Chapter 6
Life Cycle Assessment and Life Cycle Costing for PSS

Donatella Corti, Alessandro Fontana, Michele De Santis, Christian Norden and Reinhard Ahlers

Abstract The increasing awareness towards sustainability issues from both practitioners and customers makes it necessary to adopt a lifecycle perspective since the design phase of PSSs. In this chapter, a tool aimed at carrying out the Life Cycle Assessment (called MaGA) and one for the Life Cycle Costing (called BAL.LCPA) are introduced starting from the analysis of requirements carried out to make sure their use is suitable in a PSS design context. In order to seamlessly include environmental and economic considerations into the design process, the two stand-alone tools have been integrated with the Manutelligence design platform. Their application in a Fablab-like environment is described to show how they interact with design tools and to provide examples of the results they get.

6.1 Introduction

The holistic approach promoted by the Manutelligence platform for the design of product service systems (PSSs) integrating a suite of collaborative tools adopts a lifecycle perspective towards a more sustainability-aware design process. In this context,

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the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) tools developed for the Manutelligence platform enable the calculation of the expected environmental impacts and economic measures characterizing a certain design concept before the product/service is actually produced. In the current industrial practice, these tools are mainly used ex-post to assess the actual impacts generated by a product or a process; whereas the concepts of integrated LCA and LCC tools into the platform allow to compare, in real-time, alternative PSSs concepts also on the base of their sustainability impact. Therefore, the LCA and LCC tools have to seamlessly communicate with other databases that provide the necessary input data for the evaluation and that, in turn, could use the obtained assessment in their procedures. In this chapter, a brief state-of-the-art of LCA and LCC tools in the field of PSS is presented before introducing the tools developed in the Manutelligence context along with examples of their validation with project pilots.

6.2 Life Cycle Assessment (LCA) for Product Service Systems (PSS)

LCA quantifies all relevant emissions and resources consumed and the related impacts on environment, human health and resources that are associated with any good or service. The main reference to carry out a Life Cycle Assessment (LCA) is the ISO 14040:2006 family of standards [7, 8]. They provide a set of international guidelines internationally recognized and used as reference at global level. The identified and renowned structure of an LCA study is organized into four phases:

Definition of the goal and scope of LCA. It defines why the LCA is performed, the possible applications and other preliminary elements needed as a basis for the study such as the functional unit, the system boundaries or the allocation procedure.

Life Cycle Inventory (LCI) analysis. The exchanged natural elements between the eco-sphere and the tecno-sphere (the system analyzed), thus the resources entering (e.g. raw material, energy and ancillary material) and those leaving the system of interest (e.g. emissions, waste, products and co-products) have to be identified and quantified. This step involves data collection from several different actors and related processes along the supply network.

Life Cycle Impact Assessment (LCIA). It is meant to calculate the impacts and the effects on the environment generated by the identified LCI data.

Interpretation. This is the final phase, where the report with the quantified impacts is prepared and the critical review of the LCA results is performed.

The ISO 14040:2006 [7] standard has been developed with a physical product focus and, even though services are conceptually considered, the PSS concept is not considered explicitly. For this reason, the ISO-based LCA approach might not be applied to the PSS context directly. The main difficulty when carrying out an

LCA for a PSS is how to integrate the service component into the LCI [4]. In literature, the benefits of methodologies to perform the assessment of PSSs are frequently described (see for example [2, 13, 17], whilst more rarely contributions describing how to effectively carry out these evaluations can be found [6, 10]. Often, the sustainable design of solutions focuses mainly on the physical product and potential optimizations are directed towards its physical subsystems, whilst only later services are paid attention. This procedure is not due to a lack of methodologies but rather due to lack of system thinking [2]. Many contributions dealing with sustainability assessment of PSSs depict the maintenance like the only service type [11] and, typically, even if a few methodologies are proposed to assess the environmental impacts [1, 15, 16], what they propose mainly refers to a specific type of PSS and cannot be easily generalized. The lack of general procedures that could be applied to any type of PSS could be due to the wide range of services that can be combined with a product. As a consequence, the complexity and heterogeneity of the systems that represent the PSS challenge the development of a method to systematize the information collection. Corti et al. [3] propose an approach to support the LCI phase aimed at formalizing the integration of information related to the service part of the offer.

6.3 Life Cycle Costing (LCC) for Product Service Systems (PSS)

Life Cycle Costing (LCC) is an accounting method that considers every cost flow throughout the lifecycle of a product (as defined in ISO 15686:2008 [9]).

Life cycle costs [14] can be divided into three categories: development costs, utility/service costs and recycling/reprocessing costs. Similarly to the cost, also revenues are allocated to the individual phases of a Product System: design phase, usage phase and recycling phase.

The results of the life cycle cost analysis are also used to optimise the design within an improvement cycle. Niemann et al. [14] have identified possible uses, such as calculation of total costs for products; identification of cost and revenue drivers; impact on outsourcing decisions; analysis of "what if" scenario or analysis of customer lifetime value.

A comprehensive review of the literature on PSS has revealed that currently no quantitative methodologies exist to assess the economic potential of a PSS [18]. Datta and Roy [5] explain that methodologies to calculate the LCC for a PSS diverge depending on the PSS model, since the estimation techniques depend on the kind of service-orientation of the system. Considering the estimation of costs, the main differences between different kinds of PSSs are the hidden costs, that cannot be quantified with traditional cost estimating methods and are due to the intangible nature of services.

Van Ostaeyen et al. [18] suggest a methodology to calculate the Life Cycle Costs for a result-oriented PSS. The methodology follows the main steps of the environmental assessment, beginning from goal, scope and definition of a unit of functional delivery. Mannweiler et al. [12] provide a step-wise procedure to calculate the LCC (and in particular Life Cycle Cost Indicator, LCCI) with the final aim of choosing the most appropriate PSS variant. They state that the only way to calculate the exact LCC is to collect the detailed information of the lifecycle characteristics that are used to describe the PSS-application, yet no methodology to correctly get this information is suggested and, in particular, there is no mention to the service part of a PSS. In order to compete in a transformed environment, companies need to properly assess the cost of their service offerings to stay competitive [5]. A classical example of application of the LCC on a service regards the maintenance. The maintenance service includes direct labour, materials, fuel, power, equipment and purchased services.

6.4 Definition of Requirements for LCA and LCC Tools

In engineering activities, such as the development of software tools, the requirements analysis is often the first step in the system design process and development, in which user's requirements are gathered and analysed to generate the corresponding tool specifications. Requirements have to be documented, actionable, measurable, testable, traceable, related to identified business needs or opportunities, and defined at a level of detail sufficient for system design. The requirements analysis carried out in Manutelligence for LCA and LCC tools had a twofold aim: first, to list the requirements these tools should satisfy in order to comply with the integration needs of the Manutelligence platform and the use for the design process; second, to decide whether to adopt existing tools (available in the market) or to develop new solutions that could better fit with the project needs.

Conceptually, requirements analysis included three types of activities:

- **elicitation**: requirements are gathered through interviews and brainstorming sessions involving different stakeholders;
- **analysis**: identified requirements are analysed to make sure they are clear, complete, consistent and unambiguous;
- **prioritization**: requirements are weighted and scored to distinguish between crucial requirements to fulfil the basic functionality and additional features.

Since technical expertise was required as well as knowledge of the Manutelligence platform features, the project partners involved in the development and integration of LCA and LCC tools have elicited the first list of requirements.

The list has been then refined through some iteration of discussions and revisions involving not only the software developers and experts, but also users represented by the pilots participating to the project. In particular, the involvement of users has been fundamental for the prioritization of requirements.

The requirements have been split in two categories: Global Requirements (coded as GR1 to GR27 in Table 6.1) and Phase requirements (coded as PR.B.1 to PR.D.6

in Table 6.1). Global requirements concern the software functionalities and their integration with the Manutelligence platform. Phase requirements are focused on the specificity of the analysis and look at features related to calculation and presentation of results. For sake of clearness, the Phase requirements have been further clustered according to the analysis phase they refer to: (i) Life Cycle Inventory (LCI) (coded as PR.B.1 to PR.B.5); (ii) Life Cycle Impact assessment (coded as PR.C.1 to PR.C.4) and (iii) interpretation of results (coded as PR.D.1 to PR.D.6). The final list of requirements used to develop the tools including the indication of their priority is shown in Table 6.1.

In order to make easier the integration of the LCA and LCC tools into the Manutelligence platform and to adapt their use to the design process, the use of GaBI (the most widespread commercial LCA tool to assess environmental impact) has been excluded since it has been considered not flexible enough. It has been decided to extend the functionalities of two proprietary tools internally developed by the project partners, namely MaGA (Manutelligence Green Application) tool for LCA and BLA.LCPA for LCC. Working on their existent versions, they have been extended in order to cover as best as possible the elicited list of requirements.

6.5 The LCA Tool: MaGA

This section describes the MaGA (ManuTelligence Green Application) tool, the software that in the Manutelligence Platform is meant to perform LCA for PSSs. According to the Manutelligence needs, MaGA allows the performing of real time analysis aimed at improving the PSS design thanks to the possibility of evaluating alternative product or process configurations from the environmental point of view. To better manage the tool's complexity, a modular approach has been adopted. The software is therefore made of many modules, each one providing specific functionalities and user-interfaces. Figure 6.1 shows the MaGA architecture and its main components.

Main components providing the functionalities needed to allow a user to carry out the LCA analysis are: *Global Editor*, *Project Editor* and *Operation Editor*.

Global Editor. It allows to edit the data needed for the sustainability assessment that concern the company's supply chain actors (such as the list and the impacts of the materials/operation used, the transportation distances or the supply chain partners location) that are involved in the whole PSS life-cycle and the set of materials and operations currently used by the company. Through this module, it is possible to introduce new data (e.g. adding a new supplier to the supply chain or to add one indicator type) or update the existing one. This data are inserted into the platform once and can be then exploited every time a new assessment is carried out. This avoids repeating the data entry process of company-specific information that are common for all the PSS projects.

Table 6.1 Final list of requirements for the LCA and LCC tools (P = Primary; S = Secondary)

Requirements
(GR.1) Easiness of integration in the Manutelligence platform (P)
(GR.2) Ability to generate real time assessment which constitutes input for design of product/processes (P)
(GR.3) Tool(s) should have programming interfaces towards other systems (P)
(GR.4) Tool capacity to adapt to platform requirements (P)
(GR.5) Integration of both LCA and LCC methodologies (P)
(GR.6) Software maintenance/upgrades available (S)
(GR.7) Intuitive user interface (S)
(GR.8) Client server architecture, within client (S)
(GR.9) Capability to deal with Product Service Systems as the object of the analysis (P)
(GR.10) Adaptability to specific ISO standards (i.e.: ISO 14025 for Environmental Product Declaration) (S)
(GR.11) Compliance with PEF/OEF Recommendation (2013/179/UE) (P)
(GR.12) Quality review instruments of modelled processes also between different locations (S)
(GR.13) Social aspects evaluation (S)
(GR.14) Persistence data backup (S)
(GR.15) Possibility to perform concurrently different activities (S)
(GR.16) Ability to support benchmark analysis and comparisons between alternatives (S)
(GR.17) Easily extensible to different industrial sectors (S)
(GR.18) Ease of deployment (multi-platform, simple installation, etc.) (S)
(GR.19) Low user skills & knowledge requirements (S)
(GR.20) Use efficiency (average time required to model a scenario) (S)
(GR.21) Cooperative multi-user capability (S)
(GR.22) Allow to perform the assessment both during the design phase and on already existing products-service systems (S)
(GR.23) Consistency check (with alarm in case of discrepancies) (S)
(GR.24) Performance of running complex LCPA (S)
(GR.25) Consider dynamic timelines like operation cost increase throughput the lifecycle (S)
(GR.26) Direct comparison of different objectives (numerical and visually) (S)
(GR.27) Comparison of different future scenarios like different fuel price development (S)
(PR.B.1) Integration of specific database (i.e.: Worldsteel, Ecoinvent, ELCD) (P)
(PR.B.2) Management of allocation procedures (S)
(PR.B.3) Possibility to modify inventory references/insert specific documents for datasets included in available database (S)
(PR.B.4) Product- Service Life Cycle modelling aligned with the designer's needs (S)
(PR.B.5) Processes parametrization (S)
(PR.C.1) Pluggability of new impact assessment methods/models (P)

(continued)

Table 6.1 (continued)

Requirements
(PR.C.2) Evaluation of specific quantities (P)
(PR.C.3) Evaluation of LCC-related indicators (P)
(PR.C.4) Possibility of structuring and analysing the results considering the different contribution of the calculated impacts (S)
(PR.D.1) Capability of creating in automatic way reports with LCIA results (S)
(PR.D.2) Sensitivity Analysis (S)
(PR.D.3) Monte Carlo Analysis (S)
(PR.D.4) Availability of normalization factors (S)
(PR.D.5) Possibility of using a customized set of indicators (S)
(PR.D.6) Different views for different users and objectives (different modes) (P)

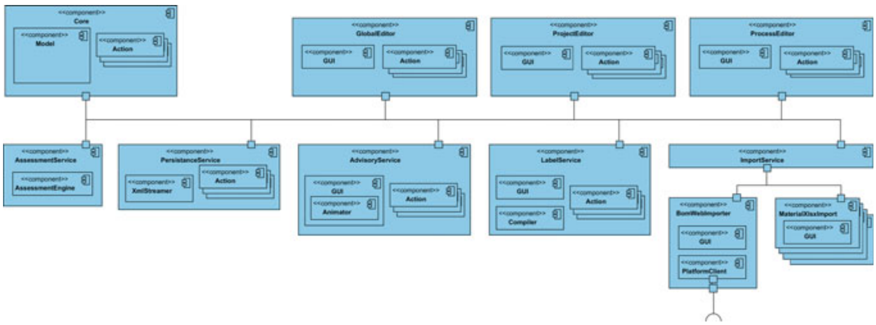


Fig. 6.1 MaGA software architecture

Project Editor. It is used ever time the assessment of a new product/service is started and project specific information (i.e. the Bill of Material or the specific set of operations) need to be edited (see Fig. 6.2). It supports the modelling of the whole PSS life cycle: design, purchase and production of sub-assemblies/components; final assembly and delivery of the PSS, the PSS middle of life (use, maintenance…) and its end of life. It is worth of notice that MaGA has the possibility to directly import information from external database, such as ECOINVENT, that provides impacts of elementary operations, thus supporting the overall calculation.

Moreover, the Project Editor provides the user with a real time calculation of the environmental indicators. Results are presented in a table-like form or with graphs and can be analysed with different level of aggregation (impact of the whole product, of a single phase or of a single components). Further, there is the possibility to compare impacts of different versions of the same product when some elements, materials or suppliers, change. Examples of impacts obtained with MaGA are shown in what follows.

Operation Editor. It directly supports the user during the design phase of PSS allowing to model the PSS lifecycle and create customized operations that are not available in the General Editor database and are not even available in existing database. Figure 6.3 shows how the Operation Editor has been used, for example, to model the 3D printing process.

The integration of MaGA with the Manutelligence platform enables the following activities (Fig. 6.4):

- import of the bill of material (BOM) from the CAD;

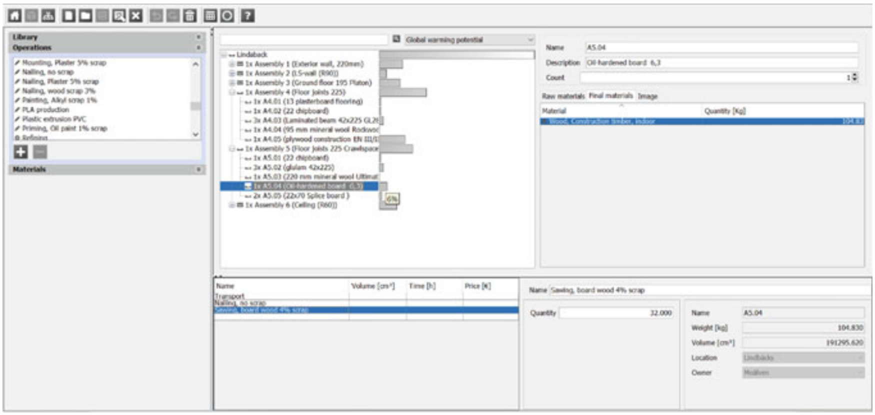


Fig. 6.2 Snapshot of the Project Editor of MaGA

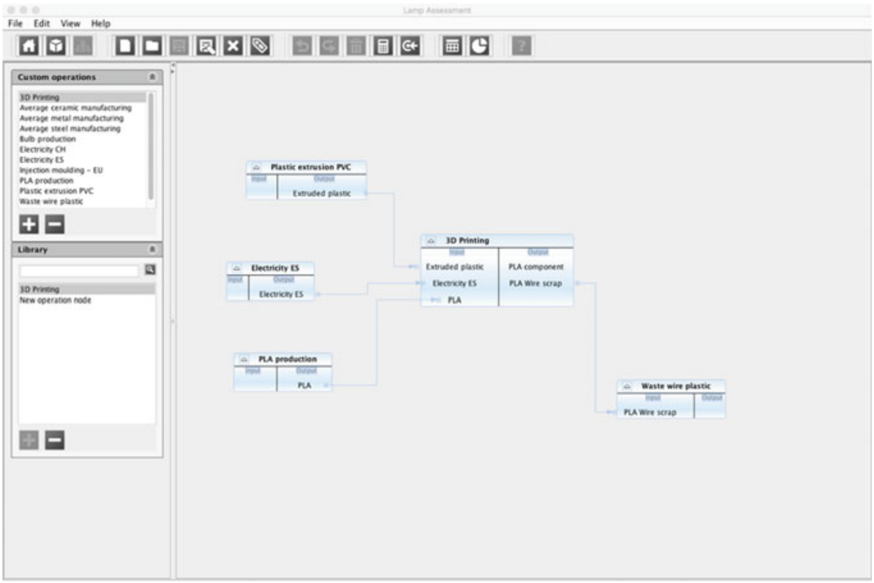


Fig. 6.3 Snapshot of the Operation Editor of MaGA showing the modelling of the 3D printing process

- export of the assessment results and possibility to carry out query of them directly in the 3D experience;
- import and export of the MaGA project files from/to the 3DExperience platform;
- import and export from/to zip files.

6.6 Testing the MaGA Tool in a FabLAB Environment

The MaGA tool has been tested by carrying out the LCA analysis for 3D printed products in the FabLAB facility based in Barcelona participating to the project. In particular, the environmental impact of a table-lamp (shown in Fig. 6.5) has been evaluated.

First, the BOM created in the CAD has been imported in MaGA and then the missing data have been inserted manually. The impacts have been calculated also

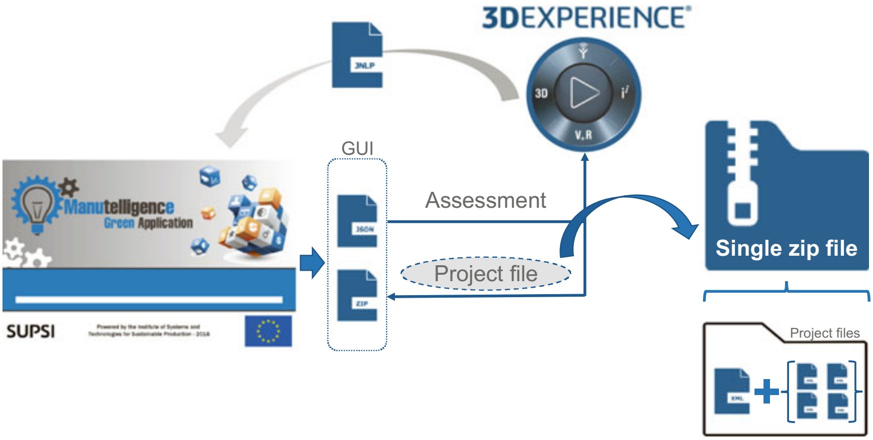


Fig. 6.4 Integration features between MaGA and the 3D Experience Testing the MaGA tool in a FabLAB environment

Fig. 6.5 The 3D printed lamp used to test the MaGA tool

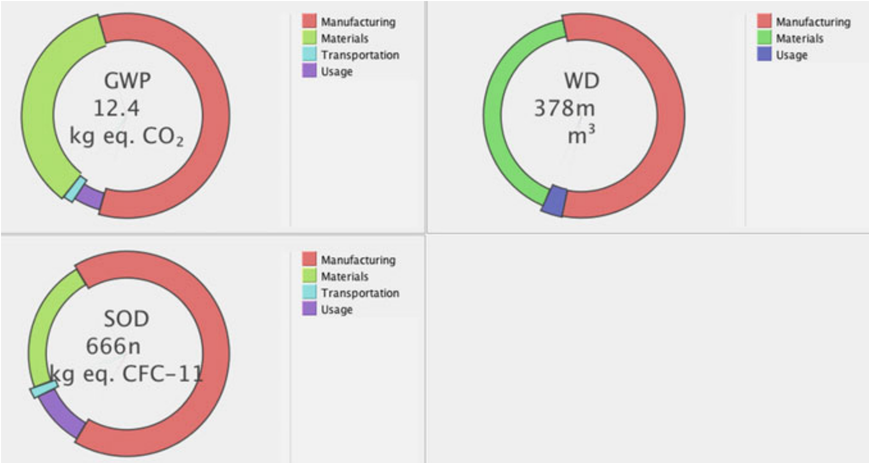
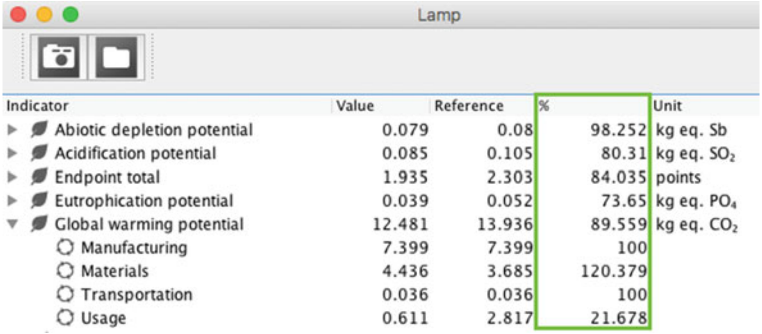


Fig. 6.6 Graphical representation of environmental impacts got with the MaGA tool when two scenarios are compares against each other

considering the use of alternative materials (PLA vs. ABS as printing material) and alternative energy mix changing the country where production is based (Spain vs. Switzerland). Figure 6.6 shows the graphical representation of the relative impact of the two alternative scenarios: Spanish mix and PLA (taken as a reference) against Swiss energy mix and ABS. Three indicators have been selected in this case out of the 11 available in MaGA, namely the Global Worming Potential (GWP), measured in eq. kg od CO_2, the Water Depletion (WD), measured in m^3, and the Stratospheric Ozone Depletion (SOD), measured in eq. kg of CFC-11, an ozone depleting gas. For each indicator, the total impact is split into the contribution of the single lifecycle phase (Manufacturing, Materials, Transportation and Usage). For example, for the GWP indicator, the graph shows that the impact on climate change generated by the production of the polymer (thus affecting the Materials phase) is higher when ABS is used, but the Usage phase impact is lowered if energy consumption is evaluated with the Swiss mix instead of the Spanish mix since nuclear power and hydroelectric power that characterize the majority of the Swiss mix have a low carbon footprint.

While the graphical representation provides an immediate idea of the impact variation of different scenarios, the tabular representation of the indicators calculated provides the precise quantification of the impacts and the corresponding percentage variation moving from the reference scenario to the alternative one. Figure 6.7 shows the results for the two-abovementioned scenarios and in the % column it reports how much an impact varies (for example, the Abiotic Depletion Potential is the 98.252% of the reference value when the ABS is used as material passing from 0.08 to 0.079 kg eq. Sb).

Since not all designers are LCA experts, in particular in a context like a FabLAB, the use of a summary label translating the impact of the assessed product into the



Lamp

Indicator	Value	Reference	%	Unit
Abiotic depletion potential	0.079	0.08	98.252	kg eq. Sb
Acidification potential	0.085	0.105	80.31	kg eq. SO_2
Endpoint total	1.935	2.303	84.035	points
Eutrophication potential	0.039	0.052	73.65	kg eq. PO_4
Global warming potential	12.481	13.936	89.559	kg eq. CO_2
Manufacturing	7.399	7.399	100	
Materials	4.436	3.685	120.379	
Transportation	0.036	0.036	100	
Usage	0.611	2.817	21.678	

Fig. 6.7 Tabular representation of results in MaGA when two scenarios are compared against each other

equivalent impact of simple examples, like km travelled by cars in order to represent the burden generated by the emissions of CO_2 (see Fig. 6.8), has been developed.

Fig. 6.8 Sustainability summary label generated by MaGA

6.7 The LCC Tool: BAL.LCPA

In order to satisfy the LCC requirements of the Manutelligence platform, the existent BAL.LCPA (Life Cycle Performance Assessment) tool has been adapted. The main economic KPI of the LCPA is the net-present value (NPV), which considers every cash flow throughout the life cycle and discounts the cash flows according to the specific point in time of their occurrence. Since the NPV accounts cash outflows and cost inflows, the flexible approach satisfies the need of determining the life cycle costs and enhances the functionality to a full investment assessment, if the user requires it. The comparable approach allows the direct investigation of different investment opportunities against each other.

A meaningful result of the LCC analysis relies on the quality of the input data. As a part of the BAL.LCPA adoption process, the tool is able to connect to the Manutelligence database in order to retrieve the required data to perform a life cycle analysis. Therefore, a dedicated interface has been developed to ease the data import, as depicted in Fig. 6.9. The data import is getting translated into a basic LCPA model, in which the different cost items and their associated cost type are assigned (Fig. 6.10). The user has the chance to modify the basic LCPA model according to his/her assessment needs, like adding an additional life cycle phase or adding additional cash flows.

In addition, the user can determine an individual cash flow development for each cash flow type. Thereby, the tool allows the generation of a cash flow timeline with a fixed annual growth rate or an individual cash flow development to reflect, for instance, an over proportional increase of maintenance costs throughout the life cycle.

In the “Global Values” section, the user can determine the NPV interest rate. Moreover, the user determines the price developments for certain global costs categories, like energy prices. BAL.LCPA also allows to consider external costs. The corresponding external cost rate per ton of harmful emissions, like CO_2, can be set in the “Global Values” as well.

The life cycle cost results are presented in tabular form as well as bar chats and curves throughout the lifecycle. Each result representation focuses on the comparison of different objects, like different design alternatives, to support the life cycle cost analysis. Each visualisation can be customised according to the needs of the user. The life cycle cost results depend on the input data as well as on the assumed circumstances of the considered lifecycle. Therefore, BAL.LCPA offers a sensitivity analysis to test the robustness of the LCC results, when certain input parameters vary. In this way, the impact of a significant energy price increase on the LCC can be tested and analysed (see sensitivity example in Fig. 6.11).

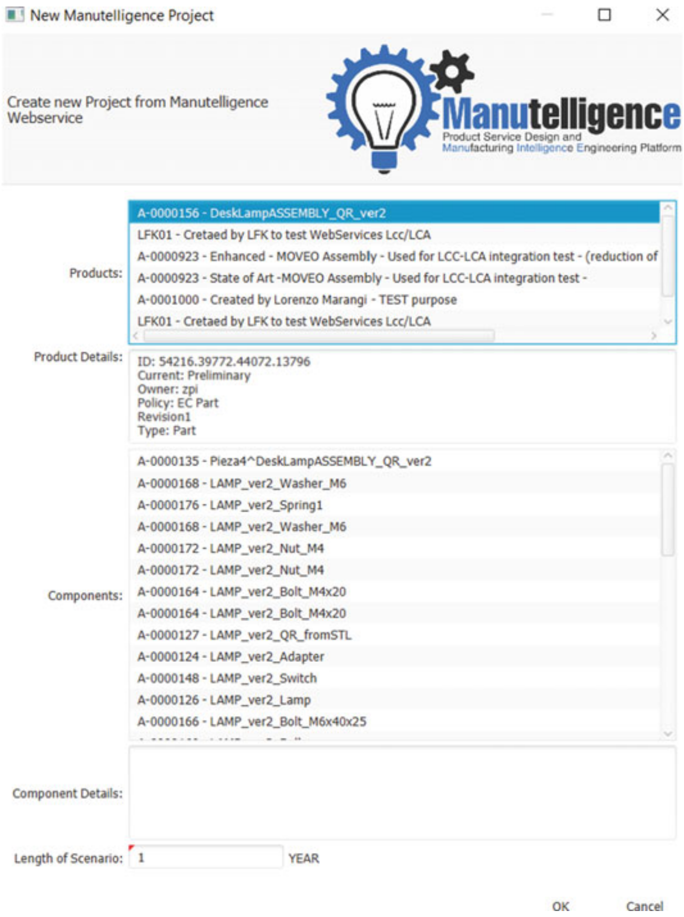


Fig. 6.9 Data import from the Manutelligence platform into BAL.LCPA

6.8 Testing the BAL.LCPA Tool in a FabLAB Environment

The described workflow to perform a LCC calculation within the Manutelligence Platform has been tested in a practical example for the FABLAB use-case: the same 3D-printed lamp used for the LCA analysis (Fig. 6.5).

To trigger the LCC analysis, the tool can be started directly from the dashboard of the Manutelligence platform. In the next step, the bill of material of the 3D-lamp stored in the Manutelligence platform, containing also life cycle cost information, is imported into BAL.LCPA. The imported data basically represents the production costs of the 3D-lamp in the beginning of life phase of its lifecycle. After the import, a simplified use-phase has been assumed to demonstrate the opportunities of a full life cycle cost analysis. Thereby, the assumed use-phase comprises a

Fig. 6.10 Life cycle model based on the imported data of the Manutelligence platform

3D-lamp equipped with a standard light bulb that operates 8 h per day and is compared to the usage of a LED light bulb with the same utilisation. The assumed lifecycle amounts to one year.

The results of the comparison between the two light bulbs mainly focus on the differences in the investment and energy costs. The 566% higher investment costs of the LED light bulb are compensated by the massively reduced energy consumption and the associated energy costs, as visualised in Fig. 6.12.

The overall LCC of the LED 3D-lamp version are 41% lower than for the standard 3D lamp, thanks to the enormous energy cost savings. Figure 6.13 depicts and compares the life cycle cost of the two 3D-lamp versions and highlights the significant life cycle cost savings. Moreover, the higher investment costs of the LED 3D-lamp are amortised in only 23 days, as an indicator for the limited economic risk of the investment.

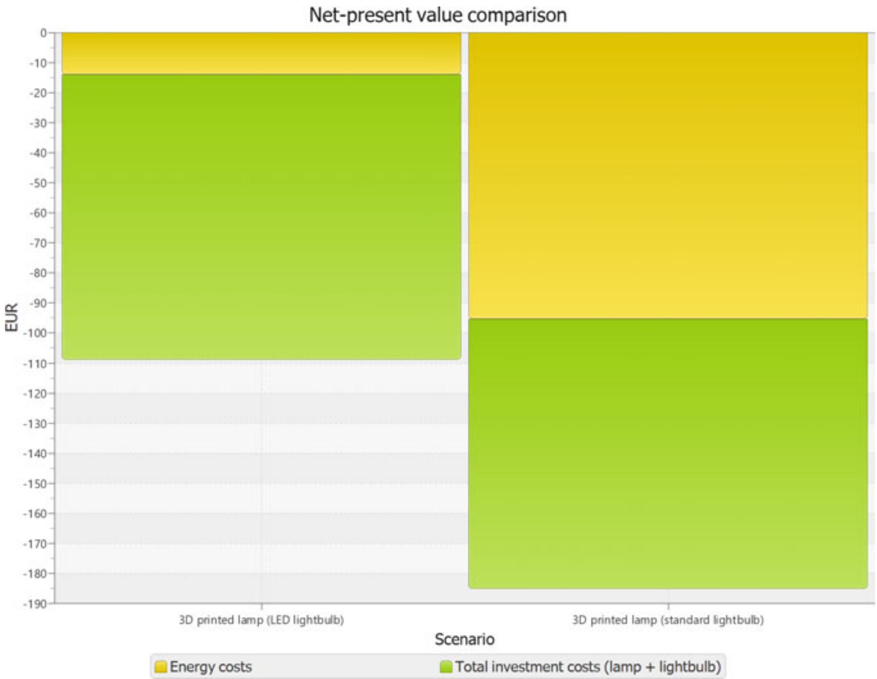


Fig. 6.11 Graphical representation of LCC results comparing alternatives scenarios

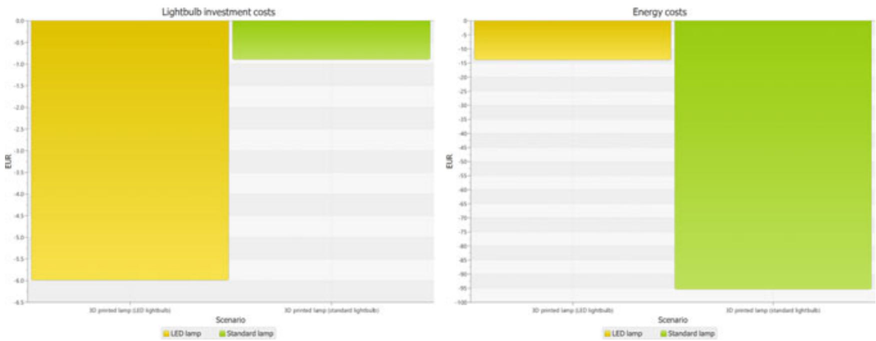


Fig. 6.12 Cost comparison of the 3D-lamp alternatives

In general, the LCPA approach can be adapted for the assessment of PSSs. Besides the relevant input data for products, like investment costs, energy costs, maintenance and other operating costs, the analysis of the service part requires input data that is more focused on, for instance, personnel costs, equipment usage to perform the service, travel costs, as well as service fees as revenues. As a result, the comparative LCPA approach enables the evaluation of different PSS concepts against each other.

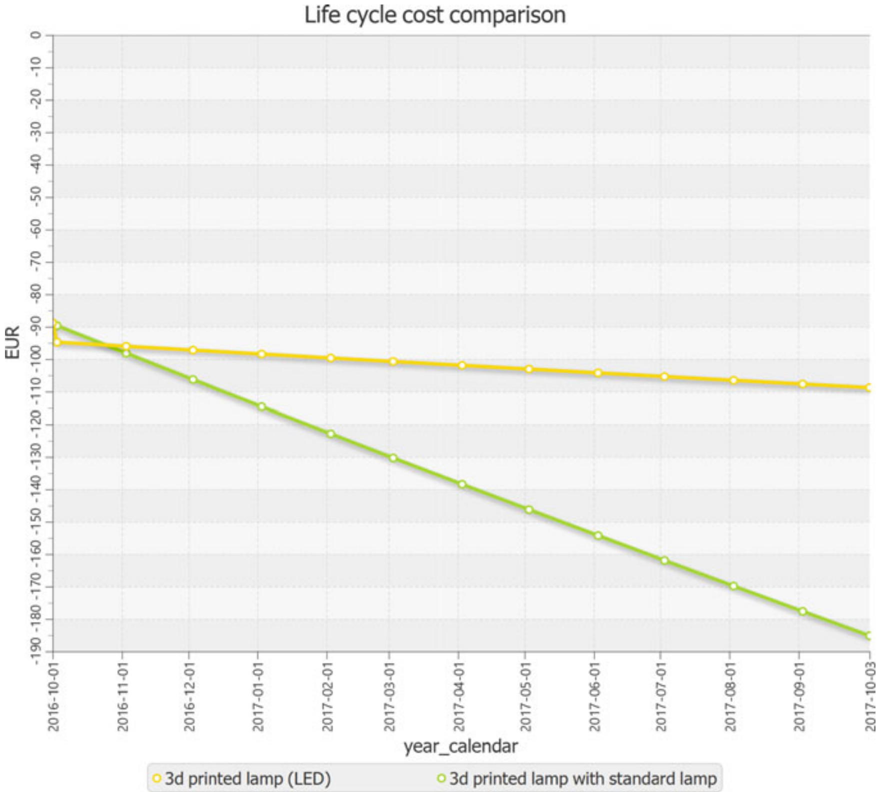


Fig. 6.13 Life cycle cost comparison of the 3D-lamp versions

6.9 Conclusion

The two tools developed for carrying out LCA and LCC analysis compliant with the Manutelligence needs have been introduced and their application to the assessment of a 3D-printed lamp has been described. The main advantage of these tools compared to commercial ones is their integration with the Manutelligence platform that allows a seamless use of the assessment results into the design process. Though any designer can benefit from the obtained results when comparing different alternatives, the assessment procedure and, in particular, the PSS modelling require some expertise in the field of LCA and LCC. Yet, both MaGA and BAL.LCPA tools pave the way for a more widespread use of LCA and LCC analysis for PSSs among practitioners.

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