpet, 2003) Reliance Industries Limited. PET Business Group. Drying RELPET. Available at http://www.ril.com/cmshtml/drying.pdf

(Rodenburg 2012) Aaik Rodenburg, Development of Solanyl, from BPM (Biobased Performance Materials) symposium, June 21, 2012, available at www.biobasedperformancematerials.nl

(Rostkowski, 2012) Rostkowski KH. Criddle CS. Lepech MD. Cradle-to-Gate Life Cycle Assessment for a Cradle-to-Cradle Cycle: Biogas-to-Bioplastic (and Back). Environ. Sci. Technol. 2012. 46. 9822–9829

(Ryan, 2010) Ryan, C. Biobutanol potential for bio-based monomers and polymers, Gevo. Presentation given at the conference "Emerging Trends in Single and Multi-Use Plastic Packaging". Atlanta, USA, April 26-28, 2010.

(Samantaray, 2012) Samantaray S. Mallick N Production and characterization of poly-β-hydroxybutyrate (PHB) polymer from Aulosira fertilissima. J Appl Phycol (2012) 24:803–814

(Schut, 2003) Schut JH, Stretching film's limits, Plastics Technology, 2003. Available at http://www.ptonline.com/articles/stretching-film's-limits

(Shen et al, 2012) Shen L.. Worrell E.. Patel M.K. Comparing life cycle energy and GHG emissions of bio-based PET. recycled PET. PLA and man-made cellulosics. 2012. Biofuels. Bioprod. Bioref. 6:625-639 (2012).

(Signori et al., 2012) Signori F, Pelagaggi M, Bronco S, Righetti MC, Amorphous/crystal and polymer/filler interphases in biocomposites from poly(butylene succinate) Thermochimica Acta 543 (2012) 74-81

(Spielmann, 2007) Spielmann M. Dones R and Bauer C (2007) Life Cycle Inventories of Transport Services. Final report ecoinvent v2.0 No. 14. PSI. Swiss Centre for Life Cycle Inventories. Dübendorf. 2007

(TetraPak, 2013) Tetra Pak and Braskem to sign supply agreement on bio-based plastic for carton packaging in Brazil. Press release: 2013-06-26. http://www.tetrapak.com/about_tetra_pak/press_room/news/Pages/Bio_based_plastic_Brazil.aspx (accessed July 2013).

(Thiriez, 2006) Alexandre Thiriez and Timothy Gutowski, An Environmental Analysis of Injection Moulding (2006). Available at http://web.mit.edu/2.810/www/Thiriez_ISEE_2006.pdf

(UK Environment Agency, 2011) Life Cycle Assessment of Supermarket Carrier Bags Report: SC030148

(US 2012/0296015 A1 (2012)) Van Heemst JJ, Zant E, et al. Starch-based biodegradable polymer; method of manufacture and articles thereof. United States Patent of Nov. 22, 2012

(US 6,482,341 B1 (2002)) Jongboom ROJ, Stuut PI, Rodenburg JA. Biodegradable mouldings. United States Patent of Nov. 19, 2002

(U.S. Department of Energy, 2010) Environmental Assessment for the Myriant Succinic Acid Biorefinery (MySAB). Lake Providence. Louisiana U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Golden Field Office Golden. Colorado December 2010 Report DOE/EA 1787

(Veith and Barr, 2008) Veith S, Barr S, Life Cycle Assessment: Flexographic and Rotogravure printing comparison & flexographic plate imaging technologies, E-I- Du Pont de Nempours and Company, DuPont Engineering and Research Technology (DuET), 2008

(Ventura. 2013a). Ventura M. Personal communication (May 2013)

(Ventura, 2013b). Ventura M. Personal communication (April 2013)

(Vidal, 2007) Vidal R. et al J Polym Environ 15 (2007):159–168

(Vink et al. 2007) Vink ETH. Glassner DA. Kolstad JJ. Wooley RJ. O'Connor RP. The eco-profiles for current and near future NatureWorks® polylactide (PLA) production. Industrial Biotechnology. 2007. Vol 3 (1) pp 58-81

(Vink et al., 2010) Vink ETH. Davies S. Kolstad JJ. The eco-profile for current Ingeo® polylactide production. Industrial Biotechnology. 2010. Vol 6 (4) pp 212-224

(WRAP, 2008) LCA of Management Options for Mixed Waste Plastics. Final report.

(Wittmann, 2009) Wittman: Andreas Vierling. Extended Standard for Energy Rating with Resin Driers and classification of dry air quality. Version 2009-11-25. Available at http://www.wittmann-group.com/uploads/tx_templavoila/Energy-Rating-Standard_engl_2012_11.pdf

(Wittmann, 2010) Wittman: Matthew H. Naitove, close up drying: New Standard & Labelling Proposed for Dryer Energy Ratings. Plastics Technology, May 2010. Available at http://www.ptonline.com/articles/new-standard-labeling-proposed-for-dryer-energy-ratings

(WO 99/29733 (1999)) Jongboon ROJ, Stuut PI, Rodenburg JA. Biodegradable mouldings. World International Property Organization of June 17, 1999

WRI/WBCSD GHG Protocol Product Life Cycle Accounting and Reporting Standard

References for electronics sector

[Tange 2012] Tange, L.; van Houwelingen, J.A.; Hofland, W.; Salémis, P.: Recycling of plastics with flame retardants of electronic waste, a technical and environmental challenge for a sustainable solution, Electronics Goes Green, September 9-11, 2012

[ACTA 2012] Institut für Demoskopie Allensbach: ACTA 2012 – Allensbach Computer- und Technik-Analyse, October 2012

[Böttner 2011] Böttner, Hellmut; Schischke, Karsten; Nissen, Nils F.: Carbon Footprinting of Information Technology Products based on ISO standards - Fujitsu Case Study, ICCE - IEEE International Conference on Consumer Electronics - Berlin 2011, September 6-8, 2011, Berlin, Germany

[Brusselaers 2006] Brusselaers, Johan; Mark, Frank E.; Tange, Lein: Using Metal-Rich WEEE Plastics as Feedstock / Fuel Substitute for an Integrated Metals Smelter, A Technical Report produced by: PlasticsEurope in cooperation with Umicore and EFRA, November 2006

[Buchert 2012] Buchert, M.; Manhart, A.; Bleher, D.; Pingel, D.: Recycling kritischer Rohstoffe aus Elektronik-Altgeräten, LANUV-Fachbericht 38, Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen, 2012, Recklinghausen, Germany

[Chancerel 2010] Chancerel, P.: Substance flow analysis of the recycling of small waste electrical and electronic equipment - An assessment of the recovery of gold and palladium. Dissertation, Technische Universität Berlin. Schriftenreihe des Instituts für Technischen Umweltschutz, Band 09, 2010

[Energy Star memo] ENERGY STAR® Version 6.0 - Notes on Draft 1 Dataset, no year stated; https://www.energystar.gov/products/specs/system/files/Data_Analysis_Memo.pdf

[EuroStat 2012] EuroStat: Collection of WEEE, by country, year and EEE-Category, in tonnes, percent and number, http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key_waste_streams/waste_electrical_electronic_equipment_weee

[Intel 2009] Intel: Computer-Atlas, 2009; in: RP-online: Kuriose Fakten zur Computer-Nutzung der Deutschen, http://www.rp-online.de/digitales/neuheiten/kuriose-fakten-zur-computer-nutzung-der-deutschen-1.2174338

[Prieur 2012] Prieur, Marc: Les taux de retour de composants, hardware.fr, url: /articles/881-1/taux-retour-composants-7.html, October 25, 2012

[Slijkhuis 2011] Slijkhuis, Chris: Kunststoffrecycling – Herausforderungen einer neuen Industrie, 8. Schweizer Sonderabfalltag, Olten, Switzerland, June 7, 2011

[Stocker 2013] Stocker, Raphael: Stock and Lifespans elektronischer Geräte, Studie der Fachhochschule Nordwestschweiz über die durchschnittliche Lebensdauer von Elektronik-Geräten, 2013

[Stutz 2012] Stutz, Markus; O'Connell, Scott; Pflueger, John: Carbon Footprint of a Dell Rack Server, Electronics Goes Green 2012+, September 9-12, 2012, Berlin, Germany

[test 2013] Stiftung Warentest: Das kauf ich wieder, test, 2/2008, p.37-39

[Wäger 2010] Wäger, P.; Schluep, M.; Müller, E.: RoHS Substances in Mixed Plastics from Waste Electrical and Electronic Equipment, 2010 / VKE 2000

[Kahhat 2011] Kahhat, Ramzy; Poduri, Soumya; Williams, Eric: Bill of Attributes (BOA) in Life Cycle Modeling of Laptop Computers: Results and Trends from Disassembly Studies, The Sustainability Consortium, White Paper #103, March 2011

References for Sensors sector

[Fleiter 2013] Fleiter, Tobias; Schlomann, Barbara; Eichhammer, Wolfgang: Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien - Einsparpotenziale, Hemmnisse und Instrumente; Fraunhofer ISI, Fraunhofer Verlag, Stuttgart, 2013

[IPPC 2010] Integrated Pollution Prevention and Control, Draft Reference Document on Best Available Techniques in the Pulp and Paper Industry, Draft, Sevilla, April 2010

[VDEh 2010] Stahlinstitut VDEh: 9. CO2-Monitoring-Fortschrittsbericht der Stahlindustrie in Deutschland - Berichtsjahr 2009

References for Smart Textiles sector

[FS11] Andreas R. Köhler, Christl Lauterbach, Axel Steinhage, Joost C. Buiter, Axel Techmer „LCA and eco-design of a textile-based large-area sensor system",Joint international congress and exhibition Electronic Goes Green 2012, September 9-12, Berlin, Germany (2012)

[FS12] http://www.ecocostsvalue.com

[FS13] J.G. Vogtländer, "The model of the Eco-costs / Value Ratio, a new LCA based decision support tool," Delft University of Technology, DfS, Delft, 2001.

[FS14] J.G. Vogtländer, H.C. Brezet, and C.F. Hendriks, "CT /Methodology, the virtual eco-costs'99." In-ternational Journal of Life Cycle Assessment, vol.3, no.6, pp.157-166, 2001.

[FS15] J.G. Vogtländer, A. Bijma, and J.C. Brezet, "Communicating the eco-efficiency of products and services by means of the eco-costs/value model." Journal of Cleaner Production, vol.10, pp.57-67, 2002

[FS16] M. Becker and P. Knoll, „Energieeinsparpotenzial und Energieeffizienz durch Bustechnik sowie Raum- und Gebäudeautomation" Hoch-schule Biberach (HBC). 2008.

Appendix 2 - Authors and contributors

Table 22. Authors and contributors

Name	Institution	Function	Sector
J. Sitek	ITR	Work Package 4 leader/ Sector leader/ Researcher	Electronics/PCBs
G. Koziol	ITR	Researcher	Electronics/PCBs
M. Koscielski	ITR	Researcher	Electronics/PCBs
W. Steplewski	ITR	Researcher	Electronics/PCBs
A. Arazna	ITR	Researcher	Electronics/PCBs
A. Girulska	Eldos	SME representative	Electronics/PCBs
Antonio Dobon	ITENE	Sector leader	Bio-based plastics
Anne Sophie Le Meur	ITENE	Researcher	Bio-based plastics
Miguel Ventura	ITENE	Researcher	Bio-based plastics
Ion Ajuriagoxeascoa	Valsay	CEO	Bio-based plastics
M. Saint-Mard	TAIPRO	SME representative	Sensors
K. Schischke	Fraunhofer IZM	Researcher	Sensors / PV / Electronics
M Anzizu	TTA	SME	Photovoltaics
P Arranz	TTA	SMA	Photovoltaics
Carl Diver	CDAMC	SME representative	Industrial Machines
Rainer Pamminger	TUW	Sector Leader	Industrial Machines
Florian Krautzer	TUW	Researcher	Industrial machines
Wolfgang Wimmer	TUW	Researcher, methodology adviser	Industrial machines
N.M. van der Velden	TU Delft	Researcher	Smart textiles
A.R. Köhler	TU Delft	Researcher	Smart textiles
Christl Lauterbach	Future-Shape	SME representative	Smart textiles

Appendix 3 - Development of the sectoral software tool for bio-based plastics – Status - RE

The table 3 summarizes the level of implementation of SME needs in accordance with Valsay's case study.

Table 3. Summary of Valsay's contributions for the development of the bio-based sectoral software tool (as of May 2013) and implementation of suggestions in the First Beta Version (mid June 2013) and Final Beta Version (July 17th 2013).

Valsay's need	Reply from ITENE	Comments from Simpple	Implemented in the software (Yes/No)
The chance to compare one product against other products (including own products and/or market products through use of internal data) Comparisons should be made by life cycle stage, material and/or the whole life cycle	In accordance with the meeting with Simpple, the software tool is only capable to compare a maximum of two products. We recommend you to not make comparisons of more than four products at the same time.	We suggest the use of the export function. The concept is that the user will be able to export the results into an Excel spreadsheet. Then the user will be able to make personalized comparisons	First beta version: No Final beta version: Yes
The chance to discard some of the processes in the life cycle, focusing just in the more sensitive processes	We understood that you are talking about the way for a quick discrimination of those processes with the less environmental impact. The tool is capable to calculate the percentages as well as mark out the processes and stages as function of the contribution to the environmental impact. If you are talking about a preliminary withdraw before calculation with the software tool, this is not possible since: a) non-expert LCA users will hardly predict which one/s of the life cycle stage/s will have less contribution to environmental impact. b) input data for the bio-based plastics tool is just based on material, transport and energy inputs that are easy to collect for every SME, so there is no need for preliminary withdraw of processes	N/A	First beta version: No Final beta version: No
To create different life cycle schemes for the same product as function of the customer requirements (e.g.: different end-of-life and use scenarios)	This can be easily done with the Product Copy functionality. You can copy an existing product, then edit for instance the end of life scenario and finally save it with other product name	N /A	First beta version: Yes Final beta version: Yes
The functional unit must be considered in all the processes	It is intended that the info about the functional unit will be entered when the user creates a new product. Results will be ever shown in accordance with the functional unit.	Simpple agreed to include a functional unit reminder in all the software screens	First beta version: No Final beta version: Yes
The chance to enter data estimations	This is not so clear for us. If you are talking about make estimations with the data to be entered by the user (material, energy and transport), users are totally free of enter whichever he/she wants.	For the time-being customized KEPI's cannot be entered in the tool. This is an aspect for further discussion in the	First beta version: No Final beta version: No (entering of customized KEPI's

	In case of estimations for KEPI's, it is intended that users will be able to enter their own estimated KEPI's under his/her responsibility.	consortia. A general approach should be defined if required.	is still under discussion)
The chance to enter either indicators or set of indicators at any point of the life cycle	The calculation of environmental impacts will be based on KEPI's database which will be used to characterize the impact as function of the amount of material, energy or transport entered by the user. It is expected that users will be able to enter their own KEPI's under their responsibility.		First beta version: No Final beta version: No (entering of customized KEPI's is still under discussion)
How does the uncertainty of data will be treated?	A procedure for assessment of quality data has been established based on five main criteria: (1) The origin of the data, (2) the representativeness, (3) how old the data is, (4) the geographical correlation and (5) the technological correlation. All DQI criteria are described in Table 4.	Simpple will integrate it in the tool	First beta version: No Final beta version: Yes
Save and compare estimations	This completely depends on Simpple	Pair-wise comparisons have been enabled in the final beta version. Future advanced versions will allow users to compare more products at the same time	First beta version: No Final beta version: Yes
How to deal with complex products (i.e.: add more life cycles to the life cycle of a single product)	N/A	Such function is not possible with the current version of the software	First beta version: No Final beta version: No
Is it possible to use external databases with the bio-based plastics LCA to go tool?	N/A	No, this is not possible	First beta version: No Final beta version: No
Do the users will be able to use different databases at the same time?	Users will be only able to use the internal KEPI database, although enter your own KEPI will be also possible in certain cases	For the time-being customized KEPI's cannot be entered in the tool. This is an aspect for further discussion in the consortia. A general approach should be defined if required.	First beta version: No Final beta version: No
To keep track of product versions as well as the date for which the calculation is made. The idea is to keep track of the KEPI results in case the database is updated and therefore results may change	N/A	Users can introduce the version of product they are modelling, although for the time being is not possible to keep track of results with older versions of the database	First beta version: Partially Final beta version: Partially
Is there any chance to users to enter personalized information about the processes, materials, etc.?	A comment field will be enabled in the tool in order to users will be able to enter additional information. This will be implemented as text field.	Text field added in almost all data entry fields to keep track of the origin of the data	First beta version: Yes Final beta version: Yes
Is there any chance to show the whole impact results (i.e.: all life cycle stages together)?	Yes, it is. The Results module allow to make whole impact analysis	N/A	First beta version: Yes Final beta version: Yes
Does the ISO Ecodesign standard (ISO 14006:2011) considered in the development of the software	Yes, it does. The tool considered the following main concepts of the ISO ecodesign standard:	N/A	First beta version Yes, except the ecodesign

tool?	a) A cradle-to-grave approach since EOL is also taken into account b) The tool is aimed at the minimization of environmental impacts c) The tool will be capable to quantify and identify the most relevant environmental aspects d) The tool will ensure that the impacts are not transferred between life cycle stages e) We intend that some ecodesign recommendations will be included in the result screen as well as in the final report. However this will be prepared when the Beta version of the tool will be tested		recommendations which will require from further analysis Final beta version: Yes, except the ecodesign recommendations which will require from further analysis
Is there any chance to modelize complex products?	Yes, whenever we talk a product comprised by several different materials. As pointed out above users will be not be able to add other life cycles to the life cycle of a single product.	N/A	First beta version: Yes, for products comprised by several materials Final beta version: Yes, for products comprised by several materials
Does the tool include data about packaging?	Yes, it does. A pre-defined set of packaging materials with its own KEPI will be available in the software tool.	N/A	First beta version: Yes Final beta version: Yes

Table 4. Suggested Data Quality Indicators for LCA to go software tool for bio-based plastics.

Indicator	Data quality		
	Robust	Indicative	Illustrative
	1	2	3
Reliability	On-site measured data or verified data provided by a third party	Data partly based on assumptions or combined on-site measured data with default data	Only default data used
Completeness	Representative data from a sufficient sample of production sites or company specific data	Representative data from a smaller number of production sites	Representativeness unknown or incomplete data
Temporal correlation	Data with less than three years of difference to year of the study	Less than six years difference	Age of data unknown or more than 6 years of difference
Geographical correlation	Data from the Country where the product is manufactured	Data from a Country/area with similar production conditions	Unknown geography or data from Country/area with different production conditions
Technological correlation	Data based on current industrial manufacturing technologies	Data from pilot plants	Data based on laboratory trials

1.2.1 Development of the KEPI's database for bio-based plastics

1.2.1.1 KEPIs for raw materials

Common assumptions for the KEPI's of raw materials

Infrastructure processes were excluded from the KEPI calculation of raw materials in the bio-based plastics sectoral tool. Sunch decision was taken since impacts of infrastructure processes (buildings, equipment, etc.) are usually considered to be negligible over the course of the life-time of a production plant in respect to the overall product throughput.

Polylactide (PLA)

In accordance to Shen (2012), PLA is produced mainly from the fermentation into lactic acid of two carbon substrates, corn and sugarcane sources. The two main producers of PLA, Natureworks LLC and PURAC polymerize PLA by the indirect ring-opening polymerization of lactide (Chen, 2012).

Natureworks LLC manufactures PLA from corn produced in USA. Vink (2010) published an eco-profile for PLA production in Blair, Nebraska, USA, which is a cradle-to-polymer-factory-gate life cycle inventory. The eco-profile provides data for Natureworks' trademark, Ingeo, according to the production system of 2009. This eco-profile was developed with the methodology used in Plastics Europe eco-profiles (Boustead, 2005). In the Ecoinvent database, the process "Polylactide, granulate, at plant" is based on the eco-profile published by Vink (2007). In order to estimate the KEPI's for LCA to go software tool, the updated eco-profile data for Ingeo 2009 were implemented in SimaPro 7.3 because this eco-profile is based on the latest PLA production technology implemented in December 2008 and the use of Renewable Energy Certificates is no longer included. This approach is consistent with the current methodologies for carbon footprinting were carbon offsetting is not included in the calculations (PAS 2050:2011, ISO/TS 14067:2013, WRI/WBCSD GHG Protocol Product Life Cycle Accounting and Reporting Standard).

On the other hand, PURAC is the main producer of lactic acid and lactides from sugarcane cultivated in Thailand. PURAC produces lactides for its PLA production partners (Groot, 2010). Groot (2010) published a LCA study of the manufacture of lactide and PLLA (poly L-lactic acid) from sugarcane in Thailand, with a cradle-to-gate scope. In this study, it was considered that PLLA is made from L-lactide, on the same site than lactide production. Due to confidentially reasons, the authors did not publish any LCI data but they gave the environmental impact indicators for the production of PLLA of some impact categories, namely: renewable and non-renewable Cumulative Energy Demand (CED), Abiotic Depletion, Global Warming, Acidification, Eutrophication, Photochemical Ozone Creation, Human Toxicity and Farm land use. From this list, all impact categories covered by the LCA to go software are considered, except for respiratory inorganics and water footprint. Due to the lack of detailed inventory data, it was decided to take the values given by Groot (2010) as KEPI's for the LCA to go software tool, whereas KEPI's for respiratory inorganic and water footprint were omitted due to the lack of data.

Blended thermoplastic starches (TPS)

As explained in Deliverable 2.1 of LCA to go project (LCA to go, 2012), from the family of starch-based plastics, Novamont is the main producer of thermoplastic starch-based plastics, under the trademark Mater-Bi®. Mater-Bi® is a biodegradable thermoplastic material made of a blend of natural components (corn starch) and biodegradable polyesters.

Publicly available data for Mater-Bi® production is scarce and only related to a couple of specific grades of Mater-Bi® for film processing: CF05S and NF-type. In both cases data has been published as an ISO 14025:2006 Environmental Product Declaration under the umbrella of the International EPD® System, managed by the Swedish organisation Environdec. Mater-Bi® NF-type represents the first generation Novamont's materials whereas the CF05S grade belongs to the second generation of Mater-Bi® materials.

The Environmental Product Declaration for Mater-Bi® CF05S (Novamont, 2010) provides some inventory data in a cradle-to-gate approach. Such EPD is valid for three years from September 2010. Mater-Bi® CF05S consists of a blend of native corn starch with biodegradable copolyester based on their proprietary technology (based on diacids and a glycol from renewable and non-renewable sources). The EPD provides the environmental performance of 1 kg of Mater-Bi® CF05S, as the consumption of natural resources and the potential environmental impacts (GW, OD, AC, POF, EU and AD). Other indicators are also considered (Materials for recycling, hazardous waste, other waste). The cradle-to-gate inventory is given distinguishing between three main modules: upstream, core and downstream modules, in accordance with the Product Category Rules for Plastics in primary forms (EPD, 2013). For the calculation of the KEPI's in LCA to go, the consumption of natural resources (Table 5) in the upstream and the core processes of the EPD were considered, since downstream process only considers the distribution of the pellets to the customer. Data given in Table 5 were implemented in SimaPro 7.3.3 in order to obtain the estimated KEPI's for LCA to go software tool.

Table 5. Consumption of natural resources for the production of 1 kg of Mater-Bi® CFO5S (Source: Novamont, 2010)

	Indicator	Unit	Upstream	Core
Non-renewable resources	**Materials**			
	Calcite	kg	0.099	0.002
	Gravel	kg	0.339	0.045
	Sodium chloride	kg	0.44	0
	Gas	kg	0.228	0.001
	Oil	kg	0.188	0
	Energy			
	Gas	kg	0.284	0.001

	Oil	kg	0.134	0.0093
	Uranium	kg	1.85E-06	4.00E-08
	Indicator	**Unit**	**Upstream**	**Core**
Renewable resources	**Materials**			
	Corn	kg	0.349	0
	Seeds (oil plants)	kg	0.325	0
	Energy			
	Energy, potential converted (hydropower plant)	MJ	7.63	1.46
	Water	m^3	0.232	0.001

On the contrary, the Mater-Bi® NF-type EPD (Novamont, 2001) is no longer valid since it dates from 2001. However, data published was used as a reference for the production of NF-type grade. This grade is mainly used as a raw material for the production of films. The NF-type Mater-Bi® consists of a blend between corn starch and vegetable oil derivatives with synthetic polyesters. The EPD refers to NF779 and NF803/1 grades but in accordance with the authors the results are applicable to other grades of NF-type Mater-Bi® for films (Novamont, 2001). Although the EPD of NF-type considered a cradle-to-grave approach, for the purpose of extraction of data for the LCA to go tool only the cradle-to-gate was considered. This EPD gives the consumption of resources, the production of dangerous wastes, as well as the potential impacts for several impact categories, namely: renewable and non-renewable primary energy consumption, climate change (renewable and non-renewable), ozone layer depletion, acidification, eutrophication, POCP. The water consumption has been extracted from resource use. All impact categories considered in LCA to go approach were covered, except land use.

Potato-based starch plastic

Potato starch-based plastic refers specifically to the product manufactured by Rodenburg Biopolymers B.V, under the brand Solanyl®. The manufacturing process of Solanyl® has evolved since the first commercial grade appeared in 2001. According to Rodenburg (2012), the third generation Solanyl® has been commercialized since 2010 and it is a full compound obtained from a single production step system that is patented. Even though Rodenburg Biopolymers has performed LCA studies of the production of Solanyl®, these are not publicly available. In the Material Safety Data Sheet for Solanyl® (MSDS Solanyl® C 2010), the Solanyl® C is described as a compound comprising thermoplastic starch, polylactic acid and polyvinyl ester. In addition, the latest patent found about starch-based polymer (US 2012/0296015 A1 (2012)) details a process for manufacturing biodegradable composition that involves the compounding of at least thermoplastic starch (TPS), a vinyl ester polymer and one or more plasticizers for vinyl ester polymer. The manufacturing is a single extrusion-compounding process that is divided into two stages, (1) starch destructurization and compounding, and followed by (2) pelletizing.

On the basis of such information dated from at least 2010, it is concluded that Solanyl® C is based on side stream potato starch from potato processing industry and that it is no longer partially fermented starch plastic as found in references prior to 2010 (Jongboom 2005; Gueskens 2008) and neither based on potato skins as also found in references prior to 2010 (US 6,482,341 B1 (2002); ES 2175821 T3 (2002); WO 99/29733 (1999); Jongboom 2005).

In the patent US 2012/0296015 A1 (2012), the components and their relative amounts are given for examples of the compositions (Table 6).

Table 6. List of the components and their relative amounts of examples of the compositions described in US 2012/0296015 A1 (2012)

		Content %				
	Component	Ex. 1	Ex. 2	Ex. 3	Ex. 4	Type of component
1	Potato starch (cake starch)	69	55	31.5	30	starch
2	Vinnex® 2504	30	7.5	15	4.3	vinyl acetate polymers
3	Vinnex® 2505	0	0	0	21	vinyl acetate polymers
4	Vinnex® 2510	0	14	8	0	vinyl acetate polymers
5	PLA	0	22.5	45	37	biodegradable polymer
6	Magnesium stearate	1	1	0.5	0.5	lubricant
7	Added water*	14	12	10	0	plasticizer for starch
8	Glycerol*	12	10	30	7	plasticizer for starch
9	Palm oil*	0	1	1	0	lubricant
10	Diacetin**	3	3	3	3	plasticizer for vinyl acetate polymers
11	Joncryl ADR 4370	0	0	0	0.2	additive

* The percentages of added water, glycerol and palm oil are calculated with respect to the total of component 1, 2, 4 and 6 in example 1 to 3.

** The percentage of diacetin is calculated with respect to the total of components 1-4, 6, 8 and 9 in example 1 to 3. In example 4, the percentages of the components are with regard to the total (100%) with the exception of diacetin. Here the diacetin is 3% of the total composition.

In the patent US 2012/0296015 A1 (2012), the pellets obtained in example 1 to 3 were used for injection moulding. Furthermore the composition of example 4 was used for film blowing. Since Solanyl® products are available for injection moulding, extrusion, thermoforming, extrusion film blowing and extrusion film casting, and that the examples of compositions data are available only for two processes, it was decided to model the production of Solanyl® considering an average of the four compositions given.

In order to model the process of manufacture of Solanyl® for the calculation of KEPIs, only the processes mentioned in US 2012/0296015 A1 (2012) were considered. Moreover the processes referred as optional (i.e. the purification step prior to compounding or the drying step after pelletizing) were not included in the model. Indeed, if a drying step is necessary prior to processing, the user can take it into account in the processing module of the bio-based plastic sector LCA to go tool. The extrusion-compounding process is said to be more preferably realised using a twin screw extruder. The energy, cooling water and lubricant oil consumption of extrusion-compounding process and pelletizing were considered for calculating the KEPI, according to data from Thiriez (2006) and Hischier (2007).

Bio-based PE

Bio-based polyethylene is kind of material of bio-based origin with the same properties than conventional oil-based PE. Bio-based PE is obtained from renewable resources such as sucrose feedstock (sugarcane, sugar beets, or sweet sorghum), starchy biomass (corn) or ligno-cellulosic biomass (wood and stalks) (IEA, 2013). Raw materials are then converted into ethanol, which is catalytically dehydrated into ethylene. The ethylene is finally polymerised into polyethylene. The polymerization process of ethylene is identical for both bio-based PE and oil-based PE. Only the source to obtain the ethylene monomer change. In case of bio-based PE the source is ethanol whereas in case of oil-based PE the source is liquid hydrocarbons treated by steam cracking.

Currently, the only commercial bio-based PE available in the market is produced by Braskem in Rio Grande do Sul (Brazil) under the trade name of Green PE (IEA, 2013). Green PE is made from sugarcane feedstock that is converted into ethanol by fermentation. This material is available as HDPE and LLDPE, as well as LDPE as recently announced by TetraPak (TetraPak, 2012). Dow Chemical is also expected to process its first full harvest of sugarcane in Brazil in 2014, which will be converted into ethanol in a plant under construction. However, the expansion into bio-PE among other derivative products was postponed (Dow, 2012). As regards ligno-cellulosic biomass, a number of new commercial-scale bio-ethanol production facilities have been announced but they are not yet linked to the production of bio-ethylene (IEA, 2013). Therefore the life cycle inventory that represents current bio-based PE production must be based on the sugarcane-based PE route.

On the other hand, Liptow and Tillman (2012) published a LCI for sugarcane-based LDPE from sugarcane cultivated in Brazil. The LCI provide data for the main materials and energy consumption within the four stages of bio-PE production (sugarcane growing and harvesting, ethanol production, conversion to ethylene and polymerization). The emissions caused at each one of the steps were not reported in Liptow and Tillman's (2012) article. However, the authors gave the references used for each input and output, which allowed us to build an LCI based on elementary flows from each one of the references. Alternative data sources were also found in the literature like the paper of Chen and Patel (2012) on modeling of the bio-based PE production. However, their paper was only focused on the methodology followed but LCI data are not provided. Table 7 makes a comparison between the methodology and references followed by Liptow and Tillman (2012) and Chen and Patel (2012).

Table 7. Methodological comparison of existing studies on the LCA of bio-based PE

Bio-based PE production steps	Main references used in Liptow and Tillman (2012)	Main references used in Chen and Patel (2012)
1) Sugarcane cultivation in Brazil	Macedo et al. (2004), data from 2002 season	Macedo et al. (2008), data from 2005/2006 seasons
2) Sugarcane to ethanol by fermentation	Macedo et al. (2004)	Macedo et al. (2008)
3) Ethanol to ethylene by catalytic dehydration	Industrial data on polymer-grade ethylene from Kochar et al. (1981) checked with the patent used in Braskem plant (Barrocas and Lacerda 2007) that was simulated in Aspen Hysys®. Both datasets in the same range.	Own approximation of the energy use with the theoretical heat of reaction, calculated from heats of formation due to lack of consistent industrial data
4) Ethylene to polyethylene	Data from the Swedish producer Borealis (2008): data for the production of LDPE and HPDE. Allocation between LDPE and HDPE based on energy consumption (BREF 2007). LDPE production is considered in final LCI.	Calculated as the difference between the cradle to factory gate values for ethylene and polyethylene, from Plastics Europe (Boustead, 2005b,c,d) Average for LDPE, HDPE, LLDPE

One important point is that for sugarcane production and processing, both authors use the methodology developed by Macedo et al., although Liptow and Tiilmann (2012) used the old data from 2002 whereas Chen and Patel (2012) used updated data from 2005/2006 seasons that take into account the legislative changes to move from manual harvesting to mechanical harvesting of unburned cane, and technical improvements. Unfortunately, a deep analysis of the new paper from Macedo et al. (2008) with updated data showed that not all the flows where disclosed in terms of mass. For instance, data on the chemicals and lubricants use during ethanol production were published in terms of energy (kJ/L ethanol) instead on mass. The reason was that the updated study from Macedo et al. (2008) was just focused on GHG emissions. Due to the lack of data to change from energy to mass for some of the materials included in the inventory from Macedo et al. (2008) it was decided to use the old inventory (Macedo et al. 2004) for the modeling of sugarcane cultivation and ethanol production in the LCA to go bio-based plastics KEPI database.

The remaining two steps (ethanol to ethylene and polymerization) were modeled using LCA data from Liptow and Tillman (2012), which gives the possibility to consider the country of origin for the electricity mix. Such decision was taken since, the LCI of Liptow and Tillman (2012) allows to build the different steps independently. On the contrary Chen and Patel (2012) only provided aggregated values for GHG emissions (in CO_2-eq) and NREU (in GJ) which did not allow us to build a LCI for bio-based PE.

It should be taken into account that Liptow and Tillman (2012) provided also inventories for both attributional and consequential approaches. For the purpose of calculating the LCA to go KEPI's for the database, it was decided to keep the attributional approach which considers the current Brazilian electricity mix.

Polyhydroxybutyrate (PHB)

In accordance with Samantaray (2012), nowadays the commercial production of PHB is being carried out with *Wautersia eutropha* (now called *Cupriavidus necator*) by Metabolix, Massachusetts, USA, under fermentation conditions. However, the use of PHB produced by bacterial fermentation is rather limited due to the high production costs (Rostkowski, 2012). Such high costs are mainly due to the expensive carbon sources used such as corn and sugar cane (Rostkowski, 2012) and rich oxygen supply during the fermentation process (Lee, 1996). Indeed, the cost of cultivated PHA feedstock accounts for 40–50% of total production costs (Rostkowski, 2012).

In the absence of realiable data from Metabolix process, a deep research on the available LCI data about PHB production was made. For instance Rostkowski (2012) has explored the LCA of PHB production from waste biogas by extrapolation from laboratory scale studies. On the other hand, Gallardo (2011) has analysed the use of biorefinery approaches to obtain PHB from lignocellulosic materials derived from Eucalyptus with very detailed life cycle inventories. Samantaray (2012) has also explored the possibilities for production of PHB based on *Aulosira fertilissima*, although any life cycle inventory has been disclosed. Harding (2007) has also simulated the production of PHB based on bacterial growth of *Cupriavidus necator* with a detailed life cycle inventory available (Table 8).

Table 8. Life cycle inventory for PHB production (Source: Harding, 2007)

Type	Item	Amount	Unit
Product	PHB	1000	kg
Inputs	Electricity	3942	MJ
	Energy from steam	12700	MJ
	Natural gas	2123	MJ
	Air	290	kg
	Process water	65.2	m^3
	Cooling water	13.1	m^3
	Sucrose (from sugar cane)	1810	kg
	H_2SO_4	3.02	kg
	H_3PO_4 (conc.)	8.12	kg
	H_2O_2	52.9	kg
	Optimase L660 (MKC) (enzyme)	2.4	kg
	Symperonic NP8 (wetting agent)	0.033	m^3
	$MgSO_4·7H_2O$	20.9	kg
	K_2SO_4	18.6	kg
	$(NH_4)_2SO_4$	14.8	kg
	Na_2SO_4	3.0	kg
	$ZnSO_4·7H_2O$	1.16	kg
	$MnSO_4·H_2O$	0.92	kg
	$FeSO_4·7H_2O$	0.82	kg
	$CuSO_4·5H_2O$	0.12	kg
	$CaCl_2·2H_2O$	2.3	kg
	K_2HPO_4	0.095	kg
	$NaHPO_4$	0.078	kg
	PPG.EEA 142 antifoam	0.005	kg
Outputs	Wastewater	65.2	m^3
	COD	0.8	te O_2
	Solid waste (biomass)	420	kg

Having these different carbon sources it was decided to consider current industrial process of PHB production by Metabolix which is based on the bacterial growth of *Cupriavidus necator*. As a result of that, the model provided by Harding (2007) was effectively implemented in SimaPro 7.3 in order to obtain the estimated KEPI's for LCA to go software tool.

Partially bio-based Polybutylene Succinnate (PBS)

Current market for PBS is mainly dominated by oil-based PBS (Ichikawa et al. 2012). PBS is synthetized by using mainly succinic acid and 1,4-butanediol. An exhaustive review on the state-of-the-art and data availability has revealed that the production of 100% bio-based PBS is still under development since the production of bio-based 1,4-butanediol is on a research stage (Nexant, 2012) (Nexant, 2013).

On the contrary, the production of the second one of the precursors (succinic acid) is carried out industrially by some companies like Myriant (U.S. Department of Energy, 2010).

Due to this fact, it was decided to compile a life cycle inventory based for partially bio-based PBS (succinic acid from biomass and 1,4-butanediol from petroleum). Consequently, the production of bio-based succinic acid was modelled in Sima Pro using data available in the Environmental Assessment Report delivered to the US Department of Energy for the new succinic acid biorefinery facility based on grain sorghum at Lake Providence, Louisiana (U.S. Department of Energy, 2010). This new succinic acid facility has started up in late June 2013 (Myriant, 2013), although the data contained in the Environmental Assessment Report (U.S. Department of Energy, 2010), represents the most of accurate data source found in the literature for the production of bio-succinic acid precursor.

On the other hand, the production of 1,4-butanodiol was taken from the Ecoinvent database in SimaPro, which depicts the production by Reppe process based on acetylene, which is still used by BASF, Ashland (formerly ISP), and DuPont (Nexant, 2013).

PBS from succinic acid (SAC) and 1,4-butanediol (BDO) is usually produced in a two-step polymerization process of: (1) esterification of succinic acid with an excess of butanediol and water at 170-200ºC with an aprox. mole ratio of 1.1-2.0 (BDO/SAC) followed by (2) a polycondensation of the esterification product with butanediol at 200-240ºC at low pressure (0.1-1 mbar) (Bioplastics Magazine, 2012). Unfortunately no life cycle inventory data was found for the polymerization step. Therefore, the modelling of production of PBS was just an estimation on the % of main PBS constituents in accordance with UK Environment Agency (2011), consisting of 67% 1,4-butanediol and 33% succinic acid from bio-based origin, since no life cycle inventory data for the production of PBS was found in main references to LCA of PBS (Petchprayul, 2012) (Moussa, 2012).

Partially bio-based PET

Polyethylene terephthalate can be produced via two routes, either from dimethylterephthalate (DMT) or purified terephthalic acid (PTA), and ethylene glycol; however the preferred process is direct esterification of PTA with ethylene glycol (PRO-BIP, 2009). Bio-based ethylene glycol can be produced via direct oxidation of bio-based ethylene into bio-based ethylene oxide, followed by thermal hydrolysis. Bio-based ethylene is industrially produced from renewable resources, such as sugarcane, corn or plant waste. Oil-based terephthalic acid is produced from the oxidation of p-xylene, which is further purified into PTA. This PTA is then reacted with bio-ethylene glycol and the obtained monomer is polymerised in the liquid phase to produce amorphous PET suitable for the production of fibres or film (Plastics Europe, 2011). A second polymerization in the solid state produces a partially crystalline resin that can be used to produce bottle via injection stretch blow moulding (Plastics Europe, 2011).

Currently, partially bio-based PET, which is composed at 30% by bio-ethylene glycol and 70% by oil-based PTA, is commercially available. In Deliverable D2.1 (LCA to go, 2012), it was decided not to include bio-based PET into the tool since a market report was highlighting that commercial scale production of fully bio-based PET was unlikely before 2015 (Freedonia, 2011). However, in late 2012, European Bioplastics published updated data about worldwide bioplastics production capacities in 2011 and 2016 (European Bioplastics and IfBB, 2012). In 2016, bioplastics production capacity will be dominated by bio-PET 30, accounting for 80.1% of total production capacity. On the contrary, bio-PE and PLA production capacities are expected to represent respectively 4.3% and 5.1%. As a result of that, the market share of non-biodegradable bio-based plastics will increase to 86.6 %. Due to the promising potential of bio-PET and non-biodegradable bio-based plastics, it was decided to include partially bio-based PET into the database of LCA to go tool according to the data publicly available.

Currently partially bio-based PET is commercialized under the name PlantBottle™ and under Coca-Cola license. PlantBottle™ is made using sugarcane ethanol from Brazil (Coca-Cola Company, FAQ 2013). Bio-based monoethylene glycol (MEG) is supplied by the company India Glycols that converts Brazilian sugarcane ethanol to ethylene glycol (Plastics Engineering 2012).

The production of fully bio-based PET is feasible with the latest progress in technology. In fact, bio-based PTA can be produced via several routes: via bio-based xylene produced by depolymerisation of lignin (PRO-BIP, 2009), via the production of PTA from 2.5-furandicarboxylic acid (FCDA) (PRO-BIP, 2009), replacing TPA by FCDA, or by the conversion of biotechnologically produced iso-butanol to p-xylene via dehydration, dimerization, and aromatization (Ryan 2010). However, life cycle data is currently not available for these processes. In any case, main actors in the field like Coca-Cola, Pepsi and Heinz have declared the goal of a 100% bio-based PET bottle. Through the partnership of Coca-Cola with Virent, Gevo and Avantium, Coca-Cola announced a plan to launch a 100% bio-based PlantBottleTM by 2015 or sooner (Coca-Cola Company, 2011). Companies such as Gevo, Draths, Annelotech, Virent and others have announced they have developed different methods for manufacturing PTA from renewable sources: Virent is targeting early 2015 for the opening of its first full-scale commercial plant, to produce PET from bio-based para-xylene (Coca-Cola Company, 2011) and Gevo plans to convert renewable raw materials into iso-butanol, which can be directly integrated into existing chemical and fuel products. Moreover, M&G group, which is one of the world's largest producers of PET for packaging applications, operates the world's first commercial-scale cellulosic ethanol plant, Beta-renewables, which started operations in the last quarter of 2012, in Italy. This plant applies the licensed PRO.E.SA™ technology to convert non-food biomass into sugars. M&G is also looking to build a cellulosic ethanol plant either in Brazil or Mexico as well as a chemicals production unit integrated to the plant that will initially produce bio-based glycols and at a later stage, bio-paraxylene. The biorefinery could be up and running in 2015, according to M&G. 100% of the bio-EG output will be taken to M&G on a long term basis for use at M&G PET plants in the Americas (Green Chemicals 2012). Since the companies who produce bio-based materials are presently up-scaling the production capacity of the 100 % bio-based bio-PET, this is not yet available to the market but it is expected to be commercially available by 2015 or sooner.

Calculation of KEPI for partially bio-based PET was a challenging task due to the lack of data. Several sources were consulted. The search started with the updated Eco-Profile for bottle grade PET based on petroleum feedstock of Plastics Europe (2011). Main difference with prior Eco-Profile is that an intermediate Eco-Profile for amorphous PET is no longer available and it is included in the bottle grade PET. Moreover, primary data from foreground processes of PTA and PET producers were updated, whereas background processes such as ethylene and ethylene glycol production were said to have underlined fewer changes. The ethylene glycol production from ethylene via ethylene oxide was modelled using datasets available in the public domain, based on measurements on operating plants and literature data, supplemented by their own knowledge. The main data sources used are BREF (2003) and Rebsdat (2005). However, the Eco-Profile gives aggregated data and it is no possible to distinguish the contribution from each unitary process in order to be able to prepare our own model. The Plastic Division of the American Chemistry Council (ACC, 2011) also published a cradle-to-gate LCI of PET that includes data on the unitary processes. Nevertheless, data are given for the production of ethylene oxide but the energy and emissions data for the production of ethylene glycol from hydration of ethylene oxide came from a confidential source and was not given in the LCI. Chen and Patel (2012) and Shen et al. (2012) analysed the life cycle energy and GHG emissions of partially bio-based PET, but they did not publish the LCI data used in order to calculate these indicators.
In conclusion, since partially bio-based PET will soon be fully bio-based and LCI data are not available for the partially bio-based PET production, it was decided to include the KEPIs available in Shen et al. (2012) for NREU and GWP 100a. These indicators are given for partially bio-based PET based on sugarcane-derived ethanol from Brazil and maize-derived ethanol from the US. In LCA to go tool, only data for partially sugarcane-based PET are included since, the main commercial bio-PET product is PlantBottle^{TM} which is produced from sugarcane. Moreover, European Bioplastics updated statistics highlighted that bioplastics production has shifted to Asia and South America, accounting for 46.3% and 45.1% of global production, whereas North America will account for 3.5%.

Oil-based plastics (PP, LDPE, HDPE, LLDPE, PVC, PET)

For oil-based plastics, the Eco-profiles published by Plastics Europe were used in order to include the inventory data in SimaPro and calculate the KEPIs (Table 9). Plastics Europe Eco-profiles are based on a cradle-to-gate system, from crude oil extraction to granules or resin at plant. The production covers all life cycle processes from extraction of natural resources, up to the point where the product is ready for transportation to the customer.

Table 9. Oil-based plastics considered in the LCA to go tool and reference data sources for KEPI calculation

Oil-based plastic	Reference
Polypropylene (PP)	Plastics Europe (2005a)
Low density polyethylene (LDPE)	Plastics Europe (2005b)
High density polyethylene (HDPE)	Plastics Europe (2005c)
Linear low density polyethylene (LLDPE)	Plastics Europe (2005d)
Polyvinylchloride (PVC) by suspension polymerization	Plastics Europe (2006)
Polyethylene terephthalate (PET) as bottle grade	Plastics Europe (2011)

As regards PVC, it can be obtained by suspension polymerization, emulsion polymerization and bulk or mass polymerization. Suspension PVC accounts for more than 80% of the PVC market (Plastics Europe, 2006), being used for most rigid and flexible PVC applications. Consequently, the production of PVC by suspension polymerization is considered. For PET, the updated Eco-profile (Plastics Europe, 2011) refers to the bottle grade PET.

Additives for PVC compounding

Suspension PVC needs to be compounded with some additives prior their converting into products (PVC, 2013). PVC compounds have specific formulations whether they are used for flexible or rigid applications. The main additives for all PVC materials are stabilisers and lubricants. In the case of flexible PVC, plasticizers are also used. Other additives which may be included are fillers, processing aids, impact modifiers and pigments (Ventura, 2013b).

When the inventory available for the calculation of KEPIs follows the methodology used in Plastics Europe eco-profiles, such LCI or eco-profiles were used to modelize and calculate the KEPI for the additives. Otherwise, in order to ensure that all KEPIs for additives are calculated in the same way and consider the same life cycle steps, the additives were modelled as organic or inorganic chemicals with its associated KEPI. Such KEPIs were calculated in accordance with Althaus et al. (2007). Althaus et al. (2007) gives a general lCI module for both organic and inorganic chemicals that is based on an unweighted average of the twenty organic and twenty inorganic substances, which are part of the top 100 chemicals in Europe, Switzerland and Global level (Table 10).

Table 10. List of substances considered in the generic inventories for “chemical inorganics” and “chemical organics” (Althaus et. Al 2007)

20 inorganic substances considered in Althaus et al. 2007 inventory for inorganic chemicals	20 organic substances considered in Althaus et al. 2007 inventory for organic chemicals
Sulphuric acid, liquid	Ethylene
Nitrogen, liquid	Propylene
Oxygen, liquid	Urea
Quicklime	Ethylene dichloride
Ammonia, liquid	Benzene
Phosphoric acid	Vinyl chloride
Sodium hydroxide	Ethyl benzene
Chlorine	Styrene

Nitric acid	Methanol
Soda	Formaldehyde
Ammonium nitrate	Methyl tert-butyl ether
Ammonium sulphate	Toluene, liquid
Hydrochloric acid	Xylene
Aluminium sulphate	Ethylene oxide
Titanium dioxide	Ethylene glycol
Sodium silicate	Acetic acid
Sodium sulphate	Phenol
Calcium chloride	Butadiene
Hydrogen fluoride	Vinyl acetate
Sodium chlorate	Acetone, liquid

For each family of additives (stabilizers, plasticizers, lubricants, fillers and pigments and impact modifiers), the user can choose between the main additives or if the additives he currently uses is not listed, he can select the generic one (either organic or inorganic as function of the nature of the additive). The use of generic chemicals was considered as in many cases the exact composition is not disclosed for confidentiality issues. Next, the main families of additives are described in detail:

Stabilizers: The main PVC stabilizers are Ca/Zn and Sn stabilizers since under the Vinyl 2010 Initiative lead-based systems are being voluntarily phased out within Europe (PVC, 2013). Moreover epoxidised soybean oil is also used as a co-stabilizer and plasticizer in many applications (PE Europe GmbH, 2004). Ca/Zn and Sn stabilizers are metal-based and inorganic substances. Ca/Zn stabilizers are generally based on metal carboxylates, incorporating sometimes other elements such as aluminium or magnesium (PVC, 2013). Heat-stabilizer manufacturing was analysed in EPA (2008) and primary data for Ca/Zn based stabilizer were provided by two companies. EPA (2008) gives the stabilizer formulation but not a complete LCI: hydrocalcite/zeolite, calcium stearate, zinc stearate and proprietary additives. Thus the exact formulation is confidential. The main component is hydrotalcite/zeolite, where hydrotalcite is a carbonate mineral. Since stabilizers account for 1 to 3 % of the PVC compound's composition (PE Europe GmbH, 2004) and the unavailability of any LCI with the exact composition and production, it is preferred to consider Ca/Zn as an inorganic substance according to Althaus et al. (2007) in order to calculate the KEPIs. As for Sn stabilizer, they are composed of a central tin atom, surrounded by alkyl and acidic groups (PVC, 2013). No LCI data was found about its composition and production. For instance, PPFA (2008) did not find available data for its use in pipe system, and since the substance accounted for less than 1% of the total weight of a PVC pipe, it was excluded from the modelling. Consequently, for the calculation of KEPIs, Sn stabilizers are considered as inorganic chemicals. Finally, epoxidised soybean oil is manufactured from soybean oil through the process of epoxidation. Datasets about the production of soybean oil in Brazil and US are available; however, since the process of epoxidation is omitted in these datasets, it was decided to consider epoxidized soybean oil as an organic substance.

Plasticizers: The plasticizers most commonly used are phthalates, which account for 87% of the global market for plasticisers and high molecular weight phthalates (DINP, DIDP, DPHP, DIUP and DTDP[6]) account for around to 85% of the European market for phthalates (ECPI 2013). KEPIs were calculated in accordance with the eco-profile of high commodity phthalate esters (DPHP, DINP, and DIDP) that follows the methodology of Plastics Europe Eco-profiles, formerly the Association of Plastics Manufacturers in Europe (APME) (ECPI, 2001). This is relevant to use this inventory for plasticisers since it follows the same format chosen as the basis for the LCI of raw materials and plasticizers represents the most significant additives for flexible PVC, with around 20 to 40% of the weight of the PVC product (PE Europe GmbH, 2004). If another plasticizer is used, the user can select the category "other plasticizers" which is considered as organic substances for the KEPI calculation.

Lubricants: In addition, lubricants are generally used that can be paraffin wax, fatty acid ester (PE Europe GmbH, 2004) or other lubricant. The amount of lubricants is around 1% in the PVC compound's composition. Moreover, paraffin wax is derived from crude oil, in ground, which is also the precursor for most of the substances listed in Table 10. As regards fatty acid ester, there are types of ester that result of the combination of a fatty acid with an alcohol. The alcohol can be methanol which is included in Table 10. Therefore, all lubricants are considered as organic substances for the KEPIs calculation.

Fillers: The most common filler used in PVC formulations is calcium carbonate. Moreover talc is also used (PE Europe GmbH, 2004). Both fillers are minerals that are considered as inorganic substances for the KEPIs calculation. Indeed, in Table 10, quicklime, also known as calcium oxide (CaO), is obtained from the calcination process of limestone that comes from the mineral calcite in ground. Calcite is a carbonate mineral, a form of calcium carbonate ($CaCO_3$). Moreover, limestone is also one of the precursors for the production of soda, also known as sodium carbonate (Na_2CO_3), by the Solvay process. As regards talc, it is a mineral composed of hydrated magnesium silicate ($Mg_3Si_4O_{10}(OH)_2$). In Table 10, sodium silicate is obtained from the reaction of silica (SiO_2) with sodium carbonate. Talc is a silicate mineral that can be formed via different reactions: carbonation from a magnesium mineral (e.g. serpentine), reaction between dolomite and silica, from chlorite and quartz. Indeed since talc is a silicate compound as sodium silicate, it is coherent to assimilate it to an organic chemical. The user can also choose between the generic categories of organic or inorganic fillers.

Impact modifiers: Moreover, in order to improve the impact resistance of PVC products, impact modifiers which have rubber-like properties are mixed with PVC, such as Acrylonitrile-butadiene-styrene (ABS), Methyl methacrylate-

[6] DINP: Di-isononyl phthalate; DIDP: Di-isodecyl phthalate; DPHP: Di(2-Propyl Heptyl) phthalate ; DIUP: Di-isoundecyl phthalate; DTDP: Di-tridecyl phthalate

butadiene-styrene (MBS), Chlorinated polyethylene (CPE) and Ethylene-vinyl acetate polymer (EVA). The inventory for ABS production is available an Eco-profile from Plastics Europe and thus it was used for the KEPI calculation. For MBS and EVA, inventory is not available or based on calculated data with a large uncertainty. Moreover, MBS is produced from butadiene, styrene and methyl methacrylate. Both butadiene and styrene are included in Table 10 whereas methyl methacrylate is another organic precursor. As regards EVA, it is produced from ethylene and vinyl acetate, that are both included in Table 10. Therefore it is relevant to consider MBS and EVA as organic compounds for the KEPI calculation. Finally, CPE is a produced from HDPE that is randomly chlorinated in aqueous slurry (HallStar, 2009). Chlorine contents generally range from 25 to 42%. Since there is no LCI data about the reaction of chlorine with HDPE, CPE was considered as an organic substance for the KEPI calculation. The user can also select the category "other impact modifiers" which is considered as organic substances for the KEPI calculation.

Pigments: Finally, the most common pigments are titanium dioxide (PE GmbH, 2004) and carbon black (Ventura, 2013b). The substance titanium dioxide is covered by the list of inorganic substances in Table 10 and thus it is considered as inorganic substances for KEPI calculation. Carbon black is an organic chemical. Althaus et al. (2007) prepared a dataset for the production of solid carbon black at plant. However, the author highlights that there is a large uncertainty of the process data and thus stoichiometric data were used. In order to be coherent in the calculation of KEPIs for all additives, due to these uncertainties, it is preferred to consider carbon black as an organic substance for KEPI calculation. The user can also choose between the generic categories of organic or inorganic pigments.

Table 11 summarizes how each additive is considered in the LCA to go tool for the KEPI calculation purposes.

Table 11. List of additives considered in the LCA to go tool

Type of additive	Name of additive	Material for LCA to go tool	Source
Stabilizers	Ca/Zn stabilizer	Inorganic substance	Althaus et al. (2007)
Stabilizers	Sn stabilizer	Inorganic substance	Althaus et al. (2007)
Stabilizers	Epoxidised soybean oil	Organic substance	Althaus et al. (2007)
Stabilizers	Organic stabilizers	Organic substance	Althaus et al. (2007)
Stabilizers	Inorganic stabilizers	Inorganic substance	Althaus et al. (2007)
Plasticizers	Phthalate esters (DEHP/DIDP/DINP)	Phthalates esters	ECPI (2001)
Plasticizers	Other plasticizers	Organic substance	Althaus et al. (2007)
Lubricants	Parrafin wax	Organic substance	Althaus et al. (2007)
Lubricants	Fatty acid ester	Organic substance	Althaus et al. (2007)
Lubricants	Other lubricants	Organic substance	Althaus et al. (2007)

Fillers	Calcium carbonate	Inorganic substance	Althaus et al. (2007)
Fillers	Talc	Inorganic substance	Althaus et al. (2007)
Fillers	Organic fillers	Organic substance	Althaus et al. (2007)
Fillers	Inorganic fillers	Inorganic substance	Althaus et al. (2007)
Pigment	Titanium dioxide	Inorganic substance	Althaus et al. (2007)
Pigment	Carbon black	Organic substance	Althaus et al. (2007)
Pigment	Organic pigments	Organic substance	Althaus et al. (2007)
Pigment	Inorganic pigments	Inorganic substance	Althaus et al. (2007)
Impact modifier	Acrylonitrile-butadiene-styrene	ABS	Hischier (2007) from Plastics Europe Eco-profiles
Impact modifier	Methyl methacrylate-butadiene-styrene	Organic substance	Althaus et al. (2007)
Impact modifier	Chlorinated polyethylene	Organic substance	Althaus et al. (2007)
Impact modifier	Ethylene-vinyl acetate polymer	Organic substance	Althaus et al. (2007)
Impact modifier	Other impact modifier	Organic substance	Althaus et al. (2007)
Other additives	Organic additives	Organic substance	Althaus et al. (2007)
Other additives	Inorganic additives	Inorganic substance	Althaus et al. (2007)

1.2.1.2 KEPIs for transport (raw materials, processing and distribution stages)

As shown in the final layout of the tool (Figure 2), transport can occur at several life cycle stages of the bio-based plastic product: (1) for the supply of raw materials to the manufacturer in the raw material module, (2) as additional transport for intermediate products (e.g.: PET bottle preforms) in the processing module, (3) delivery of the packaged products in the distribution module and (4) waste transport from waste collection points to waste treatment facilities. Users can select and customize their own transport system (transport mode and distance) in all cases, except for waste transport where the user is only able to modify the distance covered. Table 12 summarizes the different transport modes and the data sources used for KEPI calculation in the bio-based plastics LCA to go tool. Users should take into account that the infrastructure processes (like construction of the trucks, maintenance of the roads, etc.) have been excluded from KEPI calculation.

Table 12. Transport modes and types included in LCA to go tool

Mode	Type	Included processes	Reference
Road	Delivery van < 3.5 t	Direct energy and working material consumption and emissions during operation.	ETH-ESU (1996)
	Lorry 3.5 – 7.5 t EURO 5 Lorry 7.5-16 t - EURO 5 Lorry 16-32 t - EURO 5 Lorry > 32 t - EURO 5	Operation of vehicles, Diesel.	Spielmann (2007)
Rail	Freight rail	Operation of vehicle	Spielmann (2007)
Ship	Transoceanic freight ship	Operation of vessel, HFE based steam turbine and diesel engines	Spielmann (2007)
Airplane	Aircraft, freight intercontinental	Operation of aircraft	Spielmann (2007)

	Aircraft, freight		Spielmann (2007)
Waste	Waste collection lorry	Diesel fuel consumption, air emissions from fuel combustion for Stop&Go driving, tyre abrasion, brake lining abrasion, road abrasion and re-suspended road dust. Waste collection and hydraulic compression vehicle. Gross load capacity 8.2 tons. Load factor 50%. Average load 4.1 tons	Doka (2007)

For road transport, the standard in force, Euro 5 standard, defines the acceptable limits for exhaust emissions from light passenger and commercial vehicles. The EURO 6 standard will come into force on September 2014 for the approval of vehicles (Regulation (EC) No 715/2007).

1.2.1.3 KEPIs for processing and finishing processes

Electricity

In order to take into account the differences in the electricity mix from a country to another, when the user has to enter a data about electricity consumption, he can choose the country in which the production (and therefore the electricity consumption) takes place. The KEPIs for electricity production were calculated for the 27 countries of the European Union (until May 2013), plus Switzerland and Norway. Electricity mixes from the United States, Brazil and China were also included since these are leading producers of some bio-based plastic materials.

The KEPIs were calculated in accordance with the life cycle inventory of Country-specific electricity mixes from Frischknecht et al. (2007), which includes the electricity production, the transformation from high-voltage to medium voltage and the medium-voltage transmission. Imports are not included.

There are some exceptions like Cyprus, Estonia, Lithuania, Latvia and Malta, where there is not a specific inventory for electricity mixes available. Therefore, for these countries, the average data for EU-27 is used to calculate the KEPIs, which is based on the electricity production in UCTE.

Lubricating oil

The KEPIs were calculated in accordance with Althaus et al. (2007), which gives a dataset for a generic kind of lubricant, based mainly on stoichiometric extrapolations. The dataset includes raw materials used for production (diesel), transport of materials to manufacturing plant, an approximation of the energy demand and infrastructure of the plant (electricity and natural gas), and estimated emissions. The values for energy demand were approximated with data from a larger chemical plant, due to the absence of available information.

Water for cooling purposes

Water is used for cooling of converting machinery in the processing module. Water is supplied from the water system. The KEPIs were calculated in accordance with Althaus et al. (2007), which gives a dataset for tap water, at the user's site. The dataset includes the infrastructure and energy use for water treatment and transportation to the end user. Data are extrapolated to Europe situation, taking into account an estimated share of resource uses (ground and surface water). The infrastructures' processes for water supply (pipes, construction of water treatment plants, etc.) are excluded from the KEPI calculation.

Chemicals

In the finishing sub-stage of the processing module, inks and adhesives are used for printing and laminating.

As above mentioned, bio-based plastics applications are dominated by packaging. As a result of that, printing of bio-based plastic products was considered as packaging printing. The most common techniques for plastic packaging printing are flexography and sometimes offset for few PE products (Ventura, 2013a). Flexography is especially important in the case of production of carrier bags. Gravure printing is also used for packaging printing, although continues losing market share (Conover, 2008). As a consequence, for the LCA to go tool, it was decided to calculate the KEPIs for the most common flexographic ink.

The three main flexographic ink systems are solvent-based, water-based and UV-cured. Water-based inks are used as an alternative to solvents in flexographic package printing (Norden, 2012) whereas UV-curing systems are considered another good way to eliminate solvents and are used in applications as printing of labels (Norden, 2012). Therefore, our focus is on flexographic solvent-based inks. Veith and Barr (2008) carried out a comparative LCA on flexographic and rotogravure printing, for Dupont Engineering and Research Technology. For LCA to go tool, the interest of this LCA is the LCI data that are given in order to carry on the environmental performance of flexographic printing of a film for the flexible packaging. Data represents an average for Europe and North America based on primary data collected from printers serving the flexible packaging so as tag and label markets, during 2006-2007. Infrastructure processes are not included. In this study, the printers all use solvent inks and print on various substrates (paper and plastic). The LCI for flexographic printed substrate manufacture is based on an average substrate mix (11.5 % PET, 11.5% OPP, 68% PE, 1% OPA, 8% paper) and thus two types of inks are considered, nitrocellulose ink and offset ink. The offset printing technique is the most used technique for printing paper and cardboard. As a consequence, only the composition of nitrocellulose ink was used to model flexographic ink in SimaPro 7.3.3. The flexographic ink composition is summarized in Table 13.

Table 13. Composition of common flexographic ink for plastic packaging

Family	Component	Amount
Resin/binder	Nitrocellulose	10-15 %
Pigment	Pigment	5-10%
Additive	Polyurethane	3-5%
Additive	Wax	1-5%
Solvent	33% ethanol and 67% ethyl acetate	65-80%

For the energy consumption and emissions from processing and the transportation, an offset printing ink model proposed by Hischier (2007) was used as a basis for estimations.

Adhesives

Adhesives are used in laminating process, in order to combine two or more layers of single materials. Laminating is generally used to combine substrates from different materials (plastic with paper or aluminium). Additionally laminating can be used when previously to combination, it is necessary to print materials, and thus the adhesive acts as print protector. This is this latter function of laminating that is considered in the LCA to go tool since only polymers are taken into account. Moreover when the multilayer material is composed only of polymers, co-extrusion is the most common process. Laminating adhesives commonly used in flexible packaging are water-born, solvent-based, reactive and hot-melt; and according to the adhesive used, the lamination processes are different.

For the laminating process considered in LCA to go bio-based plastics sectoral tool, polyurethane laminating adhesives are used, which can be 100% reactive solvent-less adhesive. Polyurethane is formed by reacting an isocyanate with a polyol. Two types of polyurethane adhesives can be distinguished. On the one hand, they can be moisture-cured polyurethanes, where the adhesive is coated onto a substrate and atmospheric moisture reacts with excess of isocyanate groups to cross-link the adhesive after the secondary film has been joined (Petrie, 2007). On the other hand, two-part solvent-less polyurethane is based on the reaction between isocyanate terminated resin and polyol. In order to calculate the KEPI for polyurethane laminating adhesives, it is considered that the composition is solvent-free, based on the reactive chemistry of two components: 60 % of isocyanate functional pre-polymer and 40% of polyol curative (Fuller 2012). The most commonly used isocyanates are the aromatic diisocyanates, toluene diisocyanate and methylene diphenil diisocyanate. The KEPIs are calculated according to Hischier (2007) on the basis of Plastics Europe Eco-profiles for both reagents.

1.2.1.4KEPIs for packaging materials at distribution stage

The bio-based plastics tool has been designed in such a way the user will be able to select the packaging materials and transport requirements for the delivery of the finished products. The most common packaging materials (wooden pallets, stretch films, corrugated board, etc.) have been included in the tool, according to the expertise of ITENE and some examples given for the packaging of mouldings, bottles, pipes, etc. (Hischier, 2007). In order to calculate the KEPIs of each packaging material, it is necessary to consider both the material's production and its transformation into packaging material. Table 14 summarizes the information that was used for the calculation of KEPIs.

Table 14. Packaging materials included in LCA to go tool

Packaging material	Material	Production process	Source

Corrugated board box	Double wall corrugated board from 100% recycling fibre	Production of boxes out of carton board: cutting, folding, offset printing.	Hischier et al. (2007) Hischier et al. (2007)
Wooden pallet	EUR-flat pallet (800x1200 mm): particle board for outdoor use, sawn timber and steel	*Not included*	Kellenberger et al. (2007)
Stretch film LLDPE	LLDPE	Cast film extrusion	Plastics Europe (2005d) Hischier (2007)
PE bag	LDPE	Film blowing and bag forming (cutting and sealing)	Plastics Europe (2005b) Edwards et al. (2011)
Shrink film LDPE	LDPE	Cast film extrusion	Plastics Europe (2005b) Hischier (2007)
PET strapping	PET	Cast sheet extrusion	Plastics Europe (2011) Hischier (2007)
PP strapping	PP	Cast sheet extrusion	Plastics Europe (2005a) Hischier (2007)
Cushioning EPS	Expandable polystyrene	Thermoforming	Hischier (2007) Hischier (2007)
PVC blister	PVC (suspension polymerisation) compounded with additives	Thermoforming	Plastics Europe (2006) Thiriez (2006) Hischier (2007)

Corrugated board box

For the distribution of products, corrugated board boxes are commonly double wall, made with recycled fibres. In accordance with Hishcier et al. (2007), the module "corrugated board" includes the production of corrugated board out of the corrugated base papers. Estimations are based on average data from European producers, collected by FEFCO. As regards the module for the production of boxes out of carton board, it includes cutting, folding, printing with an offset machine and thus inks, glues and electricity consumptions are considered (Hischier et al., 2007).

Wooden pallet

As regards the use of pallet, the most common is the EUR-pallet, made of wood. In accordance with Kellenberger et al. (2007), this module should only be used for the packing and transportation of products. Moreover, the inventory includes only the materials and not the process of construction of the pallet. However, this has not been considered as relevant since EUR-pallets are reused many times, so the contribution to the environmental impact of the construction of the pallets per each use has been assumed almost negligible. The process output is one pallet. Therefore the KEPIs calculated for one EUR-flat pallet are divided by the pallet's weight, i.e. 22 kg in order to obtain the KEPIs per kg of pallet, (Kellenberger et al., 2007).

Stretch film LLDPE

Stretch films are often used to unitize pallet loads and may be used for bundling smaller items. Most stretch film is made from LLDPE and some is made from PVC (PIRA, 2009). Stretch film is produced at 65 to 70% by cast film extrusion, mostly for machine wrapping, and 30 to 35% by film blowing, mostly for commodity hand wrap and a few highly puncture-resistant specialty films (Schut 2003). In

LCA to go tool, the application of stretch film is thought to unitize pallet loads for the distribution of packaged products, which is done automatically with a wrapping machine. Therefore, cast film extrusion is the process considered in order to model the production of stretch film in SimaPro 7.3.3. Hischier et al. (2007) generated a process for the production of packaging film from LDPE that served as a reference for the modelling of stretch film LLDPE for LCA to go. The process from Hischier et al. (2007) includes the plastic amount, the transport of plastic from the production site to the converting site and the plastic film extrusion process. Standard distances are considered for plastic supply, i.e. 100 km by road and 200 km by rail.

PE bag

PE bags for packaging are generally made from LDPE, by film blowing. Once the film blown, it is cut and welded in order to get the final shape of the bag, which is called forming. The production of PE bag was done in the same way as stretch film LLDPE, i.e. considering the amount of LDPE, standard distances for LDPE supply to the converting site (as given by Hischier et al. (2007)) and finally the film blowing and forming processes. For the bag production processes, the energy consumption for both film blowing and bag sealing are taken from Edwards et al. (2011), in the specific case of LDPE bag.

Shrink film PE

Shrink film is used as an overwrap for products (beverage cans, cartons, large appliances, foods) and pallet loads. Shrink film is applied loosely around an item and then shrinks tightly over the item with heat. The most common shrink film is made from PE and PVC is also used (PIRA, 2009). The production of shrink film PE for the calculation of KEPI in LCA to go tool was modelled identically to the production of stretch film LLDPE, except that the raw materials are different, instead of LLDPE, shrink film is made from LDPE.

PET and PP strapping

In order to transport finished products made from bio-based plastics, plastic straps are conventionally used, since they are designed for light to medium duty unitizing, palletizing and bundling. Plastic strap is most commonly made from PET and PP. Strap production consists of an extrusion system followed by a stretch plant, which consists of stretch systems, embossing, fixing and cooling until the strap coiler (Interempresas, 2008). At this stage, for the calculation of KEPI in LCA to go tool, it was decided to consider only the contribution of the first step of strapping production, i.e. the extrusion process, since data about the second stretching step were not found. The small amount of strapping used per functional unit can justify that the stretch step is considered as negligible. This first approximation will be updated in the final version of LCA to go tool in case that more accurate data will found.

Cushioning EPS

Expanded polystyrene (EPS) is used as protective cushioning in packaging. It is produced from polystyrene beads that contain a blowing agent, generally pentane, for foaming. Expandable polystyrene consists of such beads ready for the transformation process into EPS products that will fit to the shape of the mould. In order to follow the methodology proposed by Plastics Europe, in first step expandable polystyrene is produced from styrene that is polymerized and pentane, according to Hischier et al. (2007). Then expandable polystyrene is expanded and moulded. Plastics Europe modelled this expansion and final moulding through the thermoforming process (Hischier et al. (2007)). Therefore the production process of cushioning EPS was modelled in SimaPro 7.3.3 considering the raw materials, the standard distances for transport as taken into account for the other plastic packaging materials, and the converting process.

PVC blister

Rigid PVC is used for the application of packaging, such as blister. Packaging composition varies with the producer and the application. An average composition of a tray product contains 92.5% of PVC, with 1% of tin-based stabilizer, 1.5% of PE wax as lubricant and 5% of MBS as impact modifier (PE Europe GmbH, 2004). On the basis of this composition, the rigid PVC compound is produced. This compound is transported until the converting site where it is processed into a blister by thermoforming. The production of PVC and the thermoforming process are calculated in accordance with Hischier et al. (2007). As regards the additives used in the compounding process, their production process is calculated according to Althaus et al. (2007), taking into account whereas they are organic or inorganic chemicals. Finally for the compounding process, the energy consumption was taken into account as explained in section 1.2.4. Distances for transport are the standard distances considered for the other packaging materials, according to Hischier et al. (2007).

1.2.1.5 KEPIs for the end-of-life

End-of-life treatments covered

Even though according to Deliverable 2.1, the end-of-life stage was excluded from the system boundaries, this decision was reconsidered due to the relevance that end-of-life stage could have for bio-based plastics. Some of them have biodegradable properties that could be interesting at end-of-life level, so therefore this stage was finally included in the general layout of LCA to go tool.

Users must also take into account that the KEPI's for the end-of-life module are based on estimated data and limited only to Climate Change impact category. Such decision was made since to date, almost all the life cycle inventory and LCA results for bio-based plastics is limited to GHG gases and to lesser extent sometimes to energy use.

Predefined end-of-life scenarios

Due to the variety of different plastic products by the LCA to go bio-based plastic tool, setting an end-of-life scenario was a challenging task. A decision has been taken in accordance with the current market for bio-based plastics. European

Bioplastics (2008a) stated that 86% of bioplastics are used in packaging applications and waste collection bags. Therefore, the pre-defined end-of-life scenarios proposed in this module refers to the end-of-life of packaging waste. Then, the users can choose between three different pre-defined scenarios for industrially compostable products (Scenario a) and other three pre-defined scenarios for non-biodegradable products (Scenario b). Users should take into account that only industrial composting was considered, since home composting is not a widespread option for the end-of-life of biodegradable plastics. Indeed, some of them do not biodegrade at all under home composting conditions, such as PLA (Hermann, 2011) (Davis, 2006).

For industrially compostable products, the three scenarios proposed under the pre-defined Scenario a, are based on the proposal of Pro-Europe for the end-of-life of bioplastics (Pro-Europe, 2009) (Table 15). Each scenario corresponds to the waste treatment whether bioplastics are collected with other packaging, residual waste or organic waste, as suggested by Pro-Europe (2009).

Table 15. End-of-life treatments for pre-defined Scenario a (for industrially compostable products)

	Recycling (%)	Incineration (%)	Composting (%)	Landfill (%)	Specific situation	Reference
Scenario 1a	0	0	100	0	Disposal of bioplastic waste with organic waste	-
Scenario 2a	0	43.48	0	56.52	Disposal of bioplastic waste with the separate household packaging waste stream	Estimated data based on Eurostat (2010) statistics for the treatment of domestic plastic packaging waste in EU-27 in 2010
Scenario 3a	0	28.95	22.37	48.68	Disposal of bioplastic waste with the municipal waste stream	Estimated data based on Eurostat (2010) statistics for municipal waste treatment in EU-27 in 2010

In the EU 27, the domestic plastic packaging waste and the municipal waste are treated in different ways. Household plastic packaging waste is currently recycled, incinerated or landfilled by a 33.3%, 29% and 37.7%, respectively. In case plastic is mixed with other types of waste the scenario for commingled municipal applies where waste is currently recycled, incinerated, composted and landfilled by a 24%, 22%, 17%, 37%, respectively. However, for the industrially compostable products targeted by Scenario a, there is neither specific collection stream nor recycling plants for such materials (PLA, TPS blends, etc.). Therefore in scenario 2a and 3a, the recycling option has been discarded. Then the percentages for the remaining waste treatments were re-calculated according to the share of such treatments considering that recycling is not applied.

For non-biodegradable products (Table 16), three scenarios are also proposed under the pre-defined Scenario b: (1b) when the plastic goes with the separate plastic collection stream (based on plastic packaging collection stream); (2b) when the plastics is commingled with other types of materials at waste collection point (based on plastic packaging collection stream) and (3b) the generic profile of Plastics Europe (2012) which is not packaging-specific and can be applied to other types of goods (building materials, automotive parts, electric/electronic products).

Table 16 End-of-life treatments for pre-defined Scenario b (for non-biodegradable products)

	Recycling (%)	Incineration (%)	Composting (%)	Landfill (%)	Specific situation	Reference
Scenario 1b	33.3	29.0	0	37.7	Plastic packaging goes with the separate collection stream	Based on Eurostat (2010) statistics for the treatment of domestic plastic packaging waste in EU-27, in 2010
Scenario 2b	28.92	26.51	0	44.58	Plastic packaging goes with the commingled household waste collection stream	Estimated data based on Eurostat (2010) statistics for municipal waste treatment in EU-27, in 2010
Scenario 3b	25.10	34.10	0	40.90	Other plastic goods (non-packaging)	Plastics Europe (2012)

Customized end-of-life scenarios

Moreover, users may create their own end-of-life scenario. This will allow users to define specific end-of-life conditions for non-packaging products (e.g.: automotive plastics, building and construction materials, plastics for electronics, toys) as well as to create accurate scenarios if this information is available. In such a case users may select between different percentages for (1) recycling, (2) composting, (3) incineration with energy recovery, and (4) landfill.

Transport for waste collection

Once the different ways of treatment for the product waste defined, whether with a pre-defined scenario or with customized data, the user indicates the average distance recovered from collection to the waste treatment plant. A default value of 25 km is given.

Avoided burdens for recycling, energy recovery and composting

All KEPI's considered for the end-of-life of non-biodegradable plastics took into account the credits due to the displacement of raw materials in case of recycling (Diaz, 2006) as well as the avoided burdens due to energy recovery both in landfill and incineration operations.

In case of bio-based biodegradable plastics, it was considered the displacement of soil conditioners as a result of the production of compost, following the assumptions provided by Hermann (2011).

Composting of biodegradable plastics

A deep search was made to find datasets for composting of bio-degradable plastics. Unfortunately life cycle inventories for composting of these materials are currently not available. In the absence of specific data for composting of biodegradable plastics, it seems scientifically sound the approach suggested by Hermann (2011). Such approach is based on the main principle of taking the results for process emissions from existing industrial composting processes of vegetable, fruit and garden waste (VFG) and material-specific biodegradation levels to derive data for the biodegradable materials. The use of material-specific biodegradation rates for is justified due to the large differences about biodegradation rates for some biodegradable plastics stated by several authors, as well as the variations on the composting technologies which affects mainly to the amount of C as CH_4 (Hermann, 2011).

All of the data considered from Hermann (2011) take into account only the waste management stage (excluding the use phase and transportation). Long-term carbon storage for each material via biodegradation of the material during composting and the degradation rate of humus is considered.

The perspective suggested by Hermann (2011) considers also nitrogen-related emissions of nitrous oxide but uses individual degradation rates of the materials. The idea behind that is that without nitrogen, the composting process would not work, and at the same time that a uniform degradation rate is too far from reality for most biomaterials.

This approach (Hermann, 2011) is the most up-to-date source of data found in the literature about the end-of-life of bio-based biodegradable plastics. Therefore, for the purpose of this deliverable and the bio-based plastics KEPIs database, it was decided to use the values suggested by Hermann (2011) for several different types of bio-based plastics (starch, PLA, starch/polycaprolactone blend and PHA).

Such KEPIs were limited only to Global Warming impact assessment category, as the data for derive other impacts is not available from the results of Hermann (2011). This is aligned with the results from other authors where the environmental impact of disposing bio-based plastics was focused on the global warming impact category because CO_2 emissions (and CH_4 emissions, to a lower extent) are the most significant (Vidal, 2007).

Results from Hermann (2011) for industrial composting were applied to calculate the Climate Change KEPIs, by assuming that this process is dominated by emissions of carbon dioxide. The emissions of methane are rather exceptional and are small when they do occur. In case of nitrous oxide such emissions are much lower. Process emissions from industrial composting of VFG and material-specific biodegradation levels to derive data for the biodegradable materials were considered. As above mentioned, credits due to carbon and nitrogen credits derived from the replacement of soil conditioners were considered, using material-specific biodegradation data. Table 17 summarizes the results obtained by Hermann (2011) which have been implemented in Sima Pro to build the LCA to go model for KEPI calculation.

Table 17 Climate Change KEPI calculation for the industrial composting of bio-based biodegradable plastics in LCA to go tool, adapted from Hermann (2011).

Family	Plastic type in the KEPI's BBDD	Process			Humus	C	N	KEPI (Climate change in CO_2-eq/kg material)
		CO_2	CH_4	N_2O	Deg.	Credits	Credits	
Starch	Potato-based starch	1.3	0.016	0.09	0.21	-0.11	-0.15	1.36
Polylactic acid (PLA)	Sugarcane PLA Corn-based PLA	1.47	0.018	0.1	0.24	-0.12	-0.17	1.53
Starch/PCL	Starch blend type I Starch blend type II	1.38	0.02	0.11	0.38	-0.2	-0.28	1.42
PHA (PHBV)	PHB	1.69	0.021	0.12	0.28	-0.14	-0.2	1.77

Landfilling of biodegradable and non-biodegradable plastics

Bio-based biodegradable plastics are generally unsuitable for landfilling (Davis, 2006). In case landfilling of biodegradable plastics is considered, Häkkinen (2010) suggests assumed that PLA behaves similarly to lignin, or polyesters such as PET, and does not degrade in well-engineered landfills where there is little moisture or warmth. This is confirmed by European Bioplastics (2011) which clearly stated that the preliminary results indicate that PLA products do not biodegrade under landfill conditions, but remain as inert as conventional plastics. Consequently for PLA was assumed the data from landfilling of PET.

For other bio-based plastics (not PLA) it was assumed the landfill emissions reported by Khoo et al (2012), which were treated in Sima Pro giving a KEPI of 2.75 kg CO_2-eq per kg of bio-based plastics[7].

In case of landfilling of PET data from Perugini (2003) the Global Warming environmental indicator was originally considered. However the high-values provided by Perugini (2003) in comparison with current literature (Diaz, 2006) (Khoo, 2012) has lead us to make a deep search on landfilling of non-biodegradable plastics. Consequently, the values assumed by Khoo (2012) were finally considered giving an average value of 0.528 kg CO_2-eq[8] per kg of oil-based plastic material.

Mechanical recycling of non-biodegradable plastics

The mechanical recycling of plastics was only applied to those which are both non-biodegradable (independently if these are either oil-based or bio-based). In case of recycling of PET it was originally assumed the approach suggested by Perugini (2005). Other authors like Diaz (2006) have also studied the LCA modelling of municipal solid waste aimed at the development of a software tool in which avoided impacts from energy recovery and material recycling were accounted. A brief comparison on the values provided by Perugini (2005) and Diaz (2006) revealed strong differences on the climate change impact for PET, with 1.4 kg CO_2-eq (for both recycled and virgin PET) and 2.99 kg/CO_2-eq for virgin PET respectively. Such differences might be caused due to the fact that Perugini (2005) considered the use of recycled and virgin PET in his recycling process, whereas Diaz (2006) clearly distinguished between recycled and virgin PET, delivering different results as function of the origin of the material. As a result of that it was decided to consider the most conservative approach and use the calculated data based on Diaz (2006). For other oil-based plastics the WASTED model proposed by Diaz (2006) was also considered. Such inventories were compiled in SimaPro 7.3.3 from which the Global Warming KEPI's were extracted using IPCC 2007 Global Warming Potentials in a 100 yr perspective (IPCC, 2007) (Table 18). For the purpose of coherence of the tool, only the recycling of virgin plastic material was considered.

Table 18. Inventory and estimated KEPIs for mechanical recycling of virgin non-biodegradable plastics. Own compilation based on Diaz (2006)

Air emissions	PET	PE	PP	PVC
CO_2	2363	2400	2100	2000
CH_4	25	28	28	22
NO_x	9.5	6.5	6.4	6.3
VOCs	7.2	7.8	7.7	5.8
SO_x	14	4.9	5.4	5.3

[7] Based on IPCC 2007 100-yr characterization factors from IPCC (2007)

[8] Based on IPCC 2007 100-yr characterization factors from IPCC (2007)

PM	4.6	1.5	1.7	1.4
HCl	0.058	0.011	0.010	0.016
Calculated KEPI (kg CO_2-eq/kg of material)	2.99	3.1	2.8	2.55

Incineration of biodegradable and non-biodegradable plastics

In case of incineration of PET data from Perugini (2003) the Global Warming environmental indicator was initially considered. This paper delivered a value for incineration of PET of 7.3 kg CO_2-eq/kg of virgin or recycled PET, which seemed very high. After a deep search on the literature, it was decided to apply a most common and wide acceptable approach as the model provided in the ELCD 2.0 database (ELCD, 2013). This database provides several LCI datasets related to the incineration of common plastic families as PE, PP, PS, PET and PVC. However, it should be taken into account that this data is only valid for the EU-27 as an EU average.

One important finding for modelling is that the ELCD 2.0 incineration model clearly stated that *"the thermal treatment of a single waste fraction (paper or plastic) or even specific wastes like PA-6 is not done in reality in a waste to energy plant for Municipal Solid Waste"* (ELCD, 2013). This is due to the fact that incineration plants always use homogenised waste to obtain a relative constant calorific value and to comply with the emission standards. This is sound for other references like WRAP (2008) which has assumed that in incineration with energy recovery, the mixed plastic waste is not sorted before and is assumed to be sent straight to the incineration plant after leaving the Materials Recycling Facility (MRF).

Therefore, the ELCD 2.0 database (ELCD, 2013) suggests the use of a common model for incineration processes for which is attributed the environmental burden (emissions and also resource consumption of auxiliaries) as well as the credits (energy and metal scrap export) to a single fraction or specific waste incinerated within an average MSW. In accordance to ELCD (2013) such assumption can be made whenever either the waste fraction share of MSW or the elementary composition is followed. It should be noted that ELCD 2.0 datasets for incineration do not include environmental impacts for waste collection, transport or any pre-treatment of the waste (ELCD, 2013).

Due to the fact that these sets represent the current average situation EU-27, it was decided to calculate the KEPI's for incineration based on ELCD model by directly applying the characterisation factors from IPCC GWP 2007 100 yr. in Sima Pro 7.3.3.

In case of bio-based plastics, data on Climate Change impact derived from Hermann (2011) was used to build the KEPIs, except for those materials from bio-based origin but non-biodegradable (sugarcane based HDPE and LLDPE, bio-based PBS and partially bio-based PET) where data from ELCD 2.0 database was adopted. KEPI results for incineration are shown in Table 19.

Table 19. Data sources for incineration of bio-degradable and non-biodegradable plastics

Material	Assumption (if any)	Source
PLA corn-based	n/a	(Hermann, 2011)
PLA sugar-cane based	n/a	(Hermann, 2011)
Starch blend type I	n/a	(Hermann, 2011)
Starch blend type II	n/a	(Hermann, 2011)
Potato-based starch	n/a	(Hermann, 2011)
Sugarcane-based HDPE	Same end-of-life characteristics as the oil-based PE	(ELCD, 2013)
Sugarcane-based LLDPE	Same end-of-life characteristics as the oil-based PE	(ELCD, 2013)
LDPE	n/a	(ELCD, 2013)
HDPE	n/a	(ELCD, 2013)
LLDPE	n/a	(ELCD, 2013)
PHB	n/a	(Hermann, 2011)
Bio-based PBS	Assumed the same behavior as PLA	N/A
PET	n/a	(ELCD, 2013)
Partially bio-based PET	Same end-of-life characteristics as the oil-based PET	(ELCD, 2013)
PVC	n/a	(ELCD, 2013)

1.2.2 Gate-to-gate cost assessment functionalities

The LCA to go bio-based plastic tool allows the development of gate-to-gate cost calculations. Such calculations will help to support environmental decisions with the best cost performance. Such cost analysis only apply to the costs which are controlled by the company, which includes cost for supply of raw materials, operational costs for converting, as well as the costs for packaging and distribution of the final products to the customer. Costs related to the end-of-life were omitted since these are not under the control of the company.

1.2.3 Equations and default data used for the calculations of environmental impact and costs

According to the final layout suggested for the LCA to go bio-based plastics sectorial tool, shown in Figure 2, and the changes proposed by Simpple KEPIs are calculated per life cycle stage: (1) raw materials, (2) transport (3) processing, (4) distribution and (5) end-of-life. Moreover, each life cycle stage is divided into sub-stages. In the processing stage (2), the user has the option to use data given by default. In this chapter, the equations and when appropriate the default data are given for each one of the modules.

1.2.3.1 Environmental assessment of raw materials module

In this module, there are two sub-stages: (a) raw materials production and (b) compounding materials and master-batch.

Raw materials production: In this module, the user indicates the amount of each raw material used. The KEPI for the production of raw materials is given by the equation 1:

$$KEPI\ raw\ materials = \sum_i [KEPI\ (raw\ material_i) \times kg\ of\ raw\ material_i] \quad (1)$$

Where $KEPI\ (raw\ material_i)$ is the KEPI for raw material $_i$ already calculated as explained in section 1.2.2.1 and included in the database of the LCA to go tool.

Compounding materials and master-batch: As already mentioned, before PVC can be converted into a product, it has to be combined with a range of additives in a compounding process. Furthermore, it is very common in the plastic converting industry the use of marsterbatches capable to add colour and/or any other properties to the final product. Consequently, a Compounding materials and masterbatch substage has been added in the raw materials module. In the case of additives, the user only needs to enter the amount of each additive used to prepare the compound which is critical for instance for PVC. Users can also enter data about masterbartch. Since masterbatches are mainly comprised by a base raw material (e.g.: PE, PP, etc.) with very low amounts of additives/colourants (e.g.: TiO2, etc.) Then for the purpose of the tool, the user just needs to enter the base material for the masterbatch if required. The KEPIs for the additives and masterbatches are calculated as follows:

$$KEPI\ additives = \sum_i [KEPI\ (additive_i) \times kg\ of\ additive_i] \quad (2)$$

$$KEPI\ masterbatch = KEPI\ (base\ raw\ material) \times kg\ of\ base\ raw\ material\ in\ masterbatch \quad (3)$$

Total KEPI for the raw material stage: Finally for the raw material module, KEPIs are calculated in accordance with the following equation:

$$KEPI\ (raw\ material\ stage) = KEPI\ raw\ materials + KEPI\ additives + KEPI\ masterbatch \quad (4)$$

1.2.3.2 Environmental assessment of transport module

Supply of raw materials: For the supply of raw materials to the plastic converters, the user only needs to enter the distance covered by each transport mode. For each transport mode and each raw material, KEPIs are calculated as shown in Equation 5. Then the KEPI for the transport stage is calculated by Equation 6.

$$KEPI\ transport\ mode_j\ (raw\ material_i) = kg\ of\ raw\ material_i \div 1000 \times \sum(km\ by\ transport\ mode_j) \times KEPI\ (transport\ mode_j) \quad (5)$$

$$KEPI\ transport\ (raw\ material\ stage) = \sum_i \sum_j KEPI\ transport\ mode_j\ (raw\ material_i) \quad (6)$$

1.2.3.3 Environmental assessment of processing module

In this module, there are four sub-stages considered: (a) an optional drying process in case of materials that need to be dried to a certain moisture level before being processed (e.g. PLA or PET), (b) a compounding process in case of PVC, (c) the converting processes, and (d) the additional finishing processes such as laminating, printing and forming.

Drying process: As shown in the matrix of materials and processes (Table 2), some polymers require a drying step prior to their conversion into a product; in particular PLA, TPS blend, potato-based starch plastic, PHB, PBS, partially bio-based PET and PET. For industrial polymer drying, the driers commonly used are desiccant ones. In accordance with Wittman (2009), the energy consumption of a drier is sum of two main variables:

- The **basic load** (basic energy consumption): This is the energy to produce hot, dry air. It is fixed for a conventional desiccant drier with constant air flow, determined by the drier and completely independent of the resin processed.
- The **resin heat-up energy**: This is the energy to heat the resin up to the optimal temperature for extracting moisture. It varies with throughput rate and it is determined by the resin's specific heat, storage temperature and drying temperature. The throughput rate is defined as the weight of material which can be filled in the hopper divided by the drying time (Relpet, 2013).

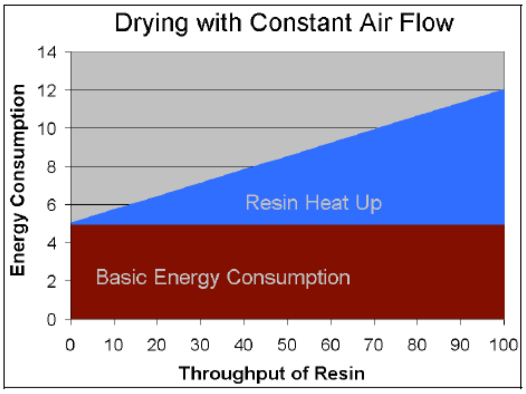


Figure 1a. Energy consumption of polymer drying (Wittman, 2009)

The energy consumption of the drier is then calculated as followed:

$$Energy\left(\frac{kWh}{kg}\right) = \frac{\left[Basic\ load\ (kW) + Heat\text{-}up\ load\left(\frac{kWh}{kg}\right) \times throughput\left(\frac{kg}{h}\right)\right]}{throughput\ \left(\frac{kg}{h}\right)} \qquad (7)$$

Where the heat-up load and throughput are defined by the following equations:

$$Heat - up\ load = c_p \times \Delta T = c_p \times (T^{o}drying - T^{o}storage) \qquad (8)$$

$$throughput\ rate = \frac{amount\ of\ material\ filled\ in\ the\ hopper\ (kg)}{drying\ time\ (h)} \qquad (9)$$

Where c_p stands for the resin's specific heat and is considered as constant for each type of resin. Resin specific heats were calculated for each type of resin by assuming that these are independent of the temperature. Table 20 summarizes the resin's specific heat for those resins that may require a drying step prior converting processes. Since potato-starch based plastic is a thermoplastic starch such as TPS blend, a mean value based on material data center (2011) of 1.54 was considered.

Table 20. Resin's specific heat

Resin	Specific heat (kJ/(kg-ºC))	Reference
PLA	1.8	(Cargill Dow LLC, 2007)
PET & partially bio-based PET	1.69	(Matweb, 2013a)
PHB	1.5	(Matweb, 2013b) (Ashby, 2002)
PBS	1.7	(Signori et al., 2012)
TPS blend	1.56	(Material data center, 2011)
Potato-starch based plastic	1.54	(Material data center, 2011)

In order to calculate the energy consumption of the drier in the bio-based plastics LCA to go tool, the values of the basic load and the storage temperature were fixed. Such decision was taken since these values are difficult to find or measure by the user. The basic load was fixed to 1.2 kW, taking as a reference the conventional desiccant drier with constant air flow Drymax D60 of Wittman (Wittman, 2010). The storage temperature was fixed at 23ºC since this is the temperature usually used in standard conditions. With these parameters fixed, the energy equation becomes:

$$Energy = \frac{\left[1.2 + c_p \times (T^{o}drying - 23) \times \frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}\right]}{\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}} \quad (10)$$

Therefore, the user only needs to enter the following three parameters in order to calculate the energy required for drying (equation 10):

- The amount of material filled into the hopper of the dryer
- The drying temperature
- The drying time

Therefore, it is now possible to calculate the energy for drying for each one of the materials with the above mentioned variables:

$$Energy_{PLA} = \frac{\left[1.2 + \frac{1.8}{3600} \times (T^{o}drying - 23) \times \frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}\right]}{\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}} \quad (11)$$

$$Energy_{PET\ \&\ part.bio-based\ PET} = \frac{\left[1.2 + \frac{1.69}{3600} \times (T^{o}drying - 23) \times \frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}\right]}{\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}} \quad (12)$$

$$Energy_{PHB} = \frac{\left[1.2 + \frac{1.5}{3600} \times (T^{o}drying - 23) \times \frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}\right]}{\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}} \quad (13)$$

$$Energy_{PBS} = \frac{\left[1.2 + \frac{1.7}{3600} \times (T^{o}drying - 23) \times \frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}\right]}{\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}} \quad (14)$$

$$Energy_{TPS\ blend} = \frac{\left[1.2 + \frac{1.56}{3600} \times (T^{o}drying - 23) \times \frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}\right]}{\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}} \quad (15)$$

$$Energy_{\ Potato\ st.-based\ plastics} = \frac{\left[1.2+\frac{1.54}{3600}\times(T^{o}drying-23)\times\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}\right]}{\frac{amount\ of\ material\ filled\ into\ the\ hopper}{drying\ time}} \quad (16)$$

Users can either enter their own data for the above mentioned parameters or use default data if required. Default values for drying are summarized in Table 21.

Table 21 Default values for drying temperature and time, used in the calculation of default energy consumption at drying step

Material	Drying temperature (ºC)	Drying time (h)	References
PLA	60	3	(NatureWorks LLC, 2013)
PET	160	4	(Indorama Venture, 2013) (Relpet, 2013) (Dupont, 2013)
PHB	80	3	(Metabolix Inc., 2013)
PBS	75	5	(Mitsubishi Chemical, 2013)
TPS blend	70	3	(Ides, 2011)
Potato-based starch plastic	70	3	(Ides, 2011)

Users should note that for PLA, drying temperature and time are given for crystalline PLA. These values were compared with the technical datasheets of the PLA/PBS blend used by Valsay for the production of carrier bags. The specific instructions for film blowing of biodegradable PLA/PBS resin recommend that if the moisture level of the resin exceeds 1000 ppm, then to be dried before being processed (at maximum 65ºC and no longer than 3 hours), which is aligned with the default data given. For PET, PHB and PBS, the drying conditions were extracted from material datasheets of several suppliers. No specific data was found only for TPS blend and potato-starch plastic. In these cases, the average drying conditions for generic biodegradable polymers obtained from Ides Prospector (Ides, 2011) were used. Finally the KEPIs for the drying step of a material are given by:

$$KEPI\ drying\ (raw\ material_i) = kg\ of\ raw\ material_i \times Energy_{raw\ material_i}(kg\ of\ raw\ material_i) \times KEPI\ (electricity)_{from\ the\ selected\ country} \quad (17)$$

Compounding process: When the user has selected PVC as a raw material and the additives, PVC and the additives are mixed by a compounding process prior to being converted into a product. The user is asked to enter its own data; however default data is also given if the user cannot fill in the data. The users have to enter:

- The amount of material processed (kg)
- The electricity consumption (kWh)
- The amount of lubricating oil (L)
- The amount of water used for cooling purposes (m^3)

The KEPIs associated to the electricity, lubricating oil and water consumption for the compounding process are calculated with the following equations:

$$KEPI\ electricity\ (compounding) = kg\ material\ compounded\ \times\ electricity\ (compounding) \times KEPI\ electrity_{from\ selected\ country} \quad (18)$$

$$KEPI\ lubricating\ oil\ (compounding) = kg\ material\ compounded\ \times lubricating\ oil\ (compounding) \times KEPI\ lubricating\ oil \quad (19)$$

$$KEPI\ water\ cooling\ (compounding) = kg\ material\ compounded\ \times water\ cooling\ (compounding) \times KEPI\ water\ cooling \quad (20)$$

Then the KEPIs for the compounding process sub-stage are calculated as the sum:

$$KEPI\ compounding = KEPI\ electricity\ (compounding) + KEPI\ lubricating\ oil\ (compounding) + KEPI\ water\ cooling\ (compounding) \quad (21)$$

Default data for the compounding process of PVC is provided in the tool. Such selection of default values was based on the current state-of-the-art of compounding of PVC. Usually the PVC compound can be obtained in several forms: (a) in powder form through compounding in a high-speed mixer, (b) in granules through blending in a mixer followed by melting into a compounding extruder, and (c) in liquid form produced as dispersions of PVC polymers particles in liquid organic media (PVC, 2013). For the default value for PVC compounding, it is considered that the compounding step consists of an extrusion step followed by pelletizing. Thiriez (2006) analysed the injection moulding process from an environmental perspective. In their study, they give the energy consumption by stage from the thermoplastic production, through compounding, to the injection moulding, based on an average of the consultation of 100 stakeholders. Due to the fact that it seems a representative and up-to-date data for the compounding process, results from Thiriez (2006) were adopted as default data for the bio-based plastics LCA to go tool. Average electricity consumption of 0.51 kWh/kg for extrusion and 0.017 kWh/kg for pelletizing during compounding were considered, which sums a total of 0.527 kWh/kg for the total compounding process (Thiriez, 2006).

Unfortunately, Thiriez (2006) did not provide any data about lubricating oil nor water use for cooling during the compounding process. As a result of that we decided to make an estimation of the lubricating oil and water consumptions during compounding. It was finally assumed that the compounding process uses a similar amount of lubricating oil and water as in the case of cast sheet/film extrusion, i.e. 1.17E-04 L/kg of polymer and 4.37E-02 m^3/kg of polymer. Table 22 summarizes the default data proposed for the compounding process.

Table 22. Default values for the compounding process considered in LCA to go tool

Process	Raw material	Default values			Reference
		Electricity (kWh/kg)	Water cooling (m^3/kg)	Lubricating oil (kg)	
Compounding	PVC	5.27E-01	4.37E-02	1.17E-04	Thiriez (2006); Hischier (2007)

Converting processes: As explained in section 1.2.1, after selecting the raw materials used, the user selects the converting processes applied to obtain products from pellets. Once selected a converting process, the user is asked to enter its own process parameters. For all converting processes, users have to enter:

- The amount of material processed (kg)
- The electricity consumption (kWh)
- The amount of lubricating oil (L)
- The amount of water used for cooling purposes (m^3)
- Any additional internal transport including the transport mode and distance covered (km), if required.

With regard to the consumption of lubricating oil, all converting machines consume lubricating oil in the gearbox and bearings in a relatively small amount (Ventura 2013b). However, hydraulic injection moulding equipment consumes a large amount of oil for hydraulic equipment. Such equipment usually has a hydraulic oil tank of around 150 to 200 L (Ventura 2013b). Therefore the lubricating oil consumption is particularly relevant for injection moulding and injection stretch blow moulding processes since such consumption can be ten times more than other plastic converting processes.

The KEPIs associated to the electricity consumption were calculated with the following equations:

$$KEPI\ electricity\ (process_i) = kg\ material\ processed\ (process_i) \times electricity\ (process_i) \times KEPI\ (electricity)_{from\ the\ selected\ country} \quad (22)$$

$$KEPI\ electricity\ (processing) = \sum_i KEPI\ electricity\ (process_i) \quad (23)$$

The KEPIs related to lubricating oil are calculated as follows:

$$KEPI\ lubricating\ oil\ (process_i) = kg\ material\ processed\ (process_i) \times lubricating\ oil\ (process_i) \times KEPI\ lubricating\ oil \quad (24)$$

$$KEPI\ lubricating\ oil\ (processing) = \sum_i KEPI\ lubricating\ oil\ (process_i) \quad (25)$$

The KEPIs related to water use for cooling are calculated in a similar way:

$$KEPI\ water\ cooling\ (process_i) = kg\ material\ processed\ (process_i) \times water\ cooling\ (process_i) \times KEPI\ water\ cooling \quad (26)$$

$$KEPI\ water\ cooling\ (processing) = \sum_i KEPI\ water\ cooling\ (process_i) \quad (27)$$

The KEPIs for the additional transport of intermediate products are calculated using the same approach as described for the transport for supply of raw materials (see equations 5 and 6). The user indicates the distance recovered by each transport mode selected. First KEPIs are calculated for each transport mode and finally the global KEPI for the additional transport in the processing module is calculated.

$$KEPI\ transport\ mode_j\ (intermediate\ material_i) = kg\ of\ intermediate\ material_i \div 1000 \times \sum(km\ by\ transport\ mode_j) \times KEPI\ (transport\ mode_j) \quad (28)$$

$$KEPI\ transport\ (processing\ stage) = \sum_i \sum_j KEPI\ transport\ mode_j\ (intermediate\ material_i) \quad (29)$$

Finally, the KEPIs for the converting sub-stage are calculated as the sum:

$$KEPI\ processing = KEPI\ electricity\ (processing) + KEPI\ lubricating\ oil\ (processing) + KEPI\ water\ cooling\ (processing) + KEPI\ transport\ (processing\ stage) \quad (31)$$

Even though we encourage users to enter their own data for processing and more accurate results, the bio-based plastics software tool also includes a set of default data. Default data for processing was a challenging task which was not available for all the materials considered in the tool. In any case the criterion was to prioritize the use of polymer-specific data for processing whenever available. If not, average data for all polymers was considered.

With regard the sources for default data, sectoral data was preferred. Therefore the Eco-profiles from Plastics Europe were selected as the main data source. The criterion for the selection of default data was to use updated data whenever available. Moreover, in order to give default data for most of the parameters, when data was lacking for a specific parameter in the updated eco-profile, it was decided to propose the data from the prior update.

In a first stage of development of the beta tool, updated Eco-profiles from Plastics Europe (2010a, 2010b, 2010c) were considered as a source for default data calculation pipe extrusion, injection moulding and injection stretch blow moulding. In these Eco-profiles, conversion data were provided by several plastic converters for 2007, and sometimes for 2008. For film extrusion, blow moulding and thermoforming, Plastics Europe has not yet updated the Eco-profiles, which are based on old data (1995, 1998 and 1996, respectively). As a result of that it was decided to use the data from the study of the most common conversion processes for plastics carried out by Hischier (2007) due to the lack of updated data for some of the processes. In his work, Hischier provided the input and output data for the mentioned processes and for different plastic types, as reported in the examined sources: a Swiss packaging study (Habersatter et al., 1998) and the former conversion report from Plastics Europe (Boustead, 1997) that includes the Eco-Profiles. On the basis of the data from these two studies, Hischier (2007) calculated the average of input and output for each conversion process, so that data are independent of the plastic type. Therefore it is possible to use the data from these two studies and the average calculated by Hischier (2007) as default values for processing. The input and output data given in Hischier (2007) refer to 1 kg of output product and thus data were re-calculated to refer to the processing of 1 kg of material. The performance of the process and the amount of waste produced are taken into account. Default data for converting processes is summarized in Table 23.

As regards film blowing, neither Plastics Europe nor Hischier (2007) studied this plastic conversion process. In order to obtain default values, at least for energy consumption, data about film blowing was found in an LCA study about supermarket carrier bags published by Edwards (2011). However the values for energy consumption are aggregated for the complete bag production process, i.e. film blowing and sealing to form the bag. In their study, data were provided by bag producers in China and Turkey since it was estimated that most bags were produced in these locations. In the beta version of LCA to go, this default data will be used whereas separated data for both steps of the production of bags will be included in the final version of the LCA to go tool.

In the up-dated Eco-Profiles of Plastics Europe, and in the process data provided by Hischier (2007), the lubricating oil consumption is given by weight unit, however for workers who are processing plastic in converting equipment it is more practical to enter this data by litre units (Ventura, 2013b). Therefore it is necessary to convert the default value with the density of the lubricating oil. The density of lubricating oil used in hydraulic equipment has an average density of 0.880 kg/L at 15ºC (Eni S.p.A., 2005a); which is the oil-type mainly used in injection moulding and injection stretch blow moulding. The density of lubricating oil used in gearbox and axial bearings has a slightly higher average density of 0.895 kg/L at 15ºC (Eni S.p.A. 2005b).

In the case of injection moulding, data are given for hydraulic powered machine since this is the oldest and most common injection moulding equipment used at industry level (Thiriez 2006). This machines use hydraulic pumps to power the machine's motions which is the reason why the consumption of lubricating oil is relevant for injection moulding process. However the user may use injection moulding machinery whose drives are powered from other sources: this is the case of all-electric powered injection moulding machines and hybrid powered machines. The type of machine used has a substantial impact on the energy consumption of the injection process, as demonstrated by Thiriez (2006) and on the lubricating oil consumption. Therefore the user must be particularly careful when using default values for injection moulding process.

Table 23. Default values for the plastic converting processes considered in LCA to go tool

Process	Raw material	Default values			Reference
		Electricity (kWh/kg)	Water cooling (m^3/kg)	Lubrica-ting oil (L/kg)	
Cast sheet / film extrusion	PVC	4.55E-01	4.37E-02 (a)	1.78E-04	(Boustead, 1997) as reported in (Hischier, 2007)
	LDPE	5.16E-01	4.37E-02 (a)	1.12E-04	(Boustead , 1997) and (Habersatter et al., 1998) as reported in (Hischier, 2007)
	PP	1.31E+00	2.21E-01	3.38E-04	(Boustead, 1997) as reported in (Hischier, 2007)
	Average	6.60E-01	4.37E-02	1.17E-04	(Hischier, 2007)
Pipe / profile extrusion	PVC	5.26E-01	8.10E-04	4.24E-03	(Plastics Europe, 2010c)
	HDPE	5.48E-01	6.89E-04	3.46E-03 (b)	(Plastics Europe, 2010c)
	PP	6.99E-01	8.98E-04	6.13E-03	(Plastics Europe, 2010c)
	Average	5.91E-01	7.99E-04	3.46E-03	(Plastics Europe, 2010c)

Injection stretch blow moulding	PET & average	1.50E+00	1.10E-01 (c)	2.22E-03 (c)	(Plastics Europe, 2010a) ; (Hischier 2007)
Extrusion blow moulding	Average	1.70E+00	2.99E-03	n.a.	(Hischier, 2007)
Thermoforming	Average	1.01E+00	1.04E-01	5.71E-04	(Hischier, 2007)
Injection moulding (d)	PVC	1.19E+00	5.22E-05	1.04E-02 (e)	(Plastics Europe, 2010b); (Boustead, 1997) as reported in (Hischier 2007)
	HDPE	1.99E+00	3.98E-07	1.04E-02 (e)	(Plastics Europe, 2010b); (Boustead, 1997) as reported in (Hischier 2007)
	PP	7.98E-01	2.25E-04	1.04E-02 (e)	(Plastics Europe, 2010b); (Boustead, 1997) as reported in (Hischier 2007)
	Average	1.33E+00	9.19E-05	1.04E-02 (e)	(Plastics Europe, 2010b); (Boustead, 1997) as reported in (Hischier 2007)
Film blowing (f)	Average	8.21E-01	n.a.	n.a.	(Edwards, 2011)

(a) Since no data was available for water consumption of PVC and LDPE, the value calculated as average water cooling consumption for cast sheet / film extrusion by Hischier (2007) is given.
(b) Since the companies did not give any data for the lubricating oil consumption, the value calculated as average lubricating oil consumption for pipe / profile extrusion is given.
(c) Since the companies did not give any data for the water cooling and lubricating oil consumption, the value calculated by Hischier (2007) was used.
(d) Default values correspond to a hydraulic powered machine.
(e) Since none company gave data for lubricating oil consumption in the updated Eco-profiles of injection moulding, the value calculated by Hischier (2007) was used for lubricating oil consumption.
(f) As explained, in this beta version of the LCA to go tool, the energy consumption indicated for film blowing also includes the finishing processes of die-cut forming and sealing of bags since it was not possible to separate the value for the different process steps. . In the final version, separated data will be included.

In order to advice the users of LCA to go tool that default values must be very carefully used, it is noteworthy to highlight that there is a difference in the consumption of water cooling between the up-dated Eco-Profiles from Plastics Europe (Plastics Europe 2010a, 2010b, 2010c) and the data sources summarized in Hischier (2007). In Hischier (2007), it was assumed that the given water consumption is 100% cooling water whereas in the up-dated Eco-Profiles the consumption of water is separated into water process and water cooling. Therefore we again encourage the user to enter their own data in order to reach more accurate results.

Additional finishing processes: As above mentioned, the three most common finishing processes in the plastics industry were considered in the tool: (a) laminating, (b) die-cut forming of bags and (c) printing. In these three processes users are asked about the electricity consumption required, although they should also enter the amount of ink for the printing process as well as the glue used for laminating processes. The following equations were considered for calculations:

$$KEPI\ laminating = laminated\ area \times [electricity\ (laminating) \times KEPI\ electricity_{from\ the\ selected\ country} + kg\ of\ glue \times KEPI\ glue] \quad (32)$$

$$KEPI\ printing\ = printed\ area\ \times [electricity\ (printing) \times KEPI\ electricity_{from\ the\ selected\ country} + kg\ of\ ink\ \times KEPI\ ink] \quad (33)$$

$$KEPI\ forming = kg\ of\ material\ processed\ \times electricity\ (forming) \times KEPI\ electricity_{from\ the\ selected\ country} \quad (34)$$

Finally the KEPIs for the additional finishing process are calculated as the sum:

$$KEPI\ finishing = KEPI\ laminating + KEPI\ printing + KEPI\ forming \quad (35)$$

Default values for the finishing process sub-stage are provided in the tool whenever data was available. According to data availability, default data are provided for the energy consumption of the printing process and laminating. As regards die-cut forming of the bags, a default value for this process is not provided in this sub-stage since it was already included in the default value for the film blowing process. However, as already said, in the final version of LCA to go tool, a specific default value for die-cut forming of the bags will be included separately from the process of film blowing.

According to Veith and Barr (2008), solvent is mixed with the ink in order to achieve the suitable viscosity for printing. Since the use of solvent depends on the storage conditions, seasonality and the viscosity targeted, it was decided to discard such parameter in LCA to go tool. Electricity is used in the printing and distillation process steps that were combined into one model in Veith and Barr (2008), since inputs and outputs could not be separated for he different processes from the information provided. Natural gas is also used in the printing with solvent-based inks. The Design for Environment programme for flexographic inks from EPA assessed the resource and energy conservation of solvent-based ink technology (DfE 2002). In their energy analysis, they evaluated two pieces of equipment for solvent-based ink system: hot air drying system that dries the ink between stations and in the overhead tunnel dryer and catalytic oxidizer that converts VOCs to carbon dioxide and water. The energy consumed by hot air drying systems includes electricity for the supply and exhaust blowers, and natural gas for the drying oven. A basic catalyst oxidizer consists of a heat exchanger, a burner and a catalyst, based on natural gas supply. The values given by Dupont (2008) for electricity and natural gas consumption are used as default values for the printing process (Table 24).

Table 24. Default values for printing process (Veith and Barr, 2008)

Parameter	Default value
Electricity (kWh/m^2)	0.05784
Natural gas (MJ/m^2)	0.21122

As regards the laminating process, as a first approximation in this beta version of the tool, it was decided to consider the estimation of the electricity use for the laminating of packaging foils with acrylic glue as binder from BUWAL (1996) (Table 25). Such laminating process is different from the one considered in LCA to go tool, which is based on the use of reactive adhesives. However it can give a first approximated default value that will be up-dated in the final version of the tool.

Table 25. Default values for laminating process (BUWAL, 1996)

Parameter	Default value
Electricity (kWh/m^2)	0.0183

Total KEPI calculation for the processing module: The global KEPI for the processing module is calculated as the sum of the drying process, converting and additional finishing processes

$$KEPI\ (processing\ stage) = KEPI\ drying + KEPI\ compounding + KEPI\ processing + KEPI\ finishing \quad (36)$$

1.2.3.4 Environmental assessment of distribution module

In this module, there are two sub-stages: the packaging of the products for their distribution and the distribution of the products.

Packaging of the products: Users must enter the weight of packaging materials used for the delivery to customer of the final product. The KEPIs for the production of packaging materials are calculated as follows:

$$KEPI\ packaging\ materials = \sum_i [kg\ of\ packaging\ material_i \times KEPI\ packaging\ material_i] \quad (37)$$

Distribution of the packaged products: The KEPIs for the distribution of the packaged products are calculated in the same way as described for the transport needs for the supply of raw materials (see equations 2 and 3). The user must enter the distance covered by each transport mode. At a first stage KEPIs are calculated for each transport mode selected and then for the overall distribution stage.

$$KEPI\ transport\ mode_j\ (distribution) = (kg\ of\ product\ packaged + \sum_i (kg\ of\ packaging\ material_i)) \div 1000 \times \sum_j (km\ by\ transport\ mode_j) \times KEPI\ \left(transport\ mode_j\right) \quad (38)$$

$$KEPI\ transport\ (distribution) = \sum_j KEPI\ transport\ mode_j\ (distribution) \quad (39)$$

Finally, the KEPIs for the converting sub-stage are calculated as the sum:

$$KEPI\ distribution = KEPI\ packaging\ materials + KEPI\ transport\ (distribution) \quad (40)$$

1.2.3.5 Environmental assessment end-of-life module

As mentioned above, the end-of-life module considers four different waste treatments (recycling, incineration, composting and landfilling) both for industrially compostable plastics and non-biodegradable ones. The transport for waste collection was also considered with a default value of 25 km, although users can change the distance as function of their preferences. The KEPIs for the end-of-life module are calculated with the following equation:

$$KEPI\ end-of-life = kg\ of\ product\ packaged \times [\,(KEPI\ recycling \times \%\ recycling) + (KEPI\ incineration \times \%\ incineration) + (KEPI\ composting \times \%\ composting) +$$

$(KEPI\ landfill\ \times \%\ landfill) + (km\ by\ waste\ transport\ \div 1000\ \times$
$KEPI\ waste\ collection\ lorry)]$ (41)

1.2.3.6 Economic assessment module

As above mentioned in section 1.2.3, economic assessment is limited only to those costs which are under the control of the company. Consequently, the end-of-life costs are outside the scope of the economic assessment.

The economic assessment of raw material stage is performed by entering the purchasing costs of raw materials, master-batch (if any) and additives (in case of PVC). Purchasing costs for raw materials must not include transport costs

$$Cost\ (raw\ materials\ stage) = \sum_i kg\ of\ raw\ material_i \times unitary\ cost\ (raw\ material_i) \quad (42)$$

$$Cost\ (transport\ raw\ materials\ stage) = \sum cost\ transport\ mode_j \quad (43)$$

In the economic assessment of the processing stage, the user only needs to enter the following parameters:

- The costs of electricity for the drying step (if required) per kg of material dried.
- The cost of electricity for the compounding step (in case of PVC) per kg of material compounded.
- The cost of electricity for converting per kg of material processed.
- The unitary cost of water for cooling purposes during compounding and converting per kg of material compounded or processed.
- The cost of lubricating oil for the compounding and converting processes per kg of material compounded or processed
- The additional costs for internal transport (if any) during the processing step.
- For the finishing processes the cost per kg of electricity, glue and ink.

The costs for the processing module are then calculated as follows:

$$cost\ (drying) = kg\ of\ material\ dried\ \times electricity\ (drying) \times unit\ cost\ (electricity) \quad (44)$$

$$cost\ (compounding) = kg\ of\ material\ compounded\ \times [electricity\ (compounding) \times unitary\ cost\ (electricity) + water\ cooling\ (compounding) \times unit\ cost\ \big(water\ cooling(compounding)\big) + lubricating\ oil\ (compounding) \times unit\ cost\ (lubricating\ oil\ (compopunding)] \quad (45)$$

$$cost\ (processing) = \sum_i [kg\ of\ material\ processed\ (process_i) \times electricity\ (process_i) \times unit\ cost\ \big(electricity\ (process_i)\big)] + \sum_i [kg\ of\ material\ processed\ (process_i) \times water\ cooling\ (process_i) \times unit\ cost\ \big(water\ cooling\ (process_i)\big)] + \sum_i [kg\ of\ material\ processed\ (process_i) \times lubricating\ oil\ (process_i) \times unit\ cost\ \big(lubricating\ oil\ (process_i)\big)] + cost\ (additional\ transport) \quad (46)$$

$$cost\ (additional\ transport) = \sum cost\ transport\ mode_j\ (process_i) \quad (47)$$

$$cost\ (finishing) = \sum_i [kg\ of\ material\ processed\ (process_i) \times kg\ of\ ink\ or\ glue\ (process_i) \times unit\ cost\ (ink\ or\ glue\ (process_i))] + \sum_i [kg\ of\ material\ processed\ (process_i) \times electricity\ (process_i) \times unit\ cost\ (electricity\ (process_i))] \quad (48)$$

Finally the overall cost of the processing module is given by the sum:

$$cost\ (processing\ stage) = cost\ (drying) + cost\ (compounding) + cost\ (processing) + cost\ (additional\ transport) + cost\ (finishing) \quad (49)$$

The costs for the distribution stage are easily calculated as the sum of costs of packaging materials and transport for distribution of products:

$$cost\ (packaging\ materials) = \sum_i kg\ of\ packaging\ material_i \times unitary\ cost\ (packaging\ material_i) \quad (50)$$

$$cost\ (transport\ for\ distribution) = \sum cost\ transport\ mode_j \quad (51)$$

The overall cost for distribution is then calculated by the sum:

$$cost\ (distribution\ stage) = cost\ (packaging\ materials) + cost\ (transport\ for\ distribution) \quad (52)$$

Finally, the overall gate-to-gate cost is calculated as the following sum:

$$cost\ (total) = cost\ (raw\ materials\ stage) + cost\ (transport\ of\ raw\ materials\ stage) + +cost\ (processing\ stage) + +cost\ (distribution\ stage) \quad (53)$$