A Step Forward Life Cycle Assessment to Optimize Products and Increase Company Eco-design Competencies

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Abstract. Besides the rising attention dedicated to environmental matters, there is the need to consider and make available for companies structured procedures that can guide managers and designers in the implementation of the right steps toward sustainability, considering their scope and context. The present paper presents a structured procedure able to guide managers and designers in the selection and implementation of the most effective analysis and capitalization tools and methods. Via the implementation in a company that produces armchairs, the method was revealed to be successful, also in an entity that approaches the environmental analysis topic for the first time. The enterprise was able to identify the best type of environmental assessment and the most accurate data collection strategy. The environmental analysis outlined the main product criticalities, both related to the employed materials and the management of armchairs at their End of Life (i.e. impact of polyurethane, disassemblability of wooden structure). Starting from the obtained results, design guidelines for designers and architects were defined and further detailed Life Cycle Assessments were planned.

Keywords: Eco-design · LCA · Environmental sustainability · Decision-making tool

1 Introduction

Environmental sustainability represents today an important driver in product design and numerous are the companies that are facing this thematic to improve the environmental performances of their products. However, the efficacy related to the implementation of sustainable strategies is still limited [1]. It depends on several factors, deeply investigated by recent literature. Among the most significant barriers: *i)* lacks of tools for the early design stages [2], *ii)* lack of knowledge in staff [3], *iii)* expanded scope of design object to larger systems (e.g. products with embedded intelligence) [4, 5]. To successfully manage the change, the following are the main outcomes in literature: *i)* analyze critical factors based on a structured methodological process [6], ii) managers' engagement in such topics and first phases [7, 8], iii) knowledge transfer from theory to practice [9] increasing the awareness level of companies in the field of environmental sustainability. In this context, particularly useful is the statement of Hjorth and Bagheri [10] which

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defined sustainability as an "ongoing process, needs to be regarded as part and parcel of everyday work". There is therefore the need to consider and make available for companies structured procedures that can guide managers and designers in the implementation of the right steps toward sustainability and the selection of the most effective tools and methods for their scope and context.

From this need, the present paper proposes a structured and modular method to face this problem and answer the following research questions (RQs):

RQ1: how to guide managers in the selection of methods and tools for effective implementation of environmentally sustainable strategies?

RQ2: how to support knowledge transfer and its use inside companies departments?

According to recent literature [11] the first tool category that companies can use to conduct environmental analysis, are those based on Life Cycle Assessment (LCA) methodology. Three main typologies of software for conducting quantitative environmental analyses can be identified (Table 1):

Table 1. Software for conducting quantitative environmental analysis

Typologies	Solution	Database	System boundaries	Impact categories	Open source	Integration
Software for detailed LCA	SimaPro	Ecoinvent & others; customizable	Customizable	Numerous customizable	No	No
	Gabi	Ecoinvent & others; customizable	Customizable	Numerous customizable	No	No
	Open LCA	Several open databases	Customizable	Numerous customizable	Yes	No
Simplified software based on LCA	Eco-concept	Limited	Cradle to grave	Limited and fixed	No	No
	IdematLight LCA	Limited	Not customizable	Limited and fixed	No	No
Simplified software oriented on material selection	CES Edu-pack	Granta database	Not customizable	Limited and fixed	No	Yes
	Eco-materials	Granta database	Not customizable; limited to material phase	Limited and fixed	No	No
	Idemat	Idemat, limited	Not customizable; limited to material phase	Limited and fixed	Yes	No

- Software for detailed LCA; these tools allows performing analysis with different level of completeness (according to the specific objective), presents a high degree of customization regarding input data and impact categories and transparency in database content;
- Simplified software based on LCA; these tools perform analysis using a limited and/or simplified number of input data, reducing the complexity for the user; on the contrary they limit the accuracy of results, the customization of data and the typology of impact categories. Often they are integrated with Computer Aided Design (CAD) tools to help and facilitate the product data collection (e.g. they can automatically retrieve mass, material, production processes from CAD model);
- Simplified software oriented on material selection; these tools have a focus on the environmental impacts of materials; they present a reduced number of impact categories, while present often integration with CAD tools supporting the selection and the comparison of design alternatives.

Near to LCA-oriented solutions, different methodologies and tools are emerging to guide companies toward the improvement of sustainability performance. These solutions include the simultaneous consideration of several sustainability aspects, e.g. economic and social near to environmental; in this case, they present a managerial approach, focusing on processes, products or supply chains, providing or not quantified results on a limited number of impact categories or KPIs [12–16]. Other solutions are instead oriented to the optimization of a specific aspect or product life cycle phase [17, 18] (e.g. reduce the impact of product packaging; optimize the energy efficiency, etc.). Table 2

Table 2. Solutions for sustainability

Solution	Main objective	Quantified output	Normative compliant	Open sources
Corporate sustainability software	Reporting ESG* goals	GWP emissions	No	No
CircolUP	Measure the circularity	No	No	No
Sustainability tool	Reporting health, safety and wellbeing; skills, employment and education, environment and collaboration level of projects	51 sustainability indicators	No	No
Environmental management software	Report on several sustainable indicators	GRI** indicator	GRI standard	No

* ESG = Environmental, Social, and Governance; ** GRI = Global Reporting Index

summarizes these solutions. Academic or prototype solutions are not included, due to their low applicability in mature industrial contexts.

2 Approach

When approaching the theme of sustainability, there is a wide variety of methods and tools available to carry out analysis, assess knowledge/awareness level, find paths towards sustainable realities, etc. None of them is the best; instead, each organization must choose the one that better fits its state when the decision is taken. In this context, the present work presents an approach to guide managers in the selection of methods and tools for the effective implementation of environmentally sustainable strategies (RQ1). Figure 1 shows the decision-making path to follow when identifying the best appropriate type of analysis (yellow filled boxes) and data collection strategy (green filled boxes). The picture is structured as follows: each hexagonal block is a question (V, in the following, i.e. variable) to which managers must answer, choosing from the boxes located below or above the hexagon. The hexagons are located into two lines, separated by the legend bar. All steps on the upper line (filled in grey) are related to the project/analysis characteristics; this means that vary according to the boundaries set by the context. Oppositely, the lower line contains questions regarding only the organization and the Supply Chain (SC) and these do not vary upon the type of analysis.

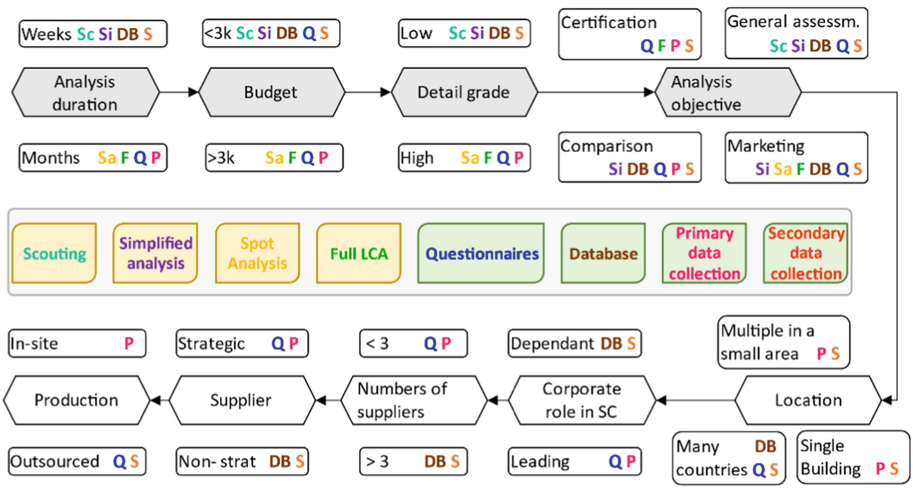

Fig. 1. Guide for an effective implementation of environmentally sustainable strategies

The nine variables to evaluate are:

- Expected duration of the analysis (V1); it can be of few weeks or longer, e.g. months.
- Budget (V2); differentiates analyses for which less or more than 3000€ are allocated;
- Expected grade of detail to achieve (V3);

- Why the analysis is performed, namely analysis objective (V4); four scopes are proposed: marketing, general internal assessment (for very first approaches to environmental matters), certification and comparison of re-designed products, processes, use phase scenarios, and/or End of Life (EoL) treatments, etc.;
- Enterprise location (V5); an organization can perform the value-adding activities in a single building, or in more than one; these can be located close to each other and in a small area or be far in distance (i.e. different countries and/or continents);
- Corporate role in SC (V6); this step distinguishes whether the organization has decision-making power towards the suppliers or it is subjected to their decisions;
- Number of suppliers (V7); this step mostly influences how the data for the environmental analysis is collected; the breakpoint is the presence of 3 suppliers involved in the analysis;
- Type of suppliers (V8); establishing whether suppliers are strategic or not can guide to the decision of collecting their data with higher or less grade of detail respectively;
- Production (V9); in-site production can allow easier primary data collection, than the case in which an organization only cares about none or few production activities.

For each option, the recurrent analysis and data collection strategies are depicted in Table 3. Nevertheless, there is not any distinct link between the project or company organization and the analysis and data collection strategies. In particular, all the factors shown in the picture can be interrelated and suggest methods and strategies according to their relation.

Table 3. Methods & Data collection strategies matrix

Variables			Duration		Budget		Detail		Objective				Location			Ro SC		Supp #		Supp. Type		Production	
			1a	1b	2a	2b	3a	3b	4a	4b	4c	4d	5a	5b	5c	6a	6b	7a	7b	8a	8b	9a	9b
V1	Weeks	1a			S		DB	S	DB	S/DB	P	DB	P/S	S/DB	S/DB	S	S	S	S	DB	S	DB	P/S
	Months	1b			Q/S	P	S	P		S/DB	P/Q	S/DB	P/S	P/S	Q/S	S	Q	Q/S	S	Q	Q/P	Q	P
V2	< 3000 €	2a	Sc	SA			DB	S	DB	DB/S	S/S	DB/S	P/S	S/DB	Q/S	DB	Q/S	Q	DB	DB	Q/S	DB	DB/S
	> 3000€	2b	SA	F				P		P/S	P		P	P	P/Q		P	P			P		P
V3	Low	3a	Sc	Si	Sc/Si	Si/SA			DB	DB/S	S	DB/S							DB		S		
	Hih	3b	SA	F/SA	SA	F			S	S/P	P	S	P	P/S	Q/S	Q	Q/P	Q/P	Q/S	S	S/P		P
V4	Marketing	4a	Si	Si/F	Si	Si/F	Si	SA					S/DB	S/DB	S/DB		Q		DB	DB	S/P		S/P
	Comparison	4b	SA	SA/F	SA	SA	SA	S/F					S/P	S/P	S/Q		Q		S		S/P	Q/S	S/P
	Certification	4c	SA	F		F		F					P	S/P	S/Q		Q	Q/P	S		S/P	Q/S	P
	Gen. Ass.	4d	Sc/Si	Si/F	Sc/Si	Si/F	Sc	Si/F					S/P	S/Q	Q/DB		Q/S	S/Q	S/DB	DB	S/Q	S/DB	P/S
V5	Single	5a	SA	SA/F	Si/SA	SA/F	Si	F	Si	SA	F	Si/SA											P
	Mul. Small area	5b	Si/SA	SA/F	Si	SA/F	Si	SA/F	Si	SA	F	Si/SA											P
	Many Countries	5c	Sc/si	SA/F	Sc/Si	SA/F	Si	SA/F	Si	SA	F	Sc/Si											
V6	Dependent	6a	SA	SA/F	SA/Si		Si																
	Leading	6b	Sc	F	Sc/SA	SA/F	Si	SA/F															
V7	< 3	7a	Si/SA	F	Si/SA	F	Si/SA	F								Si/SA	SA/F			Q/S	Q/P		
	>3	7b	Si/SA	Si/SA	Si/SA		Si/SA									Si	Si/SA			DB	Q/S		
V8	Non- str	8a	Si	Si/SA	Si		Si		Si	Si/SA	SA	Si				Si	Si/SA	Si/SA	Si				
	Strat	8b	SA	F	SA	F		F		SA/F	F					Si/SA	F	F	SA/F				
V9	Outsourced	9a	Sc/Si		Sc/Si		Si									Si/SA	F	SA/F	Si/SA	Si	SA		
	In-site	9b	SA	F	SA	F	Si/SA	F	SA	SA/F	SA/F		SA/F	SA/F	SA/Si			SA/F		SA/Si	SA/F		

To take the most advantage of the presented approach, who is willing to draft an environmental analysis should first go through the graph of Fig. 1 and answer the questions, systematically. Subsequently, by entering the Methods & Data collection strategies matrix it is possible to identify the cells that correspond to the status of the organization and the boundaries of the analysis. This must be done for each of the 9 factors (lines). Although symmetrical (9 × 9) the content of the cell is not identical above and below the diagonal. Above it, the green cells contain the outcome of the relation of factors concerning the data collection strategies, while below it the yellow cells suggest the type of analysis that best fits the combination. The content of all cells relevant to the current case must be highlighted. Once retrieved each line contains the answer to the previous questions, the resulting acronyms must be counted. Those with larger numbers reveal the type of analysis and collection strategy recommended for the current situation. In fact the method allows to identify the best (i.e. most recurrent typologies of analysis) solution. Both the Fig. 1 and Table 3 refer to the same acronyms and meaning of colored cells. The potential analysis typologies are:

- Scouting (Sc): this analysis is less detailed and aimed to discover alternatives to the current process or product;
- Simplified analysis (Si): this refers to a specific process or product but does not follow any well-stated standard;
- Spot analysis (SA): with this the level of detail rises, nevertheless it focuses on a single or few process or product aspects;
- Full LCA (F); this is the most detailed analysis, also normalized and standardized by the UNI EN ISO 14040/44.

Concerning how data can be collected, the following alternatives can be chosen:

- Database (DB): this consists in choosing statistical averages of real processes contained in databases (free or commercial); although this ensures short analysis time, the results are quite general, and may not describe accurately the specific situation;
- Secondary data collection (S); all data available in the literature belong to this category, together with all public results of previous studies (i.e. Environmental Product Declaration EPD, etc.).
- Primary data collection (P); this is undoubtedly the most detailed way to represent a process or a product, but at the same time this requires high effort, both in terms of time and resources; it consists in measuring data of what is analyzed.
- Questionnaires (Q); this is an alternative to the previous data collection strategy; by submitting questionnaires to suppliers (both back and forth the SC) peculiar data of their realities can be collected. Nevertheless, this requires time and expects a good relationship between the suppliers and the company that carries out the analysis.

As previously stated, the reason why analysis is approached may be very different and influence what comes next to the analysis. Table 4 summarizes which capitalization action can be taken, according to why and how the analysis is carried out (RQ2). The first and second columns cluster for each objective, the available analysis typology, and data collection strategy; the third column contains the actions that can originate from the analysis, then it is shown how the analysis results can be spread inside or outside the organization and possible constraints to consider and observe.

Table 4. Capitalization actions and possible constraints.

Objective	Method	Coll. Strategy	Capitalization action	Dissemination	Constraints
Marketing	Si SA F	DB Q S	• Marketing strategy • Advertising project	• External • Internal	• Budget • Timing • Competitors
General assessment	Sc Si F	DB Q P S	Redesign (process, product, material) • Professional figures selection • Training • Workshops • Standards/guidelines • More detailed analyses • Sustainability/circ. strategy	• External • Internal	• Lack of prof. roles dedicated to sustainability • Lack of partners for implementa-tion of strategies • Functional constraints • Budget • Timing • Norms and regulation
Certification	SA F	Q P S	• Certification	• External • Internal	• Quality of the analysis
Re-design comparison	SA F	Q P S	• Marketing strategy • Redesign (process, product) • Material selection • Training • Workshops • Standards definition • Guidelines definition • More detailed analyses	• External • Internal	• Lack of professional figures dedicated to sust. • Lack of partners for implement possible strategies • Functional constraints • Budget • Timing • Norms and regulation • Competitors

In particular two typologies of dissemination can happen: external or internal. The first represents strategies to communicate the analyses realized on the product to evaluate/improve its environmental performance. The second, represents how the company can capitalize the results obtained through the studies realized. All the results need to be communicated to the competences in charge of product design, from the definition of material, shape, to the identification of production processes, connection strategies and assembly procedures. Several forms can be considered, accordingly to the specific context in which they will be applied:

- Training session, to increase the competence level on environmental sustainability of designer, stimulate the consideration of environmental sustainability inside the deign process and introduce the environmental profile of the analysed company products.
- Workshop, to present and communicate the results obtained in the environmental analysis; particularly useful when analyses (simplified or detailed) are conducted by external experts to disseminate and spread the main conclusion of the studies to internal company staff; brainstorming sections can follow the workshop to identify possible solution strategies;
- Check list and procedure, to guide in a simple way the choice realized during the design phase. Accordingly to the results obtained in the analysis, the company can define a list of avoided or recommended materials, processes, assembly strategies and procedures; particularly useful to guide the design phase when no or minimal competences on environmental sustainability are detained by internal staff in charge of the design phase.
- Guideline, to summarize the results creating a direct correlation with product/process characteristics; particularly useful when the analysis are internally conducted; the competences and the awareness of product characteristics allows the company to produce specific material able to translate the results in suggestion for product design. Guidelines can be derived for all the product which present similar characteristics and support their environmental sustainable design.

3 Case Study

To validate the proposed method, its implementation was realized in an Italian company, a leader in the design and production of leather armchairs and sofas. The company faces for the first time the environmental question and the main objective is to realize recognition of the environmental performances of different models of its iconic product: the leather armchairs. The following variables of the proposed method were defined for the specific case:

- V1 &V2: Not urgency in terms of duration and limited budget for the analysis;
- V3 & V4: Low detail level for the outcomes, because it's the first time the company faces the environmental issue;
- V5, V6 & V7: Production located in a single site and leading role in a restricted supply chain (both for suppliers' number and location, mostly in the same district);
- V8 &V9: Presence of not strategic suppliers and in-site production.

According to the method, the suggestion for the company is to realize a full attributional A-LCA, based on secondary data. The full A-LCA will allow the company to derive quantitative results for the product life cycle phases, responding to the main objective; the not need for a high level of details directs toward the use of secondary data.

The company received the support of researchers to apply both the method and realize the LCA, due to the absence of internal competencies in terms of environmental sustainability. The A-LCA was therefore performed, according to the reference normative.

Object. Compare the environmental impact of three different models of leather armchairs to derive first considerations of their environmental performances.

Functional Unit and Reference Flows. According to the objective, the functional unit is to "ensure the comfortable seat of one person for 15 years". The lifetime of 15 years was fixed according to the Product Category Rules [19] for this type of product. The reference flow referring to the functional unit considers three different leather armchairs, realized with three different design principles:

- A1 - Traditional design: the structure was realized in hardwood, with a traditional springing system (steel springs bound together with jute string), a classic shape pudding in vegetable hair; it has about 8 m^2 of leather for a total weight of about 70 kg.
- A2 - Modern design: the structure was realized with the use of hardwood, plywood and steel, with a traditional springing system (steel springs bound together with jute string), and a modern shape pudding with polyurethane (PU) foam; it has about 5,5 m^2 of leather for a total weight of about 44 kg.
- A3 - Innovative design: a steel structure (optimized in mass), with an innovative springing system based on textile belts connected with the structure by a simple locking system; the cover and the seatback are padded by polyurethane foam. It has about 4,4 m^2 of leather for a total weight of about 40 kg.

System Boundaries, Databases and Tool. All the product life cycle phases were included in the analysis, from raw material extraction to dismantling processes.

The software SimaPro v9 was chosen with implemented Ecoinvent3.6 database. As a concern, the life cycle phase related to leather production, due to the absence of secondary data from the EcoInvent DB, the results of an EPD realized by a company's leather supplier were used. The leather supplier has developed in these last years a lot of EPDs to certify the environmental performances of their leathers; the specific typology of leather used in the analyzed armchairs was also certified.

All the other materials used were modeled using secondary data, as the pre-production processes. Concerning the internal processes, data on resource consumption were derived directly from the company site by a data flow management system implemented in the plant and then modeled by secondary data.

The transport of materials and the semi-finished products were modeled deriving the location of suppliers and accordingly to the means used. The transport of finished products to consumers was modeled accordingly to the related PCR: a national transport (with a 16–32 ton lorry) with a travel road distance of 1000 km.

The use phase was modeled assuming a cleaning of the product every six months using a very mild soap diluted with water and a reusable cloth, which is not included in the analysis. The EoL phase was modeled according to the following scenario: 50% in mass of the armchairs directed to the landfill as municipal waste; 50% in mass of the armchairs directed to incineration; 90% in mass of the carton box packaging directed to the recycling centre; 10% in mass of the carton box packaging directed to landfill (to include the inefficiency of the recycling process). Cut-off in input data was applied for all these components with a mass minor than 20 g, which correspond to 0.05% of the minor mass for armchairs (e.g. labels).

Impact Categories and Related Methods. The use of an EPD for the impact of leather production forces the selection of the same impact categories and methods. Consequently, the method (EPD 2018 v1.01) and the indicators considered are those used in the EPD: acidification (AP)[kg SO2 eq.], eutrophication (EP) [kg PO4 eq.], global warming (GWP) [kgCO2eq.], photochemical oxidation (POP) [kg NMVOC], abiotic depletion, elements (ADP) [kg Sb eq.], abiotic depletion, fossil fuels (ADPF) [MJ], water scarcity (WS) [m3 water eq.].

Results. At first, the trend of the LCA performed for the three reference products is obtained and shown in Fig. 2.

From the results, the use phase was excluded, because it presents a negligible impact (less than 0.01% in all the impact categories). Results show a predominance of the material phase impact for all the products and the leather covers over 70% of the total impact for all the impact categories, except ADP. This is the reason why product A1, which has the highest weight of leather, presents the higher impact, followed by A2, and A3. Different the results for the ADP category, where the presence of steel in spring and structure determines the highest impact for A2. The optimized geometry (and consequently the reduced mass) of the structure, makes the impact of A3 very low on this category, near to A1, where only steel springs are present. Other interesting results were derived for structures and pudding systems, which are the second elements most impactful after the leather. A hardwood structure and a natural pudding material determine (Table 5) the less environmental impacts (A1), in comparison with plywood, steel and PU foam (in A2 and A3).

On the contrary, based on its design the A3 has a higher potential to be disassembled, due to the use of simple and easy to disassemble liaison, with consequently better performances at the EoL if reuse/recycling strategies could be applied. However, in the present analysis, alternative EoL strategies are not considered.

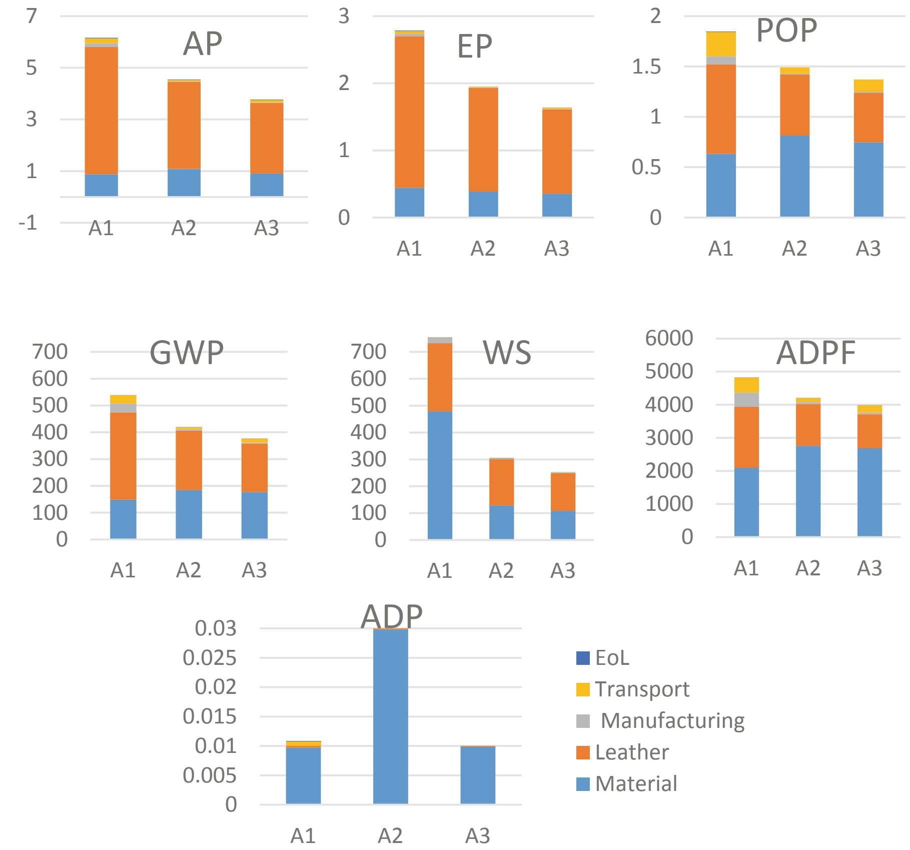

Fig. 2. Life cycle impact results for the armchairs

Table 5. Impact comparison for structures

Product	AP	EP	POP	GWP	WF	ADF	ADP
A1	2.1E−2	8.7E−2	1.8E−1	1.9E−1	3.7E+1	3.6E+2	0.1E−2
A2	8.8E−1	3.2E−1	6.6E−1	6.6E−1	7.7E+1	2.1E+3	3.0E−2
A3	8.5E−1	3.4E−1	7.0E−1	7.0E−1	9.4E+1	2.5E+3	1.4E−2

4 Discussion

Through the application to the industrial case study, the proposed structured and modular method results successfully in supporting managers in the selection of methods and tools for effective implementation of environmentally sustainable strategies (RQ1) and in using them to transfer the acquired knowledge in a convenient way for the organizations (RQ2).

In this case, the suggestion to perform a full A-LCA guides the company to derive a complete overview of the product environmental burden. At the same time, the method answers to the low level of details required, by proposing the use of secondary data. The specific context of leather production, forces the use of the EPD results, simplifying the entire analysis.

The application of the method and the related implementation of analysis involve one designer and one manager, directly and respectively involved in the LCA analysis (form the objective definition to the inventory phase), with the support of one environmental expert, and in the interpretation and capitalization phase. The method allows to fulfill the constraints both in terms of budget, internal resources and outputs obtained.

The results of the environmental analysis are used to train designers and architects in two workshops, to increase their competencies on the matter. The training material was structured in guidelines, which show and compare:

- The actual solution and its environmental impact on several impact categories;
- The reason (design solutions) related to the obtained results;
- Alternative design strategies (already implemented in other models/products or new) and their impacts, focusing on improvement strategies.

The company also planned the next steps. Detailed analysis of EoL strategies for the leather and design strategies to favor them (e.g. avoid permanent connections); comparison of impacts for innovative leathers, produced by applying more sustainable and efficient tannery processes.

5 Conclusion

The present work presented a structured procedure that in the first-place guides managers and designers in the implementation of the right steps toward sustainability and the selection of the most effective tools and methods for their scope and context. Subsequently, it suggests alternatives to capitalize on the gained knowledge. Its implementation in a case study of a company that produces armchairs and was approaching the environmental analysis topic for the first time allowed to identify the best type of environmental assessment and the most accurate data collection strategy. The results reported higher environmental impacts related to leather. Then other critical aspects are the PU used in the armchairs and the steel structure, compared to lower impacts of frames made of hardwood and natural padding. Followed-up identified actions regarding guidelines for both designers and architects and more-detailed LCA that can include detail for other EoL strategies.

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