INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED23
24-28 JULY 2023, BORDEAUX, FRANCE

A DYNAMIC APPROACH FOR LIFE CYCLE ASSESSMENT. THE CASE OF DOMESTIC REFRIGERATORS

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ABSTRACT

The Life Cycle Assessment is a well-stated methodology whose application has recently spread over a multitude of sectors. Thus the need for very accurate and reliable analysis. The present work investigates how to achieve reliable and faithful results while still maintaining a micro-systemic approach and how to handle the evolution of the real cases through commercial solutions available. The works present an innovative dynamic approach that aims at filling the discrepancy between the attributional Life Cycle Assessment which is focused on the product at the point to appear short-sighted and isolated from the surrounding evolving system and the consequential, which is willing to include the consequences of the evolution of the surrounding system, with increased complexity. The approach is applied to the case of a domestic refrigerator; the application reveals a discrepancy of 16% between the results of the dynamic and attributional analysis and registered doubled environmental impacts than the consequential, carried out with the support of commercial datasets. The approach respects the 5 main criteria for methods in environmental systems analysis, namely feasibility, accuracy, easiness in communication, inspiration, robustness.

Keywords: Research methodologies and methods, Sustainability, Product modelling / models, Ecodesign

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Cite this article: Cappelletti, F., Rossi, M., Germani, M. (2023) ‘A Dynamic Approach for Life Cycle Assessment. The Case of Domestic Refrigerators’, in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.14

1 INTRODUCTION

The Life Cycle Assessment (LCA) is one of the most recognized and applied methodologies to quantify the environmental burden of products and services objectively. Multiple tools support the application of the methodology. However, the tools' sensibility and the choice of temporal and geographical system boundaries may limit a faithful representation of the analyzed case. LCA allows the quantification of potential environmental impacts of a product's life cycle: from raw material acquisition via production and use phases to waste management (Ekvall, 2019). Following UNI EN ISO 14040-44 four are the main steps of the LCA: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. However, the stakeholders the analysis is provided to, the chosen system boundaries and the quality of selected data, i.e., practitioners' choices, may return different LCA results for the same product (Scrucca et al., 2020). In addition to practitioner choices, a variety of LCA approaches is available in the literature; the most known and discussed in the literature are Attributional LCA (ALCA) and Consequential LCA (CLCA) (Guinée et al., 2018; Almeida et al., 2020). According to Finnveden and Potting (2014), ALCA is defined by its focus on describing environmentally relevant physical flows to and from a life cycle and its subsystems. It is thus reasonable to affirm that the CLCA is a macro-systemic approach, while the classical ALCA is generally applied at a micro-system level (Herbert et al., 2016). Putting the concept into practice implies an extension of the system boundaries. Due to the stronger and stronger role LCA is acquiring in the decision-making processes and governmental regulations, the present paper proposes the following research objective: the development of an approach that combines the linearity of the ALCA with the effects of time on certain product parameters: product aging and evolution of energy grid mix.

The approach aims at evaluating the effects of changes that directly influence the flows included in the analysis of a given Functional Unit (FU). These variable quantities can either concern evolution of the analyzed system (i.e., product aging) or the evolution of external factors (i.e., the evolution of the energy grid mix over time).

1.1 ALCA and CLA

CLCA is defined by its aim to describe how several flows will change in response to possible decisions. More in detail, UNEP's Global Guidance Principles for LCA Databases (2011) defines CLCA as a modeling approach that provides information on the environmental burdens that occur, directly or indirectly, because of a decision, generally represented by changes in demand. This definition paves the way to a much broader perspective, where processes and flows that influence the product lifecycle are considered and the geo-political and socio-economical plots have their role in the analysis. A second practice implication of the definition of CLCA is that the additivity-restricted mathematical model (linearity), typical of ALCA, is more likely replaced by free mathematical modeling (non-linearity) (Schaubroeck et al., 2021). There are also linear models suitable for CLCA; however, those roughly approximate the analyzed case. One example is the consequential datasets of the Ecoinvent 3 (or superior) database. Their main limitation is their static nature: even if they are willing to describe a future condition, they do not contemplate different conditions according to a chosen timeframe. The discrepancy between ALCA and CLCA emerges from the literature: the first is focused on the product at the point to appear short-sighted and isolated from the surrounding evolving system; the latter is willing to include the evolution's consequences of the surrounding system in the FU lifecycle, at the cost of much-increased complex analysis. The trend is to employ CLCA when dealing with long-term analyses: referring to the construction sector, Almeida et al. (2020) retrieved 13 out of 25 works (10 with no information) referring to a long-term time horizon. Life Cycle Thinking (LCT) and LCA are essential for informing decisions comprehensively and holistically in both business and policy contexts (Reale et al., 2017). LCT, LCA, Life Cycle Costing (LCC), Product Environmental Footprint (PEF) have faced a remarkable evolution in policies and communications: their implementation increased tenfold in the last three decades. (Sala et al. 2021). Life cycle-based policymaking in the future must also address the means to implement policies (incentives, legislative obligations and thresholds) based on LCA results (Sonnemann et al., 2018). Several indexes are now based on LCA results, such as the conjoint economic-environmental indicator proposed by Fregonara et al. (2017) and the Recyclability Benefit Rate (Huysman et al., 2015).

Concerning more limited realities, the LCA is acquiring a more decisive role in the product and process design too: design strategies are tested, and environmental benefits are highlighted thanks to LCA analysis (Cor and Zwolinski, 2014; Subramanian et al., 2023), design strategies are defined according to the obtained results (Rossi et al., 2023) or to evaluate products in the last phase of design (Tchertchian et al., 2009). Consequently, the LCA results need to be assessed in a very accurate way, otherwise, governmental and industrial decision-making processes would rely on an unstable basis. For example, in the construction sector, Säynäjoki et al. (2017) outlined that the literature consists of highly varying results between the studies, even for similar analyzed units. The authors add that this makes it doubtful if LCA can produce reliable data for supporting policymaking.

2 APPROACH

The methodological approach started from the actual need to include in an ALCA, referred to long-term horizon, some principles of CLCA, as the consideration of parameters' evolution over time. Figure 1 illustrates the steps followed to define the product system dynamic approach proposed in this paper.

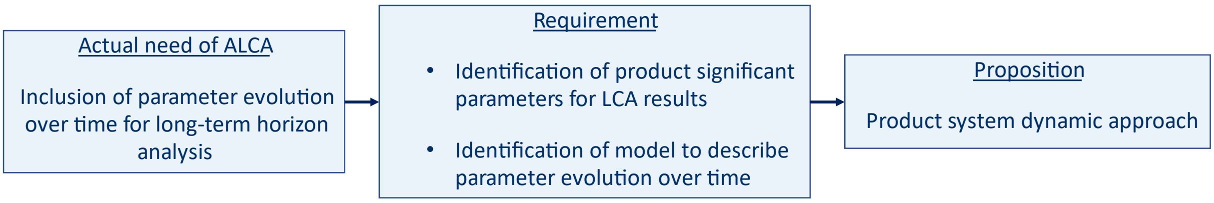


Figure 1. Methodological flow

The following describes the innovative, simplified approach proposed to obtain environmental quantities retrieved by applying an ALCA and introducing the variability over time of some parameters. ,. The simplification is the not widening through the macro-perspective level.

In Figure 2, the proposed framework is clearly placed between the CLCA and the traditional ALCA. The inner box on the left represents the product system under analysis, as it is conceived in the ALCA: it includes all the potential inputs and outputs from the system. The input can derive from the technosphere (i.e., electricity, semi-finished products) or nature (i.e., raw materials, water); the output can be different kinds of emission, by-products or waste flows.

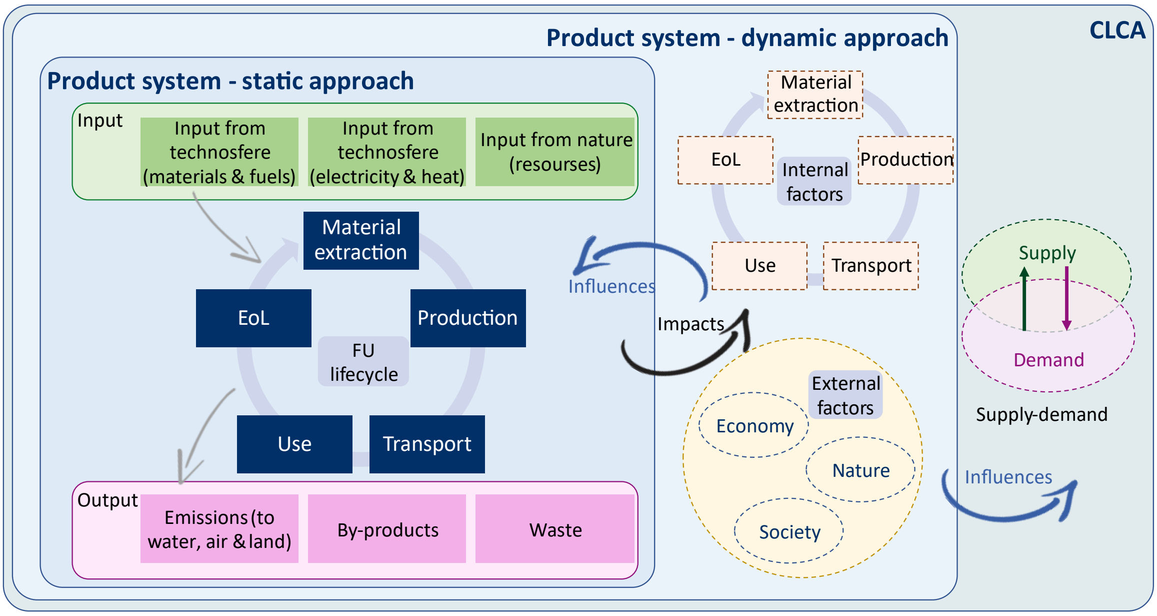


Figure 2. Novel dynamic approach for LCA and comparison with the static and consequential frameworks, inspired by Hackenhaar et al. (2022).

In the ALCA, which represents a static approach, the quantities flowing from the input through and out of the lifecycle are fixed over time. As it is common to carry out ALCA being supported by commercial tools and databases (Hischier et al., 2020; Xiao et al., 2016) the results show a fixed picture: even though the lifetime extends over multiple years, the environmental impacts considered the information collected and elaborating watching a single moment in the present or relative past (i.e., when the analysis is carried out). Comparative scenarios may be discussed and analyzed; however, this does not involve deploying the FU lifecycle's detail. In the CLCA the perspective (box on the right in Figure 2) is much wider and considers a market equilibrium that is influenced by the market of the product system analyzed in the static approach. However, this might be different from the moment when the ALCA is carried out; in fact, the CLCA can describe situations that happen far in time and also take into account factors that are far from being directly related to the flows of the analyzed FU (i.e., the introduction of innovative technology that makes the current FU obsolete and not used anymore in a certain timeframe).

In the center of Figure 2, the intermediate box describes how the static approach may be enlarged so that the flows that take part in the lifecycle are well described. The approach is dynamic as it considers how the flows change over the lifecycle, but the focus is still exclusively on the product. The FU is the center of the analysis, however, the change of flows over the duration of the lifecycle is contemplated. This may also lead to looking after the surrounding system, but only for what directly concerns the flows of the static approach. It follows that the intrinsic behaviour of the product system is investigated as external factors. As suggested for the well-established ALCA, the impact estimation results should be accompanied by an estimation of its imprecision (Srinivas and Amaresh, 2007), as the introduction of evolving parameters may increase the uncertainty of results. Table 1 summarizes the main innovative aspects of the proposed dynamic approach concerning the traditional ALCA properties.

Table 1. Overview of the covered aspects and how they are differently addressed by ALCA, dynamic approach, adapted from Schaubroeck et al. (2021)

Feature	**ALCA**	**Dynamic approach**
Basic concept	Share of the global impact linked with a product life cycle.	
Relationships and boundaries of the product system, of which the impact is assessed	All processes have interlinked relationships based on physical, energy and service flows. The product system can be infinite and propagated amount as well.	
		Internal and external factors are subjected to the time factor.
The aspect of time	Absolutely: processes can be considered in past, present or future. Relatively: considers processes also before product finalization, i.e., relative past consideration.	
		Relatively: considers processes that directly influence the lifecycle also after the product finalization, i.e., relatively future consideration
Specify product system and its impact separately or in scenarios	Separately: share of human/industrial system and its global impact. Scenario: the difference between the world and a hypothetical world without a product system and its impact.	
Constraints in mathematical modeling due to a theoretical concept	Restricted by additivity (e.g., guaranteed by linearity), necessitating a validity check or consideration of the extrapolated world.	
How multifunctionality is dealt with	Needs to be done through partitioning processes, both for LCI and, in the case of environmental multi-input processes, for LCIA. An alternative is system expansion.	
Marginal versus average considerations in the assessment	Amount-specific effects advised, but in practice average or marginal impact effects are possible and should be consistently considered.	
	Interlinked suppliers need to be considered. Average or marginal product consideration is possible.	*Interlinked suppliers must be considered. Average or marginal product consideration is advised*
Complete framing of environmental impact assessment, coupled with the product system	Environmental impact assessment is purely consequential (except for inventory indicators) but limited by additivity, e.g., necessitating partitioning. This all, necessitates a separate consideration from the product system, due to these other rules.	

The merged cells stand for common aspects of the static and dynamic approach. ALCA's typical features also belong to the dynamic approach; however, the last one involves additional aspects. The main distinguishing factor is time. Multiples are the reasons why a flow may change over time. In the proposed dynamic approach, this change is considered. The linearity is maintained; nevertheless, flows are in progress.

3 CASE STUDY

This section presents an example of the implementation of the above-mentioned approach. The dynamic approach has been applied to the case of a domestic refrigerator. Figure 3 shows the system boundaries of the product system. All flows directly affecting the product system are considered and modeled per the dynamic approach features.

The FU is to store and maintain fresh food in a household's context for a lifetime of 16 years; food is stored in a refrigerator of 193 l of volume at +4°C and a freezer of 62 l of volume at -18° C. The refrigerator considered is a single-door freestanding refrigerator and weighs 63 kg. According to the energy label, the yearly annual consumption is 214 kWh. The environmental impact assessment was supported by Simapro version 9.1 equipped with the Ecoinvent v3.6 commercial database; ReCiPe 2016 Midpoint (H) V1.04 / World (2010) method and the Aware method were chosen to obtain environmental burden for the Climate change [kg CO2 eq], Mineral resource scarcity (MRS) [kg Cu eq] and Water Use (WU) [m3] respectively. The additional factors responsible for changes over time, further described in paragraphs 3.1 and 3.2, are introduced through a linear approach: instead of considering the annual energy consumption fixed over time, this is set to change. As time passes, insulation performance degrades; simultaneously, the energy grid mix varies in percentage of renewable sources.

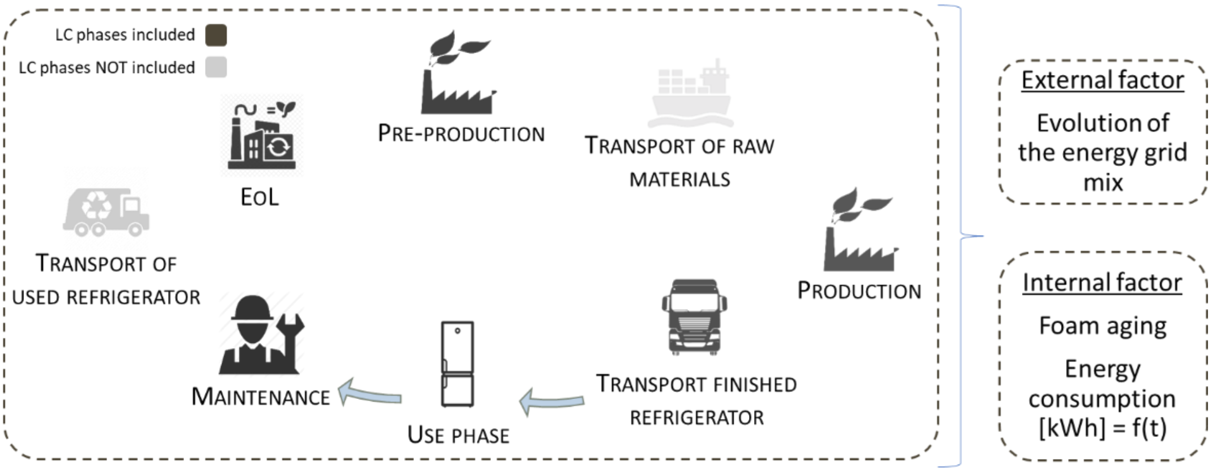


Figure 3. Dynamic approach's product system boundaries

3.1 Internal factors

A domestic refrigerator is subjected to aging along the product's useful time. The literature provides studies focused on the worsening behavior of materials and components over time; however, few correlate this to the resulting environmental impacts. Hossieny et al. (2019) evaluate potential energy savings by applying two types of liners to the foam insulation for refrigerators; the one with low gas permeability can retard or stop the diffusion of air and blowing agents. Verma and Singh (2020) review studies comparing the insulation made via Vacuum Insulating Panels (VIPs) and foams, employing different materials for their constructions and assessing the reduction of energy consumption.

Recently Paul et al. (2022) developed an aging model based on accurate electrical energy consumption data. The annual efficiency deterioration function, proposed by Johnson (2000), is frequently used to describe the annual increase rate of energy consumption of household refrigerating appliances (Kim et al., 2006). In the present work, the aging trend proposed by Cappelletti et al. (2022) has been considered (Eq. 1):

$$\Delta E = \begin{cases} r - \left(\frac{20 - t}{20}\right)^{c} & if\ t \leq 5 \\ r - \left(\frac{20 - 5}{20}\right)^{c} & if\ t > 5 \end{cases} \quad (1)$$

Where:

- ΔE is the increase/reduction of energy consumption in one year;
- r is the initial aging rate;
- t is the year of use;
- c is a factor related to the blowing agent (2.5 for all blowing agents except for HFC-245fa).

3.2 External factor

The energy transition toward decarbonization, especially in European countries, is already underway. The implementation of various policies and instruments, together with modern technologies, has strongly promoted the use of renewable energy (Borozan, 2022). As international agreements and policies may set very challenging goals, several are the available estimations on how the energy mix will vary. In the present work, the evolution of the European energy grid mix (Table 2) is modeled assuming it changes every 5 years between 2020 and 2040, per the EU reference scenario 2016 (Capros et al., 2016). The European dataset for low-voltage electricity has been modified accordingly.

Table 2. Evolution of European energy grid mix and unitary impacts

Year	**2020**	**2025**	**2030**	**2035**
Source				
Renewable [%]	36,5	40,3	44	50
Wind [%]	14	16	18	21,5
Solar [%]	5	6	7	9
Bioenergy [%]	5,5	6,8	8	8,5
Hydro [%]	12	11,5	11	11
Gaseous fuels [%]	18	18,5	19	20
Hard coal & Lignite [%]	21,5	18	14,5	9,8
Oil [%]	1	0,8	0,5	0,3
Nuclear [%]	23	22,5	22	20
Unitary impacts				
Climate Change [kgCO2eq]	0,367	0,332	0,297	0,267
Water use [m3]	0,00362	0,00332	0,00303	0,00281
Mineral Resource Scarcity [KgCuq]	0,000863	0,000874	0,000885	0,000987

3.3 Results

Figure 4 shows the LCA results obtained by applying the dynamic approach. The refrigerator is supposed to be used between 2020 and 2036. The use phase is the most impacting one for the Climate Change and the Water use (more than 70% and more than 45% of overall impacts, respectively).

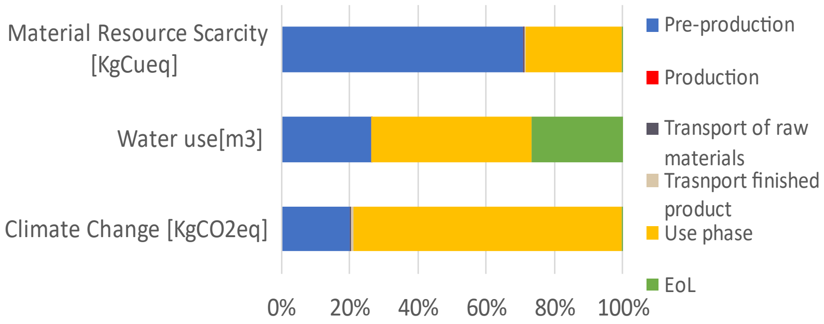
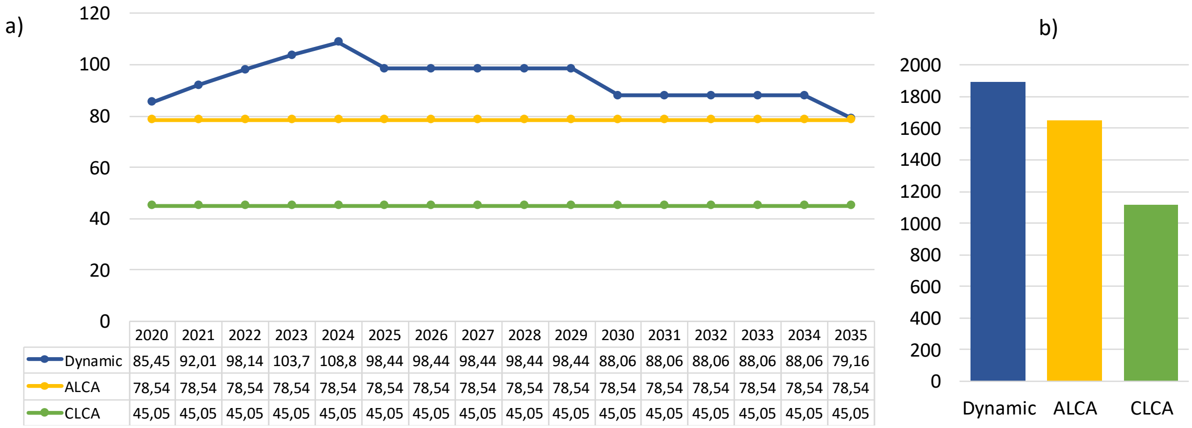


Figure 4. LCA results, dynamic approach

Figure 5a compares the results for the three approaches of LCA (ALCA, CLCA and the dynamic approach proposed) for the same product and FU. As far as the CLCA is concerned, the datasets "Conseq, U" provided in the Ecoinvent DB were used. The results are shown for the Climate Change indicator.

The yellow line represents the results of a traditional ALCA. All the input and output flows are considered static. The green line is obtained by using the environmental impact calculation, the Conseq. Datasets provided in Ecoinvent DB. The blue line is obtained by applying the proposed dynamic approach, i.e., including in the analysis the variability over time of refrigerator insulating performance and the evolution of the energy grid mix.

The result clearly shows how the Dynamic approach, even maintaining a linear approach and relative simplicity can better represent the real behaviour of the product under analysis. Impact of the use phase at first increases due to the aging of the internal components (from the first to the 5th year); later on, from the 6th year the environmental impacts remain stable, as the product aging is concerned, but the energy grid mix is expected to be obtained from more sustainable sources. As a consequence, the overall use phase impact decreases for successive years. As the use phase is the most impacting, the trend is also visible in the overall impacts. (Figure 5b).



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Dynamic	85,45	92,01	98,14	103,7	108,8	98,44	98,44	98,44	98,44	98,44	88,06	88,06	88,06	88,06	88,06	79,16
ALCA	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54	78,54
CLCA	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05	45,05

Figure 5. Use phases (a) and lifecycle environmental impacts (b) comparisons between dynamic approach, ALCA and CLCA for climate change indicator [kgCO2eq].

4 DISCUSSION

The current work presents a dynamic approach for LCA, maintaining the linear mathematical approach of the ALCA and the focus on the system. Compared to the static approach of the ALCA it considers more specifically the flows that directly enter or exit the analyzed product system. In particular, it suggests including the variation over time of such flows to better capture the real product's behaviour. This is a crucial aspect, especially for product interested by long-term analysis, due to a long lifetime. What happen in the analysis of these products (Almeida et al., 2020) is to fix at the analysis time some flows and considering them fixed over their long lifetime. The proposed approach supports companies in the environmental quantification of their products, considering a real scenario in terms of parameters modification over time.

Ekvall (2019) identifies 5 main criteria for methods in environmental systems analysis; the above-presented approach observes them all. The proposed dynamic approach:

- Is feasible: it can be easily applied and repeated. It uses commercial datasets, even though those are partially adjusted; however, it respects the feasibility criteria as the results and conclusions it generates can be generalized and reused in multiple decision situations.
- Is accurate as the case study proves that it generates comprehensive and accurate results.
- Generates results that are easy to communicate and understand, at least present the same level of understanding of the well-known and established static ALCA, since they both share the same way to present results.
- Is inspiring because it stimulates a representation of product system aligned with its actual behaviour.
- Is robust as multiple users can repeat it and the same results are retrieved.

The approach aims to exploit the potentialities of commercial datasets, making it applicable to a wider range of stakeholders, designers who apply lifecycle thinking above all. The relation with the time is the aspect that mostly differs between the static ALCA and the dynamic approach and between the last one and the CLCA:

- Compared to the ALCA, it has a view over the relative future. Even if a static approach is stated that the functional unit consists of actions carried out for a time frame (i.e., months, years), the analysis of the future flows is made as a reproduction of static photography of the present (at least present and relative past). The dynamic approach instead allocates each flow to the specific moment they occur.
- While CLCA focuses on a potential future equilibrium (that may rely on future decisions, CLCA only propagates the effects in the relative future of the decision (Schaubroeck, 2021) dependent on the choices of a multitude of stakeholders. The dynamic approach relies on already taken decisions that affect the flow of the product system.

As practitioners and environmental experts conventionally use LCA during the modelling phase to explore environmental impacts under various boundary conditions and methodical assumptions, the dynamic approach is powerful in leading designers toward consistent choices (Weber et al., 2015).

According to the results obtained by applying the innovative approach to the case of a domestic refrigerator, the dynamic approach registers variable emissions over the years, as they depend on the decreasing performances of the refrigerator (foam aging) and the lower burden due to the consumption of electricity. The static ALCA approach expects 16% lower environmental impacts for the use phase, while the CLCA returns half the environmental impacts than the dynamic approach. It can be stated that the dynamic approach has a definition of one year for energy consumption: its trend is calculated for each year and the user can contemplate either effect of flows that enter the product system and derive from the surrounding environment and the changing of flows strictly related to the product. The databases for consequential analysis currently available on the market do not differentiate between any time in the relative far future. Moreover, they aim to estimate only the effects on a macro-scale, with validity in all fields. The wide validity necessarily brings along a higher uncertainty.

5 CONCLUSION

The present paper proposes an approach that combines the linearity of the ALCA with the effects of time on specific product parameters: product aging and the evolution of the energy grid mix. The proposed dynamic approach has been applied to the case of a domestic refrigerator. Two parameters change during the time considered in the functional unit: the annual energy consumption due to insulation degradation performance and the energy grid mix, which varies in terms of renewable source rate. The static approach (ALCA) expects 16% lower environmental impacts for the use phase, while the CLCA returns half the environmental impacts than the dynamic proposed approach. The approach overcomes the actual limit related to LCA realized on a long-term perspective, providing a simplified approach to incorporate the variation over time of some product parameters. A limitation is actually related to the time perspective of the approach, i.e., to make assumptions on the future; it can be done based on forecasting or backcasting (as discussed in Broman and Ròbert, 2017 and Dreborg, 1996) and represent a possible critical aspect for LCA practitioners.

Future works will include applying the proposed approach to other products to further validate and optimize it.

ACKNOWLEDGMENTS

The authors would like to thank Electrolux Italia S.p.A. for providing the data sets for this work and giving helpful information on their utilization.

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