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ABOUT SALIENCE OF SUSTAINABILITY ASSESSMENTS

The case of Life Cycle Thinking and food system transformation perspective

RT/2019/14/ENEA

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Milena Stefanova, Massimo Iannetta

Abstract

The broad recognition of Life Cycle Assessment as a science-based methodology for environmental assessment of products has paved the way toward extending its underlying analytical framework, Life Cycle Thinking (LCT) into a methodological framework for sustainability analysis. But is it capable of capturing the diversity of food value chains and systems? This paper questions the utility of LCT in assessing options framed under a perspective of food system transformation. Following an information-based approach, LCT has been critically examined for its capability in representing and assessing agroecological options aiming at more profound transformations of contemporary food systems. In doing so this paper proposes a new system-theoretic interpretation of the epistemological criteria that justifies knowledge produced by Sustainability Assessments (SA) supporting it by a methodology for analysing salience of LCT-based assessments. Our findings confirm hypotheses expressed earlier in the literature that LCT is not appropriate in framing agroecological options for food system transformation.

Key words: *values, food system transformation, Life Cycle Assessment, epistemological criteria, agroecology*

Riassunto

L'ampio riconoscimento di Life Cycle Assessment (LCA) come metodologia scientifica per la valutazione delle performance ambientali dei prodotti ha spianato la strada all'adozione del suo quadro analitico di base, il Life Cycle Thinking (LCT), come quadro metodologico per l'analisi della sostenibilità. Ma LCT è davvero in grado di rappresentare la diversità delle catene e dei sistemi alimentari? Questo documento mette in discussione l'utilità di LCT nella valutazione delle opzioni inquadrate in una prospettiva di trasformazione del sistema alimentare. Seguendo un approccio suggerito dalla scienza dell'informazione, LCT è stato esaminato criticamente per determinare la sua capacità di rappresentare e valutare le opzioni agro-ecologiche che mirano alle trasformazioni più profonde dei sistemi alimentari contemporanei. Nel fare ciò, questo documento propone una nuova interpretazione sistemica dei criteri epistemologici che giustificano la conoscenza prodotta dalle analisi di sostenibilità supportandola con una metodologia per l'analisi della salienza delle valutazioni di sostenibilità basate su LCT. I nostri risultati confermano le ipotesi già espresse in precedenza in letteratura secondo cui LCT non è appropriato per definire le opzioni agro-ecologiche per la trasformazione del sistema alimentare.

Parole chiave: valori, trasformaione del sistema alimentare, Life Cycle Assessment, criteri epistemologi, agroecologia

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1 Introduction

In recent years the notion of sustainability has been extensively employed in order to address the multiple problems afflicting contemporary food systems. In parallel, Sustainability Assessment (SA) has emerged in many different forms as a process aiming at informing actions towards sustainability (Pope at al., 2017). Even though SAs are considered important bench-marking setting instruments for food systems reforms (IPES, 2015), they are frequently criticized for their salience, that is, their relevance for the needs of decision makers (Cash et al., 2003). The salience of SAs depends to a large extend on the analytic tools employed in measuring various aspects of the sustainability performance of analysed systems (Gasparatos, 2010). These tools determine which data are collected (and in which way), the information content produced by an SA, as well as how information should be correctly interpreted (Gasparatos, 2010; Gasparatos and Scolobig, 2012; Haas, 2004; Gray, 2010).

Salience critiques are normally addressed by enhancing the comprehensiveness of the tools selected for assessment by focusing exclusively on extending the evidence base upon which these tools operate. Such an approach leads to "a spiral of incremental methodological improvements", which often results into a complexity explosion that can have an offsetting effect on salience (De Rosa, 2018).

This study proposes a conceptually different methodological approach to address salience of SAs. It addresses the question: "how do we know that a specific tool actually measures (aspects of) sustainability performance of the system under analysis"? Its aim is to enable SAs analysts to evaluate the alignment between, on one hand, what is meant by "sustainable food" within a specific decision-making context, and on the other, the way sustainability is represented within analytic frameworks and tools employed in SAs.

The approach has been adapted to the family of assessments based on Life Cycle Thinking (LCT). LCT is a powerful analytic way of thinking about technology in terms of functions and interlinked "life cycle" stages (Fava et al., 2014). It supports a comprehensive analysis of economic systems, accounting for potential burden shifting when assessing their performance. Originally framed and disseminated in the context of environmental Life Cycle Assessment (LCA), (ISO:14040/44, 2006), LCT has been gradually translated into many other uses driving the ulterior methodological development of LCA and other LC approaches to assessment. The LC approaches are continuously improved to allow the inclusion of still missing scientific knowledge into the underlying evidence base in order to address various gaps in performance evaluation. Unsurprisingly, one of the most ambitious research programs of the epistemic community formed around LCT is to address the broader societal concerns of sustainable development (Sala, et al., 2013a,b).

The scientific evidence base upon which LCT tools operate alludes to some similarity with recognized scientific methodologies, especially from the domain of natural sciences. However, the existing literature is quite ambiguous about the epistemological criteria that allow justifying the information produced by means of LCT-tools as (useful) knowledge, while methodologies, which allow applying such criteria are completely missing.

In this respect, some scholars suggest that LCT-based methods are based on the rational method to science, since footprints can be consistently obtained from the underlying theoretical assumptions (Heijungs, 1997). Yet, there is no corresponding methodology which allows to decide whether systems under analysis satisfy them or not, also because the assumptions themselves remain rather hidden into sophisticated procedural arrangements through which LC approaches are normally defined. Therefore, even though LC approaches allow for comparison on the base of various footprint performances, they are fundamentally different from measurements in science (both in natural and in social sciences) characterized by numeric order relations, which can be empirically validated by observation (Krantz et al., 1971). Other literature sources consider LCT scientific because the corresponding inventory analysis is based on “several of the best founded laws of natural science”, e.g. mass conservation, laws of thermodynamics, etc. (Klöpffer, 2014). This interpretation however is flawed by the need of transforming the data collected empirically, by e.g. procedural arrangements aiming to solve multifunctionality. Some authors also admit that “facts” produced by means of LCA are mixtures of scientific “truths” and values (Sala et al., 2013a,b; Hertwich, et al., 2000). However, such epistemological quality claims have not been further addressed in any methodological way and as a consequence it is also not really clear how footprint performances should be correctly interpreted. In the end, some scholars suggest that the epistemological quality of LCT-based tools resides into our trust to experts (Klöpffer, 2014), but this approach would require deeper attention to the values that drive the epistemic community formed around LCT (Freidberg, 2015), which is equally missing.

Despite such state of methodological development, footprints are being recognized, even in public policy settings, as measurable attributes of products (Freidberg, 2014). But which are *the criteria* that allow information produced by LCT-tools to be justified as knowledge, and *how to know* that footprints actually measure sustainability performance is an issue that remains largely overlooked in the current research programs of the LCT community, notwithstanding the existing social science evidence about the side effect that LCT creates in practice (Freidberg, 2013, 2014, 2015; Heiskanen, 2002).

This study proposes a new system-theoretic interpretation of the knowledge justification criteria for LCT-based assessments. It is also supplemented by a new methodology, originating from information sciences, which applies these criteria in addressing the *how-question* above. The methodology has been illustrated in the context of SAs, whose aim is to inform actions for food system transformations motivated by values of social justice and equity (Garnett, 2014). The transformations motivated by such values concern the relationships between agriculture and its biophysical and social environment as well as the market relationships along the entire food value chains. Such transformations are supported by agro-ecology intended as a science, a practice and a social movement (Wezel, et al., 2009; Gliesman, 2007; FAO and INRA, 2018). Our analysis confirms the hypothesis, expressed earlier by Garnett (2014) that LCT-based assessments are not appropriate in informing food system transformations based on equity values.

The rest of the paper is structured as follows. Section 2 discusses the methodological approach of the study, introducing a new epistemological criteria for SAs based on system theory. Section 3 presents the main results. More precisely, Section 3.1 represents the theoretical content of the basic analytic framework of LCT in the form of an axiomatic theory, which can be interpreted in accordance of the proposed epistemological criteria. Section 3.2. structures some essential characteristic s of food systems valued under food system transformation perspective in a form permitting to compare them with the theoretical content of LCT. Section 4 discusses three potential implications of this comparison and summarises the findings of the study.

2 Methodological approach

The methodological approach draws upon methodologies from information sciences (Capurro and Hjørland, 2003). The starting point is the observation that *evidence-based information,* rather than *evidence* per se plays a fundamental role in SAs. It recognises that the value of information resides not simply in the credibility of the evidence from which it is synthesised, but also in its relevance for those to be informed (Kelly and Bielby, 2016). SAs are conceptualized as *communication phenomena,* between sustainability analysts performing an SA and the decision makers informed by the SA in such a way to enable a comparison between, on one hand, what is meant by sustainability within the decision-making context and, on the other, the way sustainability is represented within analytic framework and tools.

2.1 Sustainability concept

Though its origin can be traced back to earlier societal concerns, sustainability has been popularized by the World Commission on Environment and Development, better known as Brundtland Commission. The Brundtland Commission defined the term "sustainable development" as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UNWCED, 1987)[1]. Subsequently, the sustainability concept has been also declined into more specific definitions of sustainable products, sustainable value chains, sustainable food systems, and sustainable diets, some of which have appeared in various influential publications (e.g., FAO, 2010; HLPE, 2014). Such definitions of sustainability pursue a broad consensus on shared goals and in practice capture a single dimension of the sustainability concept: the one expressing the goals of sustainable development.

On the other hand, SAs aim at informing actions toward sustainability, thus their focus is on how sustainability can be achieved, rather than on the goals pursued by sustainable development. While there is enough evidence that a broad consensus on the goals of sustainable development is possible, how to achieve sustainability appears to be a matter of debate about what should be changed and what should be sustained (Giovannoni and Fabietti, 2014; Buttel, 2006; Garnett, 2014). For this reason, goal-oriented consensual conceptions of sustainability appeared to be of little use for our purposes. Indeed, in order to enable a comparison between, on one hand, the way sustainability is represented within analytic tools and, on the other, what is meant by sustainability within a specific decision-making context, we needed to assume the existence of multiple "sustainabilities"[2] which can be evaluated and compared for their similarities and differences.

In this regard, the concept of sustainability employed in (Pope et al., 2017) in classifying SAs, appears particularly useful. It allows relating an SA process both to the underlying theory of analytic frameworks and tools as well as to the normative goals underpinning the decision-making context. More precisely, Pope and co-authors(2017) identify two essential characteristics of the sustainability concept, "representation of

[1] The essential difference between the concepts of sustainability and sustainable development is that the former indicates a desirable state, while the latter the process by means of which this state can be achieved (Giovannoni and Fabietti, 2014).

[2] The expression *multiple "sustainabilities"* is borrowed from (Loconto, 2010). It embodies in the best way the main ontological commitment beneath the methodological approach proposed in this study.

sustainability" and "underpinning sustainability discourse". The first refers to the way sustainability is represented within assessment tools. The second expresses what normatively constitutes sustainability within a decision-making context.

Unfortunately, while recognizing that these two characteristics are inter-related, Pope et al. (2017) did not investigate the nature of their relationship beyond admitting that it is "somehow blurry in practice". However, in order to carry the salience analysis of SAs, we needed to appraise this relationship. In order to do so, the relationship has been structured with the help the philosophical notion of *"worldview"*. Following (Hedlund-de Witt, 2013), by "worldviews" we mean "inescapable, overarching systems of meaning and meaning-making that to a substantial extent inform how humans interpret, enact and co-create reality". In a broad philosophical sense, worldviews are characterised by various inseparable aspects, including axiological commitments (that is, fundamental systems of values and beliefs about what is a good life), ontological commitments (that is, fundamental beliefs about the nature of reality and the way real-world entities are inter-related), and epistemological commitments (that is, fundamental beliefs about what is a correct way of knowing the reality).

2.1.1 Worldview concepts

Sustainability analysts and the decision makers informed by an SA have been conceptualized in terms of their respective "worldviews" on sustainable food. These worldviews derive from, on one hand, normative perspectives within the decision-making context, and on the other, from the theoretical representations of sustainability within analytic frameworks and tools. In order to describe these "worldviews", we will make reference to the contemporary system theory and conceptual modeling disciplines (Ramage and Shipp, 2009).

In system theory, phenomena under analysis are examined in terms of systems composed by interrelated components. For a while, component composition has been considered the only constitutional principle of system thinking. However, with the advent of disciplinary fields, whose objects of study are "soft" systems, also the notions of *perspectives* and *system boundaries* have gained primary importance for system thinking (Williams, 2015). The system-theoretical notion of *perspective* expresses how different understandings of the same issue can affect performance judgments. This is the meaning of the word "perspective" as it is used in this study as well. A perspective is intended as a pointer to an worldview that integrate broader philosophical concerns about how sustainability can be achieved (see also Hedlund-de Witt, 2013). Perhaps, an easy way to think about perspectives is to imagine them as points (of view) within a cognitive space, from which the same "world" is seen in different ways. The system-theoretic notion of *system boundaries* refers to the relevant characteristics or dimensions (i.e. the differences which make the difference), in terms of which it has been chosen to represent a phenomenon as a system of interrelated components. System boundaries indicate what is important to be observed (and also what is not) when describing a phenomenon as a system. This notion entitles multiple legitimate representations of the same phenomenon as a system. It also emphasizes the actors' responsibilities in deciding what and why is being deemed relevant as well as the existence of limits of each single representation of a system. Representations of systems as interrelated parts are normally done by means of *conceptual frameworks*, which play the role of basic "language" constructs for describing phenomena of interest in a more structured way. Conceptual frameworks can be defined as "networks of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena" (Jabareen, 2009, cited in Pope at al., 2017).

In the context of this study, while perspective are intended as pointers to broader worldviews in a philosophical sense, the term "worldview" will be used in a much narrower way to schematize a limited number of beliefs and assumptions about the nature of food systems. We will distinguish between *normative* and *theoretical worldviews* representing respectively the stakeholders from the decision-making contexts and the SA analysts participating in an SA. Normative worldviews make reference to *axiological commitments,* that is, systems of values and beliefs beneath normative visions and goals, which determine how sustainable food systems are imagined as well as how sustainability questions are framed for assessment.

The "worldview" to which the SA analyst subscribes as the most appropriate way of representing sustainability by selecting analytical frameworks and tools will be called *"theoretical worldview"* (see also Gasparatos and Scolobig, 2012). Theoretical worldviews are conceptualized in terms of their *ontological commitments*, i.e. existential theoretical assumptions about theoretical entities in terms of which phenomena of interest are described or explained. Such assumptions are inevitably embedded into analytic frameworks and tools and they themselves embed deeply hidden values from which they derive (Gasparatos, 2010).

The introduction of the concepts of normative and theoretical worldviews allows for a system-theoretical justification of the way SA tools can help in orienting decisions for action. Namely, the normative and theoretical "worldviews" can be thought of as *ideal models* of the world as it might be, rather than as models of the world as it is (Williams, 2005). Similarly to the models of the world as it is, ideal models are defined by selecting relevant characteristics of the world as it is, and by defining what are their ideal or desired properties. In this way, the assessment tools allow for comparison of the world as it is and the world as it might be, identifying options for improvement where significant discrepancies exist. In this sense they can also inform action driving the existing systems toward 100% efficiency (Aithal, 2016).

With this in mind, the main methodological thesis of our study that defines the epistemological criteria for knowledge justification is that the salience of SAs implies coherence between the normative worldviews of the decision-making context and the theoretical worldviews of the analytic tools employed in the assessment process, that is between (see Figure 1):

(a) the axiological commitments motivating an assessment practice, and

(b) the ontological commitments of the corresponding analytic frameworks and tools.

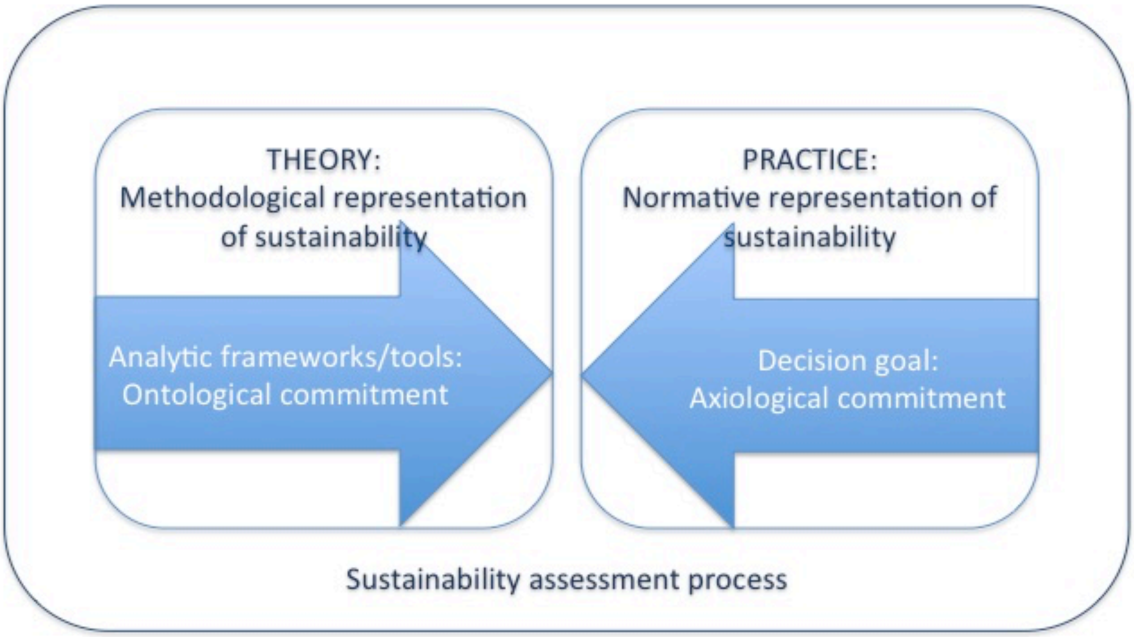

Figure 1 Methodological conceptual framework

2.2 Methodology for analyzing LCT-based assessments

In order to apply the epistemological criterion defined above to LCT-based assessments, we needed to understand how to compare the respective axiological and ontological commitments. For this purpose, the two types of commitments have been represented in such a way to share a common descriptive structure, along the analytical dimensions of LCT, whose elements are interpreted as ontological commitments when they refer to the theoretical worldviews of LCT or as axiological commitments when they refer to normative worldviews from decision-making contexts. The descriptive structure has been derived from the ontological commitments of LCT.

2.2.1 Ontological commitments of LCT

The ontological commitments of LCT have been derived by analyzing the theoretical content of the *pure analytic framework* of LCT, as specified by ISO:14040/41(2006) and translating it into a formal representation with explicit analytic dimensions and axiomatic enunciations, which constitute the ontological commitments of LCT.

Normally the theoretical content of LCT-based methodologies is explained in the form of guidelines (ISO:14040/44, 2006; JRC-IES, 2010) or by means of procedures (see for example De Rosa et al., 2016; Heijungs and Frischknecht, 1998). While such explanatory forms are surely useful in applying LCT-based assessments to the analysis of "real-world" economic systems, they appear less appropriate for the purposes of the present study, where the object of analysis is LCT itself. Nevertheless, the existing literature contains enough useful elements for facilitating the translation of the theoretical content of LCT-based assessments into a form suiting our analysis. For example, in (Heijungs and Suh, 2002; Suh and Huppes, 2005) the theoretical content of LCT has been represented into the computational structures of LCA, making use of matrix notations in order to be able to handle in a more uniform way various routine calculations as well as different procedural arrangements for multifunctionality handling (see also Heijungs and Frischknecht, 1998). Furthermore, some scholarly observations assimilate the inner structure of LCI to the one of an axiomatic system; that is, all of its theoretical content can be rationally deduced from a consistent set of non-deducible assumptions (Heijungs, 1997).

Building upon such literature sources, the theoretical content of LCT has been translated into the more concise form of an axiomatic system, which make explicit the underlying existential assumptions along the analytical dimensions of LCT, that is, the ontological commitments of LCT (see Section 3.1).

2.2.2 Axiological commitments of action-oriented LCT-based assessments

One way of understanding what is valued by decision makers within an assessment process, that is its axiological commitments, is to examine its goals. Normally, sustainability assessments explicitly aim at informing actions within a decision context toward sustainability (Pope at al., 2017). The axiological commitments of action-oriented assessments are tightly connected with the way the stakeholders from the respective decision-making contexts think that sustainability can be achieved. In this case, as some scholars argue, it is important to understand what is meant by "sustainability" or "sustainable food" prior to the commencement of the assessment process (Pope et al., 2017; Kirwan et al., 2017; Freidberg, 2014). Indeed, there is a growing amount of studies, which explicitly aim at qualifying different interpretations of the sustainability concept.

Starting from such broad qualifications of what is meant by sustainability, the proposed methodology consists in identifying the normative ideal properties of food systems along the dimensions selected by LCT, so that they can be compared with the respective ideal properties defined in terms of LCT.

The identification of these normative ideal properties, which together constitute a normative worldview comparable with the theoretical worldview of LCT, can be done if the *values* that shape different perspectives on how sustainability can be achieved are known as well as, if some form of a debate of how such values can be implemented into action is existing. These are two fundamental pre-requisites for applying the proposed methodology.

Following the classification of perspectives on sustainable food systems proposed by Garnett(2014), this study illustrates the proposed epistemological criteria it in the context of the system transformation perspective shaped by values of equity and social justice (see Section 3.2.1). A normative worldview along the dimensions of LCT has been derived for this perspective after a synthesis of existing literature on agroecology, which contains sufficient elements surrounding the debate around how agroecological systems can be implemented (see Section 3.2.2). Note that not all approaches to agroecology are shaped by the values for equity and social justice and not all of them necessarily aim at re-defining the relationships between production and consumption along food value chains (including intermediate consumption of goods or final food consumption). Indeed, in many cases agroecology is understood as application of agroecological parctices to agricultural production (Wezel et al., 2014). In order to avoid such more restrictive notions of agroecology, which not necessarily imply change in value systems, this study focuses only on contemporary literature sources that aim at defining agroecology in a unifying way as a science, a practice and a social movement (Gliesman, 2007; Therond et al., 2017; Wezel, et al., 2009).

3 Results

This section compares the ontological commitments of LCT with the axiological commitments of SAs aiming at informing the food system transformation perspective (Garnett, 2014). At their present development, various LCT-based assessments make reference to LCA as standardized by ISO:14040/44(2006). LCA is commonly described as a four-step process (see Figure 2). In "goal and scope definition", the problem and the goals of the assessment are defined. The functions and the LCT-boundaries of product systems are chosen, as well as the impacts to be considered. In "inventory analysis" (LCI), information about environmental stressors during the life cycle of the product(s) under assessment is collected and compiled into emission and resource use profiles. In "impact assessment" (LCIA), such information is categorized, compared and aggregated into respective environmental profiles with the help of linear coefficients derived exogenously from complex scientific modeling tools. Additional aggregations across categories may be performed, with the help of analytic methods from multi-criteria decision support analysis. In the end, an interpretation of the results is carried out, normally accompanied by sensitivity and uncertainty analyses, clarification of assumptions, etc.

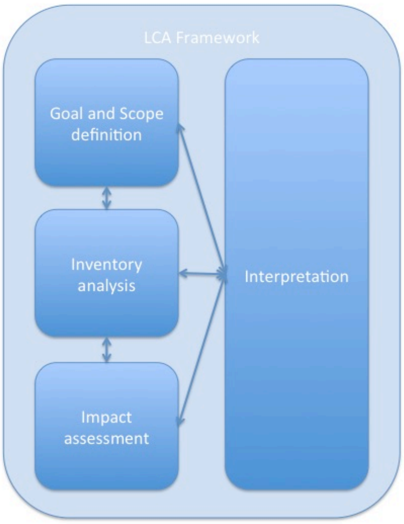

Figure 2 Stages of an LCA

The analytical framework of LCT is embedded into LCI. It determines which data need to be collected as well as how these data must be handled in order to prepare them for analysis (e.g. various procedures for multifunctionality handling).

LCT-based analyses employ some fundamental notions from system theory. Life cycles represent product systems defined in terms of their functions and parts (i.e. unit processes), which are linked with each other and with the environment by means of product, waste and/or environmental flows (ISO 14040/44: 2006). The ISO standard employs the term "system boundaries", but with a meaning that limits significantly what can vary within system boundaries compared to the meaning of the analogous general system-theoretical term. While in the case of LCT what can vary is the number of interrelated parts, system theory permits to vary the perspectives from which the same phenomenon is being represented as a system of interrelated components. That is, in system theory the analytical dimensions by means of which a phenomena can be represented are questionable and subject of variation, while this is not so in the case of LCT.

In order to avoid confusion between these two fundamentally different concepts, from now on we will use the term "*LCT-system boundaries*" to refer to the definition by ISO:14040/14041(2006) and the term "*system boundaries*" to refer to the limits of any analytic representation in system-theoretical sense.

3.1 Ontological commitments of LCT

This sub-section presents the theoretical content of LCT in the form of an axiomatic system. It has been derived from the mathematical model of LCI as defined by Heijungs and Suh (2002). The complete procedure for deriving it can be found in Applenix A (Supplementary materials).

The basic analytic framework of LCT captures two main characteristics of economic (product) systems:

- Technological relations between processes modeled by input and output commodity flows.
- Exogenous demand levels for (product) system functions, modeled by functional units, which allow establishing an equalizing base for comparison between different system commodities.

More precisely, the basic analytic frameworks beneath LCT relies on two main concepts, constrained by some assumptions as defined below:

(a) **Concept 1: Economic System**. An economic system S can be defined by means of ordered sets $C, E,$ and P of respectively n product names (i.e., names of commodity or service flows), m environmental intervention names (i.e. names of environmental or resource use flows) and n processes. Each product or environmental intervention name is associated with a unique measurement unit, which allows expressing numeric levels of flows of the corresponding types. Each process p_i is represented as an ordered $n + m$ tuple of numbers, standing for commodity or environmental flows:

$$p_i = \langle c_1^i, \dots, c_n^i;\ e_1^i, \dots, e_m^i \rangle,$$

where:

- Positive numbers indicate output flows (i.e. levels of commodities produced or emissions to the environment). Negative numbers indicate input flows.
- By convention, the i-th commodity name in the set C denotes the primary output of p_i (see the assumptions below) and the flow $0 < c_i^i \leq 1$ denotes a fraction of its primary unitary output flow, which is not used within the process itself as input.
- $c_j^i < 0\ (i \neq j)$ are constant efficiency coefficients expressing levels of input commodities necessary for the production of a unit of the primary output.
- $c_j^i > 0\ (i \neq j)$ are constant ratios of secondary outputs co-produced with a unit of the primary output.
- e_k^i is a constant ratio between so-called environmental interventions and the unitary primary output.

(b) **Concept 2: Exogenous demand and life cycles of product.** The life cycle of a product is a demand-centric configuration of economic systems. More precisely, the life cycle of a product p_i with respect to an economic system S and a functional unit f can be defined as an n-tuple:

$$LC_f^S(p_i) = \langle o_1 \times p_1, \dots, o_n \times p_n \rangle,$$

where o_j are the levels of primary outputs of each process in the system scaled-up to match the external demand level for p_i. Note that, the processes of S, which do not participate in the life cycle of the product p_i will be null-valued process tuples.

(c) Assumptions and constraints. The basic assumptions of LCT are:

1) Each product is uniquely determined by a process, which produces it as a primary output.

2) The proportions between levels of output and input flows of a process are constant, i.e., a single observation in time is assumed sufficient in order to estimate all parameters necessary for representing the process.
3) Consumption and production are ontologically separated. More precisely, it is assumed that consumption levels can be determined exogenously and that production can be always configured to satisfy them.

The second assumption is the linearity condition. It is a basic ontological assumption of LCA, considered a necessary simplification in order to solve the attribution problem (e.g. in the hot-spot analysis) in a practical way (Heijungs, 1997). It derives from an assumption that each process operates under a steady-state condition, that is, the rates between the input/environmental flows and the utility produced by a process are constant in time. As discussed by Heijung (1997), the first and the second assumptions together allow for the de-contextualization of a process from its temporal context. In a system-theoretic perspective, the time-independence of processes is convenient in setting the same time-boundaries of all processes within a life cycle.

These assumptions constitute the ontology commitments of LCT. They are very similar to those adopted in the open Input/Output (IO) model of Leontief (1986), but they are less stringent in admitting also substitutions between inputs, without necessarily leading to different technologies (see Christ, 1955 for a discussion about IO models). That is to say, the procedures of LCI for multifunctionality handling allow for substitution and system expansion (Heijungs and Frischknecht, 1998), while the original formulation of the IO model by Leontief assumed unique (rather than primary) industry outputs (which can be handled only by allocation).

In accordance with our criteria for knowledge justification (see Section 2.1), the ontological commitments of LCT can be though of as a bundle of ideal properties across the following three dimensions characterizing production and consumption activities:

- inputs to economic activities,
- outputs of economic activities, and
- relationship between production and consumption.

According to our methodological approach, the theoretical assumptions of LCT are to be interpreted as ideal properties of economic systems as *they might be* and not of the way they are. Thus, they are not intended to be validated against empirically collected data, as it is the normal practice in investigations carried from the perspective of natural or social sciences. Instead, as mentioned in Section 2.1 they serve in orienting improvements of existing systems toward the way they should be, by comparing real and ideal properties and identifying where the best opportunities for improvement exist (Aithal, 2016).

It is possible to classify four basic types of LCT-based assessments, on the base of the above formal definition of a life cycle.

1) Hot-spot analysis: Given a life cycle $LC_f^S(p_i)$ configured to satisfy a certain functional demand level f, it is possible to compare resource/emissions or environmental profiles of different life cycle stages. This

so-called hot-spot analysis is normally employed in informing the improvement of single life cycle stages (see examples discussed in Section 3.2).

2) Product comparison: Given an economic system containing at least two products/processes p_1 and p_2 delivering the same function and a certain functional demand level f, it is possible to configure the system in two ways: first in order for p_1 to satisfy f and second in order for p_2 to satisfy f. Hence, the resulting emission/resource or environmental profiles of the two respective life cycles can be compared. This is perhaps one of the most controversial uses of LCA. Indeed, in order to contrast its employment in "greenwashing" campaigns (Freidberg, 2014), some requirements for "comparability" between products have been defined by ISO:14040/44(2006).
3) Ex-ante analysis: given a certain functional demand level f and a baseline life cycle $LC_f^S(p_i)$ configured to it, it is possible to explore in a more proper ex-ante manner the effects due to change in technology or due to demand level changes. This second kind of evaluation is often done with the help of consequential LCA. Also in this case, LCT-system boundaries are an important issue and the literature proposes various ways in handling them, including integration with economic modeling tools in dealing with large enough boundaries and rebound effects (Guinée et al., 2018).
4) Multifunctionality analysis: exploration of different functions delivered by the same process/product, by changing the corresponding functional unit. It is a technique employed in assessing multifunctional agricultural systems (Repar et al., 2016). It often finds application in the debates about organic farming models as compared to their conventional counterparts (see some examples in Garnett, 2014).

The analytic framework of LCT can be used in a truly flexible and versatile manner by combining the above four basic types, changing functional units, LCT-system boundaries, or analyzing systems at micro (product), meso (sector) and macro (consumption mixes) levels. Moreover, besides the basic types of analysis listed above, there are also assessments derived by integrating into LCT elements from other analytic frameworks. For example, agro-ecosystem modeling employed in calculating emissions or land use impacts of agricultural systems (Meier, et al., 2014; de Rosa, 2017) or frameworks employed in the analysis of ecosystem services (Ripoll-Bosch et al., 2013), which will be briefly discussed in Section 4. Following such direction of extending LCT, some scholars even aim at redefining the whole LCA framework (see Figure 2) into a complete framework for sustainability assessment, in such a way as to enable model integration directly into LCT, rather than the looser coupling that exist through the LCIA phase of LCA (Guinée, 2016).

3.2 Axiological commitments of action-oriented LCT-based assessments informing system transformation

As mentioned in Section 2.2, the axiological commitments of action-oriented assessments are tightly connected with the perspectives on sustainable food systems that inform the decision-making context. Following (Garnet, 2014), this sub-section makes a synthesis of current societal perspectives on food sustainability.

3.2.1 Perspectives on sustainable food systems

Garnett(2014) identifies three ideal-type societal perspectives on sustainable food systems: efficiency, demand-restraint, and system transformation perspectives. All three perspectives are value-laden, even though options prioritized by each of them are science-based.

The efficiency perspective prioritizes incremental technological innovations affecting single value chain phases. The underlying value judgments associate "good life" with material comfort and are justified by the belief that any levels of consumption can be sustained through technological innovation. The prevalent uses of LCT-based assessments fall under this perspective. For example, LCA has been employed within different industrial settings in the context of continuous improvements along value chains. The primary objectives of efficiency options are to maximize production input-output efficiencies of single life-cycle stages identified as environmental hot spots, without affecting the rest of the system under consideration. Depending on the decision context, on the choices of LCT-system boundaries and of functional units, proposed solutions can refer to improvements within the scope of a given value chain or can concern its interfaces with other economic sectors. Examples of the first kind are various options for reducing environmental impacts of a value chain while improving agricultural productivity, such as those employed by Barilla (Ruini et al., 2013; Barilla, 2011). An example of the second kind is a famous Coca-Cola case, where an entire sector has been established, which helped Coca-Cola maintain its market strategies while reducing the respective environmental impacts through recycling of aluminum packages (Klöpffer, 2014).

The demand-restraint perspective prioritizes options, which explore synergies between reducing environmental impacts and improving human nutrition and health. Its underlying value judgements focus on the individual consumer responsibility and view consumption as a major driving force for gearing food systems toward a more sustainable pathway. Such perspective is being adopted within more recent LCA studies aiming to assess environmental performances of healthy dietary patterns, which could provide both health benefits to the individuals and environmental benefits to the society (Heller et al., 2013). The corresponding improvement options aim at changes in consumer diets. Healthy and/or culturally optimized consumer demand patterns can drive changes in land-use and trade patterns, in such a way to minimize environmental impacts (Duchin, 2005; Heller et al., 2013). A central issue here is how to reduce the consumption of livestock products and sometimes, also how to simultaneously increase consumption of foods considered ecologically significant, such as foodstuff based on leguminous crops, locally produced fresh products, traditional products, etc. (Bach-Faig et al., 2011).

In the end, options prioritized under system-transformation perspective are suggested by agroecology as a science, a practice, and a social movement (Wezel, et al., 2009). They rely on ecological knowledge internalized into farm management rather than on externally supplied inputs and technologies. At the level of food systems, agroecology aims at balancing stakeholder relationships, as well as at re-linking production and consumption by establishing non-conventional market forms or by opening production decision spaces for consumers (Gliessman, 2007). System-transformation perspective is underpinned by values of social justice and beliefs that humans are part of nature. Its primary objectives reside in reconfiguring different kinds of relationships between system components in order to optimally balance them. While options,

	Efficiency	Demand Restraint	System Transformation
Fundamental values (axiological commitments)	More is better	Getting people out of nature	Social equity
Fundamental Beliefs (ontological commitments)	Increasing population growth and affluence in the future. Negative environmental impacts are side effects of production: all products have negative impacts on nature. Separation between humans and nature.	Humans harm nature. Separation between humans and nature. Existence of absolute environmental limits, which can be crossed. Food is sufficient to feed everyone now and in the future.	Humans are part of nature. "Small is beautiful". Environmental, social and health issues are outcomes of food systems, rather than side effects; Consumption is part of food systems, not an exogenous demand.
Goals	To meet increasing levels of demand by increasing production, while minimizing unintended negative side effects.	To limit demand by optimizing it for healthy/cultural nutrition performances.	To implement new relational models of production and consumption addressing key causes of unsustainability.
Development model	Growth model	De-growth model	N/A[3]
Example solutions	Precision agriculture Valorization of waste and side streams Maximization of utility extraction from raw materials Land spare through land intensification	Changing dietary patterns to patterns with less meat Culturally acceptable and healthy dietary patterns, which regulate in a positive way trade flows and land-use patterns.	Changing models of agricultural production from input-based to biodiversity-based Changing the way production and consumption are embedded into social and institutional context (alternative food networks)

Table 1 Perspectives on sustainable food systems: goals, supported development models, societal values and beliefs, example solutions. Adapted from (Garnett, 2014).

prioritized under the perspectives of efficiency or of demand restraint, entitle actions of limited scope on behalf of single stakeholder groups, options for system-transformation require collective action by multiple stakeholders that result in more radical system-level innovations.

The three perspectives discussed above are distinguished on the base of three stylized generic societal values

[3] We were not able to identify a specific development model that corresponds to the food system transformation perspective. However, the literature on sustainability science contains some attempts of defining models for growth, where growth is considered on multiple dimensions, and not reduced to the economic dimension only (Ely et al., 2013; Stirling, 2016). These models however are not enough elaborated in order to understand whether they correspond to the perspective of food system transformation.

and associated beliefs embedded within corresponding "worldviews". Such values and beliefs translate into different normative goals and visions about corresponding socio-economic development models (see Table 1).

In practice, as also Garnett(2014) pointed out, there is a general consensus that sustainability cannot be achieved by choosing a single perspective. Instead, solutions prioritized under different perspectives need to be combined.

In the context of action-oriented decision-making, LCT certainly has demonstrated many strengths, due to its ability to detect unintended effects elsewhere (Klöpffer, 2014a). Under an efficiency mindset, for example, it has proved its utility in designing biofuel policies, by detecting undesired consequences due to land use change elsewhere (Garnett, 2014). Under demand restrained perspective it has highlighted the detrimental environmental consequences due to meat consumption and it appears also promising in detecting unintended consequences due to changes in land use or trading patterns, resulting from changes in collective dietary patterns (Duchin, 2005).

Nevertheless, as Garnet(2014) argued the use of LCA for informing decisions about agroecological options for action is questionable. The reason for this is often attributed to the current state of methodological development, which has not yet produced robust analytic tools to adequately address such novel applications (Garnett, 2014; Nemecek et al., 2016; Notarnicola et al., 2017). Our subsequent analysis shows that a second interpretation, in terms of the theoretical limits of LCT, is also possible.

3.2.2 Axiological commitments beneath system transformation perspective

System transformation perspective is supported by agroecology as a science, a practice, and a social movement (Wezel et al., 2009). When conceived this unitary way, agroecology seeks for system-level transformations in redefining the relationships within food systems (Gliesman, 2007). These include relationships between agriculture and its biophysical environment as well as between food value chains and the social context into which they are embedded.

Agroecology looks for new ways of producing knowledge about phenomena (agroecology as a science), of putting such knowledge into practice (agroecology as a technology or 'know-how') and of re-ordering social relationships into which food production and consumption are embedded (agroecology as a movement). In the context of agroecology, humans are not ontologically separated from nature nor consumption from production (Gliesman, 2007; see also Table1). Agroecology strives for establishing not simply a different paradigm for the science-technology dualism (or, knowledge – 'know-how') but above all for the science-technology-society triad|||

Agroecological conception of technology differs significantly from the way technology is normally conceived. It is referred to as "practice" emphasizing the impossibility of separation between technology and its biophysical and social context. Agroecological practices are labor and knowledge intensive rather than capital intensive. They do not depend on costly input markets and access to finance is not among the main determinants influencing agroecological innovations. This makes them suitable in empowering small-scale peasant farms as well as consumers. Agroecology indeed seeks to internalize consumption by empowering consumers to act beyond the choices of what to put into their shopping baskets (FAO and INRA, 2018; Gliesman, 2007).

In the end agro-ecological movements strive to redefine the system of social relationships, which embeds the activities of food production and consumption in reorienting it toward equity values based on social justice and thus it can support the food system transformation perspective identified by Garnett(2014).

In order to apply our methodology in deciding whether LCT-based assessments are appropriate in informing the food system transformation perspective in a salient way, it is necessary to identify which are the ideal properties of agroecological food systems across the dimensions of inputs, outputs, and consumption-production relationship (see Table 2).

Worldviews	**Theoretical worldview**	**Normative worldview**
Commitments	Ontological	Axiological
Inputs to production cycles/ systems	Nature of inputs	Valued inputs
Outputs of production cycles/ systems	Nature of outputs	Valued outputs
Relationship between production and consumption	Nature of the relationship between production and consumption	Valued relationship between production and consumption

Table 2 Common structure and interpretation keys for representing the theoretical worldview of LCT and normative worldviews from the decision making context.

The literature about agroecology contains a lot of information regarding different types of agro-ecological practices in farming systems. In our analysis, we draw upon the results of studies, which synthesize some general characteristics of both practices and farming system models (Wezel, et al., 2014; Gliesman, 2007; Therond, et al., 2017; van der Ploeg, 2008). Such studies contain synthetic elements regarding the nature of inputs and outputs of agro-ecological farming systems and practices. Such elements alone are not sufficient in order to make the comparison between the ontological commitments of LCT and the corresponding axiological commitments beneath food system transformation perspective, also because both LCT and agroecology take a food system approach. At level of food systems, the agroecological approach is translated into various alternative food system networks as forms of different institutional arrangements in society, which creates the necessary infrastructure in connecting production and consumption (Gliesman, 2007; Therond, et al., 2017; van der Ploeg, 2008; FAO and INRA, 2018). Such studies contain useful insights also about the kinds of relationships between consumption and production that are valued in agroecological terms.

Table 3 summarizes the axiological commitments of agroecological food systems along the analytic dimensions of LCT and compares them with the corresponding ontological commitments of LCT. Note that these are not ideal properties of an existing theoretical framework, such as LCT, thus they cannot be defined in a formal way. Rather they are qualitatively defined in such a way to enable a qualitative comparison with the formally defined ideal properties of economic systems supported by LCT.

	Axiological commitments of agro-ecological visions for food system transformation	Ontological commitments of the basic LCT analytic framework.
Nature of inputs to farming systems	Bio-diversity based inputs, knowledge about how to adapt production to climate, soil and nutritional needs of communities, labor.	Marketable inputs and constant input/output ratios.
Nature of outputs	Multifunctional outputs, including food, knowledge and ecosystem services to production.	Marketable outputs and existence of primary outputs for all processes of a system.
Nature of relationship between consumption and production	Participation of consumers (intermediate and final) in productive decisions and access to productive knowledge.	Conventional market relations of supply and demand.

Table 3 Axiological commitments underpinning system transformation perspective and corresponding ontological commitments of LCT

It is possible to see that the normative agroecological worldview and the theoretical LCT worldview bear consistency tensions along all of the three analytic dimensions of LCT.

First, the production inputs, valued for agroeclogical farming are accessible knowledge in the common domain (Anderson et al., 2019), ecosystem services provided from the biodiversity resources from the agro-ecosystems to farming, biomass recycled at farm or community levels, as well as knowledge-based labour (Therond, et al., 2017; Altieri at al., 2017). That is, agroecological farming is biodiversity-based rather than based on marketable commodity inputs. Agro-ecological farming systems aim at using input ecosystem services as well as other self-provisioned inputs and in doing so also at making farmers independent from the suppliers of conventional markets for commodity inputs. What matters within such production systems are the interactions between multiple biological organisms (comprising farmed species) as well as diverse abiotic factors influencing production at field and landscape levels (Gliesman, 2007). Taking into account the aims of agroecological farming as well as how they are intended to be pursued, the SAs analysts need to answer the question whether they corresponds to the LCT ideal of external inputs with constant input-output ratios.

Second, agroecological farming systems are multifunctional, that is, they produce multiple marketable and subsistence food products in such a way to also co-produce the input ecosystem services, other inputs as well as accessible knowledge on which they depend (van der Ploeg, 2008). The question here is again how the LCT ideal of considering only marketable products and only production systems into which a primary marketable product can be identified fits with the agroecological vision of multifunctional production. Indeed, the fact that under the agroecological worldview the environmental and social issues are valued as outputs and not simply as side effects of food systems constitutes one of the fundamental axiological commitments of agroecology (see Table 2; Gliesman, 2007).

In the end, most importantly, agroecology aims at also re-defining the relationship between consumption and production by empowering people to take a more active role in the decision making processes about food production. In this respect, the social relations of proximity that define and connect communities appear to be particularly important for the argoecological worldview. This implies the need to establish alternative institutional settings that connect consumers and producers, able to capture such values of proximity (Gliesman, 2007). Such values entitle different normative ways of embedding farming system into their social contexts (Theorond et al., 2017) and call for more imagination in reconnecting food production and consumption. There are various examples of defining non-conventional agroecological markets (FAO and INRA, 2018), such as Participative Guarantee Schemes, Community Supported Agriculture, or Food Cooperatives. On the other hand the LCT ideal of conventional markets, where an exogenous food demand interacts with food supply in order to configure it, allows for only a very narrow way of imagining the possible relationships that might exist between consumption and production. As explicitly emphasised by Gliesman (2007): "*Food production in this model is reduced to a merely technical problem in purely economic context*" and as far as it is able to respond to changing demand patterns, problems such as hunger, water pollution, soil depletion, etc. can appear only as unintended side-effects subject to technical solutions.

4 Discussion and conclusions

In the case of food system transformation perspective based on values of social justice and equity, Table 3 shows clear misalignment between the corresponding theoretical and normative worldviews. But is this sufficient in order to rule out LCT-based assessment as not being salient in informing this kind of food systems transformations? Or in other words, can these worldviews be aligned?

One option is to try to modify LCT without transcending its system boundaries[4], in such a way to arrive at a more general re-conceptualization of food systems that accommodates how inputs, outputs, and/or relationships between consumption and production are valued under food system transformation perspective. This option is consistent with current research programmes of the LCT community which aim at leveraging LCT as a universal way of thinking in achieving the Sustainable Development Goals (Klöpffer, 2014; UNEP, 2019). In order to implement this option some of the current methodological extensions of LCA can constitute a starting point. In particular, there are various proposals for improved inventory analysis consisting in the integration of agro-ecosystem modeling techniques into LCI (Meier et al., 2014; de Rosa, 2017), which allow representing some flows of ecosystem services as inputs to agriculture (e.g., nitrogen or carbon flows; see). Other methodological developments aim at better capturing the multifunctionality of farming systems. For example, (Ripoll-Bosch et al., 2013) proposes to allocate part of the environmental burdens of multifunctional farms to the ecosystem services they provide to society.

In principle following such a direction, it is possible to think that the misalignments regarding the nature of inputs could be resolved by simply considering both biodiversity-based as well as marketable inputs to

[4] Recalling that in a system-theoretical sense system boundaries are characteristics, deemed relevant, which determine how the "cake is cut into parts". In this case, the system boundaries of LCT are given by the nature of inputs, of outputs and of relationships between consumption and production assumed in the ontological commitments of LCT. What we mean by not transcending these boundaries is that some of the ontological assumptions of LCT can be further relaxed to modify the original definition by ISO:14040/44 (2006), while continuing to frame the analysis in terms of marketable inputs and outputs and functions matching exogenous demand levels.

farming systems, and in the same moment dropping off the assumption of constant production coefficients. Similarly, the issue of multifunctionality could be resolved on a conceptual level by modifying LCT in such a way to overcome completely the need for the procedural handling of multifunctionality (that is, dropping off also the assumption about the existence of a unique primary product). In this way, the first two ontological commitments of LCT can be simply reformulated by postulating that activities are interrelated by means of input and output commodity, ecosystem services flows, (as well as knowledge-based labour) without further constraints, such as constancy of technical coefficients or the existence of unique primary products.

This re-formulation might look simple on a purely conceptual level but it could be rather sophisticated to design a systematic methodology based upon such less stringent assumptions. Moreover the reliance of LCA upon procedural arrangements and methods, a feature shared also by more advanced LCT-based assessments, constitutes an ulterior complication in re-modulating LCT in this way. Indeed more comprehensive extensions of LCA are presented in a rather procedural form, while also steadily proliferating. This not only leads to complexities (De Rosa, 2017) and confusion about their respective methodological differences and similarities (Guinée et al., 2017), but it isn't straightforward to understand if and how they modify the assumptions beneath the basic analytic framework of LCT as well as whether their internal coherence is still maintained. Nevertheless, at their present development methodological extensions of LCA are not sufficiently mature in, e.g. considering ecosystem services in a more comprehensive way both as inputs to agriculture as well as outputs to the society. Moreover, how to reconcile the contrasting commitments concerning the nature of the relationship between consumption and production (see Table 3) does not appear trivial even at a purely conceptual level, at least not without transcending the system boundaries of LCT. Indeed the ontological separation between consumption and production is a definitional characteristic of LCT – it together with commodity inputs and outputs of interrelated activities marks out the limits of the system boundaries of LCT.

A second option is to redirect scholarly attention from LCT toward analytic frameworks, which "cut the cake into parts" differently, than focusing exclusively on commodity inputs, outputs, and consumption-production relationships characterising conventional market exchanges. The literature already contains some insights, which can support this option. For example, the works of Therond et al. (2017) and Kirwan at al. (2017) try to enlarge system boundaries in such a way to accommodate the diversity of contemporary food systems. Migliorini et al. (2018) instead specifically target agroecological systems.

While we think that following (also simultaneously) the two options discussed above could lead to better understanding of how to deal with multiple perspectives on sustainable food systems when performing an SA, there is also a third likely option, which if not properly addressed could create a lock-in factor in supporting agroecological transitions, especially if LCT becomes the dominant way of thinking in the context of public policy making.

It consists in changing the conception of sustainability under food system transformation perspective, in order to stay within the system boundaries of LCT. Indeed SAs are also explicitly or implicitly employed in supporting processes of "negotiated understanding" of sustainability, which ideally take place within democratic, power-free forums of peers, in which the best arguments determine the conceptualization of sustainability (Pope at al., 2017). In this respect, the role of LCT appears particularly relevant. In fact, as some scholars argued, LCT has already significantly shaped the way late industrial societies frame environmental issues (Heiskanen, 2002). LCT-based assessments are also notorious for their uses as epistemological devices for "falsifying" commonly held beliefs by producing facts of evidence. Such use is particularly emphasized in connection with the appearance of alternative visions which challenge the dominant models for food production and distribution, such as alternative farming models or alternative food networks (Therond, et al., 2017). "Destroying the myths and following the facts" (PRé, 2015): this is a general pattern of LCA use in bringing evidence that, e.g., organic farming is not necessarily better for the environment than conventional, or similar "myths" regarding local, seasonal, traditional, homemade, etc. products (see some specific examples in Nemecek et al., 2016).

Even though the focus of our study is on action-oriented SAs, the broad methodological approach discussed in Section 2.1 (see Figure 1) is also applicable in the context of understanding-oriented SAs. In this case, the only relevant conceptualizations of sustainability are those embedded into the corresponding analytic tools (Pope et al., 2017) and what is valued in this kind of SAs is the arguments' quality. Consequently, the axiological commitments of such SAs are closely related to the epistemological quality and to the knowledge justification criteria beneath assessment methodologies. However, as discussed in the introductory sections, the epistemological criteria allowing justification of the knowledge produced by LCT-based assessments are rather blurred and their application depends on the integrity of experts rather than on methodological arrangements, as it is the normal practice in any scientific discipline. Therefore it is necessarily to understand better how quality of arguments are valued in this kind of SAs.

In our opinion, the use of LCT-based assessment in negotiating the societal understanding of sustainability can have far-reaching consequences, if their epistemological criteria are not clarified and supported by explicit methodologies that effectively can justify the procedural arrangements that define these assessments. In this sense we think that this study by proposing one possible interpretation and a methodology for its application could contribute to better clarifying the knowledge justification criteria that drive LCT-based developments. Furthermore, as a future research the proposed broad methodological approach could be ulterior elaborated in order to cover also different kinds of assessment tools and understand how the salience of SAs can be improved in such a way without affecting negatively other important attributes, such as legitimacy or credibility (Clark et al., 2002).

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Appendix A Supplementary Material: Detailed procedures in deriving the axiomatic theory of LCT

A.1 Life Cycle Inventory Analysis

The basic analytic framework of LCT is implemented into the Life Cycle Inventory Analysis (LCI). LCI relays on the concept of economic (product) system (Heijung, 1997) and aims to numerically capture interactions between economic systems and the environment. The concept of economic system is expressed in terms of economic and environmental flows. Economic flows represent levels (or quantities) of man-made artefacts (products or commodities) and services[5]. Environmental flows (called also interventions or elementary flows in the literature), numerically represent pressures of economic systems on the environment causing potential impacts. Economic and environmental flows are simply numbers, but they have corresponding flow types, which are associated with appropriate units of measures. Economic and environmental flows are interconnected within an economic system. This is done by means of the process concept. Each process is characterised by input and output flows. Two processes p_1 and p_2 can be connected if one or more output flow types of p_1 are input flow types of p_2.

In practice, each LCA study relays on so-called background data, which are often embedded as databases in specialised LCA software or in alternative it is obtained from previous studies. The LCA practitioner empirically collects data only about a portion of the system. For example, if the study aims to analyse one or more types of farming systems, primary data about farming and post-farming practices is normally collected at the specific sites objects of the study, while background data about inputs such as energy, fertilisers, pesticides or other commodities and services, produced by other sectors frequently derive from existing literature studies and/or LCA databases.

Often, LCA practitioners use intuitive graphical notations, as the one in Figure 1, as a support tool for representing and collecting the primary data about the systems under analysis. Such intuitive diagrams are also displayed in scientific publications with LCA case studies in order to facilitate the reader. However, such intuitive diagrams often do not fully correspond to the computations LCI structures (Heijung and Suh, 2002), which correspond in a more precise way to the analytic framework beneath LCT. Indeed LCI, LCA and other LCT-based forms of analysis require that the empirically collected data are first pre-processed, by means of various procedures for resolving functionality, cut-offs, or equalisation to pre-selected functional units or impacts in order to render them ready for footprint type of analysis. The structure of such pre-processed data (both primary or background), into which economic systems are represented for analysis can be and often is rather coulter-intuitive (Suh and Huppes, 2005). It is often explicitly defined in the context of specialist software tools, but remain hidden for the LCA practitioners and other users of these tools, while in the case of ad-hoc studies which do not relay on specialist software, it is implicitly embedded into the corresponding calculation procedures.

[5] In the reality, economic flows are partitioned into product flows and waste flows. These two types of flows are treated differently in LCI, either by cut-offs or as input flows associated with waste treatment input services (Heijungs and Suh, 2002).

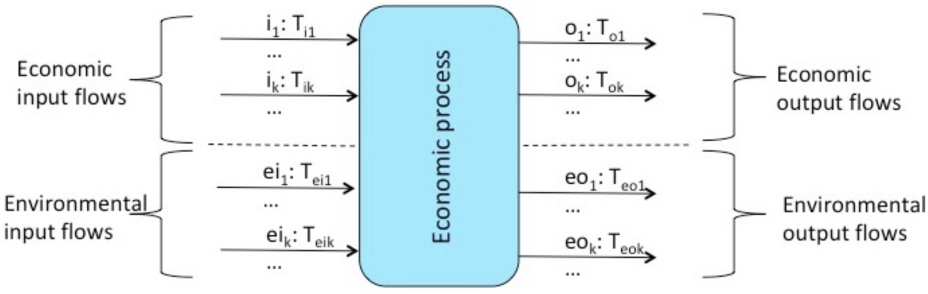

Figure 3 Graphical representation of economic processes in LCA.

This supplementary material presents the detailed steps in deriving the precise analytic structures of the analytic framework of LCT in the form of an axiomatic theory.

A.2 Computational structures of Life Cycle Inventory modelling

The literature on LCA contains some studies dedicated to the problems of calculating LCIs (Heijungs and Suh, 2002; Suh and Huppes, 2005).

According to these studies, the computational structure of LCI can be presented as a table, called technology matrix of LCI, with the same numbers of rows and columns, say n. An economic system E to be analysed is then represented in terms of such tables (Suh and Huppes, 2005). More presicely, the system E is defined in terms of n process types, p_1, …, p_n and n economic flow types (also called commodities), c_1, …, c_n . Commodity types and process types are placed respectively as row and column labels of the technology matrix (see Table 4).

	p_1	p_2	…	p_n
c_1	$a_{1,1}$	$a_{1,2}$	…	$a_{1,n}$
c_2	$a_{2,1}$	$a_{2,2}$	…	$a_{2,n}$
…	…	…	…	…
c_n	$a_{n,1}$	$a_{n,2}$	…	$a_{n,n}$

Table 4 Technology matrix of LCI.

Note that some authors choose a rectangular technology matrix, rather than a quadratic one (Heijungs and Suh, 2002). The point here is that it is easier to map a rectangular matrix into the intuitive graphical representation of processes, while a quadratic matrix can be often counter-intuitive. However, the LCA software tools (often in interaction with their users) first transform rectangular matrices into quadratic form as a result of applying methods for allocation and cut-offs and only afterward the computation of LCIs are executed. Similarly in the context of more ad-hoc studies, the selected procedures for multifunctionality handling or for cut-off are applied during the calculation of the inventory data and/or subsequent footprints, even if the precise rectangular technology matrix may not be specified in an explicit way. Therefore, following (Suh and Huppes, 2005), it is correct to conclude that economic systems are conceptually represented in LCA as a set of n different processes delivering n commodity flows.

Each process p_i of the system E is represented as a column in Table 1 (or as an ordered n-tuple), where the numbers $a_{i,j}$ express either input requirements for commodity flows or produced output of commodity c_j during the operation of the process p_i for a certain known operating time. Input and output flows are expressed by respectively negative and positive numbers, which measure quantities of the corresponding flow types in the corresponding measurement units. The concept of operating time has been introduced in (Heijungs, 1997) as a reference to the amount of utility produced by a process. The operating time is the time during which a process p produces known quantities of multiple commodities as outputs (as well as known multiple undesired environmental interventions and waste streams). The concept of operating time allows that LCA processes are multifunctional differently from similar conceptual frameworks, e.g. the original input-output (IO) modelling paradigm created by Leontief (Leontief, 1986).

The technology matrix of LCI is extended in order to account also for the environmental flows of each process during its known operating time. In this way the complete economic system under analysis is represented by means of a table, as shown in Table 5, where e_1, …, e_m are the types of environmental flows in the system, and the numbers $b_{i,j}$ denote the corresponding quantities (i.e., environmental flows) expressed in their respective measurement units.

	p_1	p_2	…	p_n
c_1	$a_{1,1}$	$a_{1,2}$	…	$a_{1,n}$
c_2	$a_{2,1}$	$a_{2,2}$	…	$a_{2,n}$
…	…	…	…	…
c_n	$a_{n,1}$	$a_{n,2}$	…	$a_{n,n}$
e_1	$b_{1,1}$	$b_{1,2}$	…	$b_{1,n}$
e_2	$b_{2,1}$	$b_{2,2}$	…	$b_{2,n}$
…	…	…	…	…
e_m	$b_{m,1}$	$b_{m,2}$	…	$b_{m,n}$

Table 5 Extended technology matrix.

There are two fundamental assumptions connected with Table 5, which are useful in order to get a clearer picture of how economic systems are represented in LCI. First, the number of processes and the number of economic flows are the same. Second, the operating time is assumed constant for each process in the system. Namely, each processes operates under a steady-state condition, that is, the rates between input flows or environmental flows and utility produced by the processes are constant in time. This is a linearity condition, which is considered basic epistemological assumption of LCA in relation to the attribution problem (Heijungs, 1997). It allows for not representing in an explicit way the operating time of the system. In this way, it is sufficient to keep some constant input-output ratios within process representations, and when process output changes (due to change in demands posed on the system), the corresponding inputs are adjusted accordingly.

The economic systems in LCA are associated with the delivery of functions. They are identified and quantified through functional units, expressing system demand (or certain performance levels). In LCA terminology, the functional unit of a system is fulfilled by a reference (commodity) flow. The reference flow, defined exogenously, expresses a demand level to the system for one or more products. In the case of more than one products, the respective commodity flows can be equalised by making reference to the selected functional units and thus their corresponding footprint performances can be compared.

Economic systems represented as set of processes and exogenous demand levels for commodities constitute the input to LCA software or for the calculations performed within more ad-hoc studies. On the basis of such input data LCIs are calculated in a similar way as this is done in IO analysis (Suh and Huppes, 2005).

A.3 Life Cycle Inventory structures and IO analysis

Existing literature often discusses differences between LCA and IO analysis (Leontief, 1986) since they entail different procedures in calculating inventories, are applied on different scales of analysis or represent the demand levels differently (i.e. in terms of monetary flows in the case of IO analysis and in terms of physical flows in the case of LCA).

Some of the differences derive from the fact that the Leontief's model does not distinguish between processes and commodity flow types. This is so, because each process can produce at most one type of commodity. In IO analysis, the economic systems are represented by means of a quadratic matrix, called structural matrix of an economy. It is a table, where the corresponding commodity types are just denoted by the process names and it assumes fixed technological coefficient rations between different inputs and the output for each process. Another difference is that IO analysis works on macro scales and thus it uses the term "sector" to name a concept corresponding the concept of process in terms of LCA.

In the end, the LCI technology matrix, the way it has been chosen to be defined by the existing literature, corresponds to the matrix $(I - \tilde{A})$, where I and $\tilde{A}$ denote the unit and the structural Leontief matrices respectively (Leontief, 1986). In fact, in the matrix $\tilde{A}$, all exchanges between a process p and the rest of the processes in the economic system are recorded as non negative numbers, while in the matrix $(I - \tilde{A})$, the inputs from other processes to p are recorded as negative or zero numbers and the output of p is recorded as a positive number.

The significant difference between the LCI technology matrix A and $(I - \tilde{A})$ is that LCI matrices can include multifunctional processes. Multifunctionality issues are often discussed also in the community of IO analysis, and apparently are problematic both in LCA and in IO. In LCA, as discussed in (Heijungs and Suh, 2002), there are several methods for solving the mutifucntionality problem in order to arrive at a quadratic technology matrix. In the general case, for each process with two or more outputs, one or more additional processes with single output are created and added to the technology matrix A. In the case of allocation partitioning methods, these additional processes are just dummies, with no references to "real" economic activities and they are not depicted in the intuitive graphical representations. Other allocation methods, e.g. the substitution method, keep the original multifunctional process in the technology matrix, while adding a process, whose commodity output is considered outplaced by the secondary commodity output of the multifunctional process. In this case, the multifunctional process p can be associated with one of its output flow types, which is not an output for any other process in the technology matrix. This flow type determines the primary output of the process p, and the process p can be uniquely identified by it.

Using the concept of primary output type, which uniquely identifies a process, it is possible to avoid a reference to the concept of "operating time of a process", by making reference to the fixed technological coefficients expressing input to primary output ratios or secondary to primary output ratios per unit of primary output for each process. In this way the technology matrix of LCA can be also represented in a table format (see Table 6), in which each process is uniquely identified by its primary commodity output.

		p_1	p_2	…	p_n
c_1	p_1	o_1	$d_{1,2}\times\left\lvert\frac{a_{1,2}}{a_{2,2}}\right\rvert$	…	$d_{1,n}\times\left\lvert\frac{a_{1,n}}{a_{n,n}}\right\rvert$
c_2	p_2	$d_{2,1}\times\left\lvert\frac{a_{1,2}}{a_{1,1}}\right\rvert$	o_2	…	$d_{2,n}\times\left\lvert\frac{a_{2,n}}{a_{n,n}}\right\rvert$
…	…	…	…	…	…
c_n	p_n	$d_{n,1}\times\left\lvert\frac{a_{n,1}}{a_{1,1}}\right\rvert$	$d_{n,2}\times\left\lvert\frac{a_{n,2}}{a_{2,2}}\right\rvert$	…	o_n

Table 6 Transformed LCI technology matrix.

For convenience, the economic flow types and processes are ordered in such as way that the primary output of a process p_i is the commodity c_i. The numbers $d_{i,j} \in \{-1, 1\}$ denote the orientation of the corresponding flows, i.e. -1 stands for input economic flows and 1 represents output flows. The number o_i expresses unitary primary output flow of the process p_i, and in most of the cases equals 1, though feedback loops and processes supplying to themselves are not excluded in LCA settings (Heijungs and Suh, 2002). In this later case it is a number, which corresponds to the total output ratio of the process to the rest of the economic system (i.e. a positive number smaller than 1).

The extended technology matrix (Table 5) can be represented in a similar way through constant coefficient ratios. On the base of this representation, the precise structures in terms of which the LCT analytic framework operates can be represented as an axiomatic system (see Section 3.1 of the main manuscript).

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