Original Article

Materials and Actor Network Theory, a way to flesh out Life Cycle Assessment?

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Abstract. LCA (Life Cycle Assessment) is an established method to measure the economic, social and environmental impact of a good or a service, with particular attention to its value chain or its life cycle. However, it is heavily biased in favor of environmental issues, actually environmental burdens or stressors: the economic dimension is only tackled in LCC (Life Cycle Costing) and the social in a restricted approach called SLCA (Social Life Cycle Assessment). The idea of developing a more ambitious and wider encompassing method has been elusive, except when MFA (Material Flow Analysis) was proposed as an alternative and a competing discipline, but, eventually, the two methods proposed separate but complementary views of the world. In order to reach beyond LCA and its present weaknesses, it would be necessary to base the new approach on concepts embedded in SSH (Social Sciences and Humanities) rather than in STEM (Science Technology Engineering Mathematics) disciplines. This article describes the process under way to move in that direction. In a first step, a panorama will be drawn of the strengths and weaknesses of LCA and of LCT (Life Cycle Thinking). The analysis will focus on LCA weaknesses. On the way to extending LCA into SSH territory, an approach developed by Knowledge and Innovation, Italy, and called SCM (Social Cycle of Materials) looks at materials from a historical perspective. It shows how various resolutions (closures) are proposed to answer issues raised at different times, as a result of society’s demand. The method proposes a distinctly new way of looking at materials cycles. The connection between this new approach and the traditional LCA cycle remains, however, to be done. In this paper, we propose to use ANT (Actor Network Theory), a concept developed by Bruno Latour, Michel Callon and Madeleine Akrich, to propose reconstructing the concept of LCA. The approach ambitions to list the various “stakeholders” related to materials in their value chain, like what is done in LCA, but also across long time, like what is done in SCM, and to include all actors in the sense of ANT, which means inanimate objects as well as elements of the geosphere and of the biosphere. It is expected to gain some insight into moving away from the indicator-based style of LCA. Clearly, we are still exploring and, most probably, we may end up complementing traditional LCA, most certainly not replacing it.

Keywords: LCA / materials / SSH / SCOT / ANT

Résumé. Matériaux et théorie de l’acteur-réseau, une clé pour renouveler l’analyse de cycle de vie?. L’ACV (analyse de cycle de vie) est une méthode largement utilisée pour mesurer l’impact économique, social et environnemental d’un bien ou d’un service, qui s’intéresse en particulier à sa chaîne de valeur ou son cycle de vie. Cependant, la méthode est surtout focalisée sur les indicateurs environnementaux: la dimension économique n’est prise en compte que dans le CCV (coût du cycle de vie) et la dimension sociale que dans l’ACV social (ACV-S). L’idée de développer une méthode plus ambitieuse ne s’est guère concrétisée jusqu’ici, sauf en ce qui concerne l’AFM (analyse des flux de matière) proposée comme une alternative à l’ACV, mais qui s’en est révélée plus complémentaire que concurrente. Pour dépasser l’ACV et surmonter ses faiblesses, il serait nécessaire d’ancrer la nouvelle approche dans les SHS (sciences humaines et sociales) plutôt que dans les STIM (science, techniques, ingénierie, mathématiques). Cet article décrit le processus en cours pour aller dans cette direction. Dans une première étape, on dessinera un panorama des forces et des faiblesses de l’ACV et, plus

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1 Introduction

The present article is an attempt to question the present status of LCA (Life Cycle Assessment) and to explore whether methods stemming from SSH (Social Sciences and Humanities) rather than from STEM (Science Technology Engineering Mathematics) can deconstruct and then reconstruct LCA methodology in depth. More specifically, we want to explore what ANT (Actor Network Theory) can offer to try and progress in this direction. An introduction and a bibliography about ANT can be found in [1,2]. As a matter of fact, the present article is a companion paper to reference [2]. This kind of questioning has been a recurring feature of the SAM (Society & Materials) conferences, since their onset [3].

The article targets a broad audience of material experts knowledgeable in LCA and of SSH scientists interested in science and technology and on the possibility to go beyond STS (Science and Technology Studies), SCOT (Social Construction of Technology) and history of technologies, i.e. by merging approaches as we would like to do in developing an ANT-compliant LCA.

2 What is Life Cycle Assessment?

Let us start by a definition of LCA, organized as a series of keywords: the FU (Functional Unit), the life-cycle, inputs and outputs (materials, elements, energy, exergy), value chain, upstream and downstream, foreground and background, indicators, midpoint and endpoint indicators, numbers, LCA database, LCI, LCA practioners, LCA users (researchers, marketing, as a tool to feed with competing materials, as a tool to ascertain GW issues, etc.), technologists, environmentalists, economists, cradle, grave, circularity, time and temporality, system boundaries and locality issues, environmental impacts, negative externalities, mass and energy balances, attributional LCA, consequential LCA, sustainability (environment, society, economy), social LCA or S-LCA, LCC, Life Cycle Thinking (LCT), etc. The above constitutes a very compact summary of LCA methodology, as it is set in stone in ISO standards and analyzed in countless books and articles [4].

3 A critical view of LCA based on ANT

LCA is thus based on a network, the value-chain: it is a flow diagram, that goes from entry to exit, e.g. from cradle to grave. MFA uses the same diagram, and therefore the same network, but in a rather different way [5]. The LCA network is organized in a series of flows and stocks, although the distinction between flows and stock is not as precisely analyzed as in MFA. It goes through a series of economic actors (mining, transport, production of basic materials, manufacturing of industrial goods or artifacts, consumption, discard and end of life, sometimes recycling or, more generally, circularity). It focuses on a particular temporality, the life (or lifetime or life span or duration). The network is a simple one, a chain, with connections to the rest of the world shown as inputs and outputs. The network can be represented as a diagram with very many numbers attached to it at each step along the chain. Like in the expression “functional unit”, the various steps of the chain are described in terms of their function: (mineral) extraction, material production, manufacturing, transport, consumption, discard, end of life, etc. Thus, they provide an abstract and rather theoretical description of the network.

Note that many possibly important issues were left aside from the methodology, when LCA was initially developed:

- for example, most people involved in the value chain are not explicitly mentioned, neither the miner nor the manufacturing plant worker, nor the truck driver, etc. who had an important physical contact with the FU during its lifetime;
- locality is neglected, for example air emissions all along the value chain are added together even though they may occur in South America, at the mine, in Japan in the steel mills and automotive plants and in the US where the car is driven until its end of life, when it is sent to the
shredder—and thus the emissions do not physically add up to contribute to air pollution, often a local phenomenon;
- the functional unit is a given. How the FU was designed, where, when, by whom, are issues that are never touched upon: this took place prior to the use of the functional unit and, thus, is out of scope. This means that, even though LCA is grounded in the temporality of its lifetime: it does not consider any longer time, such as historical time;
- there are details of the LCA, which are systematically mentioned (like who carried it out (the so-called practitioner), what software what used to collect and assemble the data, what database was used to complement the data directly measured for the particular study), but they are most often taken for granted with only a limited critical analysis of their relevance: for example, while the practitioner has to use the presently available data base, the “owners” of that database are working on a new edition of it, which would probably modify the LCA results, at the margin most of the time, but not always. Now, of course, if a critical review is undertaken, then it is the duty of the reviewer to point out any issue in this area.

An LCA constitutes a translation, in the sense of Michel Serres [6], i.e. it relates incommensurable elements and aggregates them together to produce various layers of indicators, simple (primary), mid-point and end-point indicators.

The LCA study is the result of a controversy, in the sense that all the facts that it takes on board stem from an investigation carried out by the practitioners in contact and interchange with the various actors of the chain, including with its direct client, the sponsor of the study. This essential part of the work that leads to the final LCA report is hardly exposed in details, as it is encapsuled in the model embedded in the LCA software. It usually lacks depth, probably because the process of producing an LCA is sufficiently complex and time- (and money-) consuming, that there is not much room left for this kind of epistemological reflexivity.

The LCA practitioner strives to give equal treatment to the various actors in the value chain: this has indeed been a key feature of LCA, which produces value-chain data in a system/network where, prior to the introduction of LCA methodology, each step used to ignore the neighboring steps in the chain and did not exchange detailed data with them freely [4]. In this sense, it applies a principle of symmetry among the elements of the chain.

What has been done above is to screen LCA by passing it through the grid of ANT methodology. It shows that, indeed, LCA follows a similar approach as ANT, but also that it misses on important points, one may even say on very important ones.

The criticism of LCA, as outlined above, points to the following facts:
- LCA is a methodology, anchored in very precise quantitative variables, referring to science and technology (STEM disciplines) rather than to a softer, more qualitative analyses such as what SSH disciplines could contribute. Note also the trend to continue adding more indicators, based on complex methodologies, such as toxicity methods [7], etc. The outcome is a complex set of hard numbers organized in rigid sets of indicators, which need to be summarized by using mid-point or end-point indicators to become intelligible to an educated lay person, such as the sponsor of the LCA study. Important dimensions are ignored, regarding actors in particular. This is somewhat paradoxical, as LCA is a technology that claims to belong to a sustainable development perspective and thus ought to tackle the social. S-LCA has been developed to remedy this shortcoming, but not quite satisfactorily as it focuses on the social regulations related to working conditions rather than on social matters captured in a larger context;
- an LCA is enclosed within the boundaries of the system that it describes. This is on the one hand necessary to make the job of producing an actual LCA, based on mass and energy balances, achievable. On the other hand, it is overly rigid and leads to ad hoc concepts like foreground and background data, which blur important aspects of the context and, in effect, freeze that context without too much discussion;
- there is an obvious limitation regarding space, what we called locality above. The argument is that LCA focuses on emissions of the value chain seen as an overall indicator of pollution, rather than a description of the physical phenomena where pollutants do or do not add up, depending of where they are emitted. Thus, LCA “does not really care” about space, as it describes activities scattered around the (world) map and the environmental burdens that this creates in an aggregated way;
- another limitation is that of time or temporality. Time is the finite, limited time of the life cycle time: there is no past and no future in LCA, just an indefinite present. Moreover, background information is frozen in the present. To overcome this shortcoming, it would be necessary to develop a dynamic LCA [4], although the attempts made in that direction have stalled until now.

4 Beyond LCA? Material Flow Analysis and Social Cycle of Materials (SCM)?

There have been various solutions to overcome LCA’s shortcomings.

First of all, LCA itself has evolved over time and has added new features to fix some of its shortcomings:
- the locality issues were tackled by the regionalization of impacts1 [8];
- the time issues have been handled by developing prospective LCA [9–11] and dynamic LCA [4];
- data collection has gone beyond strict STEM approaches and the usage of classical LCA databases by engaging stakeholders in the process of measuring, collecting and estimating data [12];

1 This, however, is not a panacea in itself, as a regional or world assemblage of local impacts would be needed in many cases. See, for example, the important question, today, of electric vehicles (EV): today, they are, for example, carbon-lean in Norway or in France, where the electricity grid is mostly carbon-lean, but not, in Germany or in Saudi Arabia.
new impact domains are continuously being added to LCA methodology, e.g. human toxicity, ecotoxicity and health issues [13,14], biodiversity [15–17], sobriety [18], etc. LCA, as a consequence, keeps complexifying.

These are plug-in solutions, meant to complement LCA standard methodology. They do not question LCA at the deepest level of its methodology or of its epistemological foundations. On the other hand, they increase the complexity of LCA and it is not clear if the “mythical practioner”, who is in charge of producing an LCA, can keep up with all these additions to the methodology. The consequence of this is that many of these new features take time to become mainstream and may even stay unnoticed or too complex to bother with.

MFA has probably been the most sophisticated challenge to LCA. It removes its temporal limitations and pushes its system boundaries further away into the economic value chain realm. On the other hand, as the price to pay, it forgets about the environment, which does not have as fine a granularity as in LCA [5]. An important feature of MFA is that it is open towards the future, thus that it is fit for strategic and foresight studies. At the end of the day, MFA and LCA present differing but complementary worldviews of the issue at hand: LCA helps extend the view to a broad set of environmental data and MFA helps look at a too complex landscape!

SCM (Social Cycle of Materials) [19] has been another attempt at addressing LCA shortcomings. Contrary to MFA, which was developed by STEM researchers and engineers, SCM was imagined by SSH scientists, more particularly sociologists from Knowledge and Innovation, Italy. They started from a qualitative analysis and focused on the issues of design and innovation, two related and connected concepts. They showed how various resolutions (“closures”) are proposed successively to answer issues raised at different instants in time, as a result of society’s demand. Materials, thus, emerge as an exercise in design, after a long process of proposing series of solutions to a problem until a closure is met by consensus among actors [20]. SCM is connected to STS (Science and Technology Studies), SCOT (Social Construction of Technology) and Social Constructivism.

While LCA is a well-established methodology, which is widely used and continues to grow, SCM is still under construction: it is not yet competing with LCA, if it ever will. Its major strength is that it answers ontological questions related to materials and to artefacts made of materials: where do they come from? How did they end up being what they are, which detailed design process did they go through? It also emphasizes the SCM cycle as a step in a series of successive steps, such as those embedded in the theory of product innovation in marketing theory (S-curves, following up on one another). This means that, probably, a new step, a further generation of products is in the making and, therefore, SCM opens up its temporality to the future, as in prospective, foresight or strategic planning: one can say that it fleshes up temporality as compared to LCA.

MFA and SCM reformulate the basic question that LCA tries to answer. However, they also produce a steady stream of numerical data and thus remain definitely part of the STEM worldview!

5 Introducing Actor Network Theory...

We want now to introduce ANT and explore how it can be used as a tool to broaden and redefine LCA as it is practiced today. It can also help think about materials, as developed in [2].

This is ambitious, as it is a first attempt, and it is also risky, as we do not know how close we can reasonably get to our “dream target”, as we are moving forward one step at a time.

For the sake of simplicity, we have implicitly assumed in what follows that the FU unit is physical, therefore that LCA is focused on goods, objects, products artefacts, whereas it can also deal with a service or a Product-Service System (PSM). This is due to the fact that we are interested in materials and that the connection to materials is more complex to describe and analyze if the FU is a service, for example.

5.1 Human and non-human actants

One of the strong features of ANT is that the network at its core is a hybrid network, comprising human actors and also non-human ones: this may mean animals, trees, but also inanimate objects. It may also include concepts, discourses. ANT calls these actors, actants, to make it clear that they are not simply people. Moreover, ANT is not so much, not at all actually, concerned with how well the approach matches scientific truth, but would rather make sure that all actants are considered in a symmetrical way, which goes further than the LCA practioner’s concern mentioned earlier.

Let us now try to reexamine the LCA network, based on ANT recommendations.

The network is composed of actants that we can categorize as: (1) human actors, including human organizations, (2) non-human actants and (3) discourses. Here is a tentative list of all categories of actants:

- human actants: the LCA study practitioner, the client/sponsor of the study, his colleagues, co-workers and boss, the LCA community, the anti-LCA or not LCA community (such as the industrial ecology community supporting MFA), the client of the direct LCA client (why did he order the study? To whom is he going to market it?), the journal to which the practitioner will publish its work in appropriate language and content, the various actors along the value chain, e.g. miner, steel producer, car manufacturer, waste handler, etc.), distinguishing between the blue-collar actors on the factory floor and the white-collar “engineers” with whom the practitioner interacts to understand the various processes in the value chain, model them and flesh them

\(^2\) A personal example of a development, which did not fly, is that of Dynamical LCA.
out with relevant data, the various companies involved, including competitors, therefore also the markets on which the various products at each step of the value chain are exchanged, along with volume and process, actors involved in the logistic and transport of various stages of the FU, regulators, equipment manufacturers who provide the machines, process reactors, etc. involved in the value chain, the trade union representatives, the medical doctors in charge of occupational health, the regulators in charge of public health, local people subjected to various emissions and therefore to health risks and NGOs, following these issues, the design department and researchers who contributed to the creation of the FU, other stakeholders, mankind as defined by sustainable development, including future generations, physically-challenged people, and so on... Note that human actants are often called “stakeholders” in a particular context;

- non-human actants: the materials that the FU is made of, the physical FU itself, the raw materials used to produce the FU plus the energy “consumed”, various kinds of waste and their fate, end-of-life materials, air emissions including GHG, the loss of biodiversity, water emissions, soil emissions, air, water or soil pollution, second-hand parts used to repair the FU during its life-in-use, paper and the timber from the trees, the forests and the plantations from which it originates, the computer on which the practitioner produces its LCI and LCA analysis and redacts his report, the communication tools used to exchange among human actors, sensors to collect data along the value chain, the money paid to the practitioner for his work, etc. There are many more;

- discourse actants: LCA software (several competing ones), LCA database (several competing ones), the loss of biodiversity, the language used in the exchanges, in the report (local language, native language, international language like English), the reporting of results to the various stakeholders, public communication, scientific communication, commercial information to the client, advertising and communication, fake news?, literacy vs. orality, the measurements needed for building the LCI, the results themselves, e.g. GHG emissions and contribution to global warming, the vision of the FU by its producers and its users, various theoretical discourses such as the economy of conventions, social constructivism, ethical and inspirational narratives such as sustainability, circularity, the ISO 14040 families of standards that define LCA, the organization of production of raw materials, goods, artifacts in general, including the colonial, neocolonial or postcolonial issues that it raises today and the corresponding geopolitical games that they evoke from stakeholders (human actants), etc.

The list of human actors is much easier to make than that of non-human ones: it includes the LCA practitioner and its various human networks related to the study, but maybe also his family. Non-human actants (NHA) include the FU, each of the materials of which it is made, the input (raw materials) and output into or out of the life cycle (product, emissions to the environment, waste), plus the equipment used to push the FU through its life cycle (e.g. the blast furnace in the steel mill) and to carry out the study, the things exchanged in the course of the work (data on USB keys, emails, files transferred, notes, reports, money exchanged in payment of the practitioner’s services, company gifts), the watch used by the practitioner to measure time, etc. etc.

The next question is to understand how these actants interact with each other, one to one, or as groups or sets, to create the network and make it dynamic. It would be necessary to engage in field work conducted collectively, which would consist in drawing all the possible connections and then to carry out the necessary research (through direct interaction (conversations, interviews) with the actors, allies as well as detractors) to investigate which are indeed operative, important and relevant.

A few examples:

- the MFA community sets itself explicitly apart from the LCA community: this is a typical dissenting voice that contributes to the various controversies relative to LCA;

- the practitioner provides a service to his client in the form of the LCA study: as such, it is an economic and commercial endeavor, where time is of the essence in order to fit the duration of the study within budgetary limits. This obliges the practitioner to comply with a strict and constrained agenda to produce the LCA study and to restrict its contribution in terms of new and more innovative approaches than traditional LCA within the scope of the study;

- the scope of the environmental burdens (e.g. Global Warming, Eutrophication, Atmospheric Ozone Depletion, etc.) taken on board in the study are defined initially between practitioner and client, within the framework of standard LCA-making. However, this may not be sufficient, if, for example, a particular burden was to take precedence, of its own strength (agency) or because other actors, like citizen engaged in citizen science for example, would insist on using some other list of burdens;

- etc.

We propose to move forwards by drawing the following list of major non-human actants based on experience, intuition and many discussions carried out in the recent past.

We posit that Global Warming (GW, CO2) and Loss of Biodiversity (LoB, i.e. the fact that the biosphere is rapidly “shrinking”) are the main and foremost non-human actants in the exercise, along with the material (s) that the FU is made of. This is simply acknowledging what the scientific community, but also governments, NGOs and individuals have now been saying for a while – although without using the non-human actant paradigm. We keep away from discussing whether we ought to consider Global Warming, as in the LCA GW indicator, or, more generally, Climate...
Change: this would carry us too far astray from the points we focus on in this article, but the question is certainly a valid one.

Thus, we have three major non-human actants, CO$_2$, the biosphere and materials (like steel for example).

The human actors may appear insignificant compared to the carbon dioxide accumulated in the atmosphere, a formidable level in spite of its “small concentration” of 415 ppm in 2021. However, humanity has not yet played all its cards as roadmaps are being drawn and implemented to limit warming to less than 2°C: there is still a symmetry between humans and non-humans here, even if the humans in the LCA network are but a small fraction of humanity: it is a matter of collective action against individual action.

The biosphere is also clearly an actant, which we can visualize as nature resisting society (anthroposphere, mankind) and its negative influence.

Note that the language of ANT used here replaces what would have been simply a metaphor, in more common narratives: however, it is a more powerful statement to say that CO$_2$ is an actant, as these non-human actants are explicitly described as independent and sometimes opposing and resisting humans and human action. The usual language of ANT says that they have agency$^6$.

Materials also have agency$^2$. This very important property of material is not often mentioned in material science textbooks, which originate from the STEM community, as the concept of agency is clearly born of the SSH community and of the particular school of ANT. The agency of materials is a specific property that explains, for example, why materials are both old and new, perennial and deeply innovative, or why they play such a core role in the way society has been functioning, since the age of stone until the age of silicon$^7$. A further discussion related to materials is to accommodate the dichotomic ideas that materials are social constructs while, at the same time, they have agency: it is done in$^2$.

If we accept to single out the 3 main non-human actants in the LCA system mentioned above, we are led to a series of conclusions regarding LCA:

- the other LCA indicators beyond GW and LoB are secondary and should be given less importance than these two. One may even propose a simple LCA focusing only on GW and LoB, which would be simpler to produce, to understand and to communicate about; by letting most of the indicators in the background, this would resolve one of the shortcomings of traditional LCA, its complexity;
- the centrality of materials also suggest that they should always be used in pairs within an LCA. Thus, an LCA version incorporating material A should always be compared to a version incorporating material B. This is often the case already, in LCA methodology;
- regarding GW, it calls into question the use of time in LCA and the distinction between foreground and background, thus on the fine internal boundaries that LCA commonly introduces inside its system. We try to explain this fairly complex argument in a simple way. GW has been translated in Europe (Green Deal) and in many other parts of the world, by a Net-Zero emission target by 2050 – which means that GHG emissions ought to be cut by 55% in 2030 and 100% in 2050. This applies to the FU, i.e. to the foreground of the LCA study, but also to the rest of the context, thus to the background data as well. 2030 and 2050 are close dates and probably belong to the time extension of the life cycle in many LCA studies. This means that any LCA to be carried out from now on should, in principle, take on board a decay of emissions as specified by the EU Green Deal$^2$ both in the foreground and in the background data. This is a tremendous change for practitioners, for which they probably do not have all the necessary tools at their disposal. LCA should thus become prospective and dynamic, a challenging agenda of methodological transformation, but one that we feel as both urgent and necessary;
- one may ask further if CO$_2$ will remain a major actant after 2050 and what happens then of LCA, if it has been reduced to GW and LoB. Some time will pass before this question becomes crucial, but, probably beyond 2050, some of the lesser non-human actants of today should come to the fore. Air emissions and their connection with human toxicity (i.e. human health) and ecosystem toxicity should maybe be emphasized. But this a broad question, which will need to be explored more in depth in future developments: indeed, what about issues related to (green) energy consumption, material criticity, various pollutions beyond air pollution, water use, etc.?$^2$

5.2 Translation

The next area to examine is the status of translation in LCA.

LCA may seem rather weak in this area, because it is based on a procedural, fairly rigid methodology set in stone in the ISO 14040 standard series, which “defines” it$^8$. However, this is oversimplifying what really happens in an LCA, as the issues of temporality and of circularity are not squarely defined by the standards as they stand today.

$^6$ agentivité in French, “état de ce qui est agentif”.

$^7$ Time periods in Prehistory have been organized in the 19th century. Thus, the ages of stones were followed by the ages of copper, of bronze and of iron. This terminology was meant to identify a major influence of materials in the history of mankind. School children, who learned these ages by rote, may have ended up believing that historical evolution was driven by the advent of a series of new materials. However, no Prehistorian believes this anymore, as they explain, based on abundant field work carried out in many excavations, that materials are social constructs and that they follow rather than precede the emergence of new ages. Recently, our technological times were called jestingly the age of silicon, an expression that is now dated.

$^8$ Defining an approach with a scientific ambition by a standard, as LCA does, is uncommon. This gives it a rigidity, constrains it and is actually meant to give guarantees to clients from management circles. Standards are usually required to define technologies, which points to the fact that LCA is a technology rather than a scientific discipline. Indeed, science has its own means to define itself and to structure its own story-telling, which are quite different from standards in the ISO style.
They leave room to many options and variants. From a practical standpoint, the practitioner has to select the options he will implement in a particular study to take time and circularity on board, and this indeed is a translation in the sense of Michel Serres and of the ANT approach. Each LCA study, therefore, will follow a particular translation, custom-designed to match the needs of the study being carried out. In the future, hopefully very soon, the way that translation will be carried out should change significantly, as Net-Zero strategies will need to be taken on board, as explained under Section 5.1.

At this point, there are several ways to think about that translation. The most straightforward solution is to keep the set of primary indicators as they are today, therefore a long and complex list. However, the way to carry out the translation ought to be reexamined to introduce a true, active level of controversy in the process, not simply feed the input data into a model, for example an Excel sheet, like in a rigid algorithm. This discussion will be continued in the next Section 5.3.

We might also decide to simplify the set of primary indicators, based on a reduced set of main actants (Sect. 5.1), and thus to focus on GW and LoB and drop the rest of them. The fact that GW and LoB are proceeding quickly and will generate changes in both foreground and background data. Keeping up with this evolution adds another layer of complexity to a reduced number of indicators. The translation ought to change its ways and means, as it has to take on board a fully dynamic LCA framework.

Any solution between these two extremes is in principle possible. It is clear that the latter simplified LCA scheme cannot extend beyond 2050, when Net-Zero solutions are supposed to be applied everywhere: at that point in time, GW ceases to be driven by human emissions and proceeds towards a limited temperature increase (2 °C?) by the end of the century, on its own inertia. It is probably important by then to check that the GW indicator remains at Net-Zero. But more indicators, representing critical issues, at that time horizon, ought to have been added by then: water [22], raw materials [23], air pollution [24], at the very least, and issues that will emerge between now and 2050.

5.3 Controversy

The controversy in LCA is the analysis of the results of the LCIA (Life Cycle Impact Assessment), which is the content of the report delivered by the practitioner after peer reviewing, or the analysis developed in the scientific articles published about the study, and, before that, the reporting of the findings and of the analysis to the clients of the study. It involves, as it is, only two sets of protagonists, the practitioner and its client, backed by the comments from the peer reviewers, who do not attend the presentation meeting: it is formally in agreement with the ISO standard, but it seems extremely restricted. The actants in the value chain are not physical present either, except as particular data sets used to calculate the indicators. This falls short of the ambition of LCA, which is to bridge the gap of information between various links in the value chain of the FU: the controversy did take place in the past, but only at the level of data collection and of the constitution of LCA databases.

To conform to ANT methodology, the controversy should be conducted with all actants at a later stage, i.e. that of analyzing the complete output of the study. Thus, when an LCA study commissioned by material A and comparing the FU based on two competitive materials, A and B, material B ought to participate in the controversy. Of course, getting so many players (actants) involved is certainly not straightforward and whether this makes it possible to reach a closure, the ultimate goal of the study (an ANT-compliant LCA study), is not certain and it probably would involve original approaches and methodologies compared to what a practitioner does today.

An extra layer of complexity is due to the fact that non-human actants should also be invited into the controversy. Of course, we have already taken care of that by selecting the indicators that the study focuses on, like Global Warming or Climate Change. But they should also be invited in the development of the controversy: again, a non-obvious requirement, as there is no ready-made solution for giving the floor to a non-human actant.

It would be unfair to LCA practice to claim that these matters are completely ignored, as they occur in the context of developing and growing LCA methodology, but, clearly, they are ignored at the level of a particular study. They do not participate into what ANT describes as a controversy.

We have not mentioned the discourse actants yet, which would make it possible to introduce different worldviews and even ideologies into the study. For example, an LCA study implicitly assumes economic growth, when different options like economic “ungrowth” might be relevant to be included in the discussion, when 2050 is in the timeline of study. Similarly, the discourse actants ought to debunk studies, which, implicitly, are greenwashing statements, answering to vested interests, possibly those of the client, cf. examples in [25–27].

What we are imagining here as the controversy related to an LCA study looks more like an anthropological or an ethnological investigation, which does indeed reflect the origin of ANT. It is quite different from the analysis of the LCIA carried out in a classical LCA study. It might be somewhat similar to methods used in marketing or in sociology.

We are quite far yet from proposing a clear format for reconstructing LCA, an objective that was announced earlier in Section 1. Indeed, the complexity of our endeavor is such that this is out of reach of the present paper. We could only propose a way to reformulate the questions asked from an LCA and some kind of experimental attempt should be conducted at framing responses to these questions: a case study could help progress in this direction.
We are planning to start such a study in the Spring of 2023 with students from SPEIT University in Shanghai.

There are several directions in which to proceed:
- redefine LCA on the basis of the suggestions made in Section 5.2, i.e. cut drastically on the number of indicators, for example, keep only GW on board and consider that the FU exists in a world that will achieve Net-Zero solutions globally by 2050. This would transform LCA into a dynamic version of the method applied to GW. The basis for doing this is already published, but it needs to be applied to a particular case study. This is not utterly radical and what it borrows from ANT is fairly limited: the conviction that Global Warming will become the major driver of change within the next 27 years, because it is a non-human actant and it has agency in the way the world turns;
- redefine LCA much more radically by forcing it to follow the paths of ANT methodology, i.e. engage the human actants to interact in a kind of anthropological exploration and, on the way, to propose solutions for incorporating non-human actants (NHA) into the process;
- choose any number of intermediary steps between the two above options.

6 Conclusions

This paper has explored how LCA could change, more or less radically, in particular by incorporating approaches borrowed from SSH.

It was first explained that LCA has been changing and evolving since its invention in the 1960s, but it has done so by adding new indicators and new issues to be included in its methodology. Most of them are related to environmental issues, which has led to extensions to classical LCA, but some are to social matters, like Social LCA (S-LCA) and to economic issues like Life Cycle Costing (LCC). The outcome is a profusion of indicators and of methods, which have acquired some autonomy from classical LCA. The common feature of all of them is complexity and specification compared to the initial format of LCA. All these methods require more and more expertise from the practitioner and almost as much from the client.

The SCM (Social Cycle of Materials) approach offers a different direction to move forward, as it focuses on design: in the case of LCA, this would be the design of the FU and probably, as well, of the whole artifact to which it belongs. This extends the temporality of LCA in the direction of the past. It can refer to the marketing of new products or to the first appearance of the artifact on the technology market. This would explore the ontology of the FU much further back than what is done currently. SCM, however, has been left relatively unexplored since it was initially proposed in 2014, probably because the concept was proposed from outside the LCA community. There is a potential of development there, which is not fully exploited.

A more radical approach consists in calling on ANT concepts to analyze LCA, and, thus, to criticize it, deconstruct it and, hopefully, eventually reconstruct it. This is an even more important paradigm shift than SCM, as it attempts to take on board a very contemporary method, originating from SSH and more particularly from sociologists associated with Bruno Latour in their efforts to explore how social constructivism can help in understanding creation in science and in technology (the so-called STS and SCOT schools of thought) [28].

ANT describes its object of study as a network of connections between actants, i.e. not only people but also non-humans. All actants are important in the way things proceed, which is epitomized by the expression that they all have agency. Moreover, human and non-human actants play symmetrical roles. They reach some kind of closure by arriving at a translation that stems from a lively controversy involving all actants. These premises are non-intuitive. Furthermore, they require much work to be clarified in the context of LCA.

An ANT-compliant LCA would consist of several steps: (1) describe the network of the LCA Life Cycle in terms of all actants, human, non-human and discourse actants; (2) choose the terms of the translation that is achieved by this new LCA, by selecting the essential environmental, economic and social stressors that are transformed into indicators in traditional LCA; (3) organize the controversy that leads to the translation and to what is called the analysis of an LCA study.

Clarifying who the actants are is an important initial objective. More people should be involved than is the case in a traditional LCA, which would call on appropriate methods to make them interact efficiently. Defining non-human actants and deciding how to have them represented in the study team is also a challenge. This is done in traditional LCA through numbers, data, databases, sets of indicators, but the intention would be to introduce more flexible and qualitative proxies to represent the NHA. A suggestion is that the list of stressors be shortened compared to present LCA practice, and Global Warming (GW) would be the first and foremost one. Moreover, since we assume that the world will position itself to reach Net-Zero around 2050, then the whole old or new LCA context, foreground as well as background, should adapt to this constraint and somehow become dynamic.

Before arriving at a proposal for a new method, it will be necessary to go beyond the general considerations made in the present article and run one or several case studies, to explore how to proceed in details. Only then will it become clear whether all the comments formulated here can be turned into a methodology that can help LCA move forward on the basis of ANT.

List of acronyms

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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ANT</td>
<td>Actor Network Theory</td>
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<tr>
<td>GW</td>
<td>Global Warming</td>
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<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>LCC</td>
<td>Life Cycle Costing</td>
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<td>LCI</td>
<td>Life Cycle Inventory</td>
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[10] It was proposed at a SAM conference and then published in Matériaux & Techniques in 2014, by a sociology group, which was fleshing out the concept of sociology of materials.
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