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*Review*

# Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives

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**Abstract:** Tracking the environmental impacts of production, use, and disposal of products (e.g., goods, and services) have been an important issue in the global economy. Although Life Cycle Assessment (LCA) is a widely applied method to track these environmental impacts and support policies, it has certain limitations and an isolated way of evaluating the environmental impacts with no consideration of social and economic impacts and mechanisms. To overcome the limits of current LCA, three mechanisms have been proposed in the literature: (1) broadening the indicators by including social and economic indicators in addition to the environmental impacts; (2) broadening the scope of analysis from product-level assessment to national and global levels; (3) deepening the assessment by inclusion of more mechanisms to account for interrelations among the system elements, uncertainty analysis, stakeholder involvement, etc. With these developments, LCA has been evolving into a new framework called Life Cycle Sustainability Assessment (LCSA). Practical application of LCSA requires integration of various methods, tools, and disciplines. In this study, a comprehensive literature review is conducted to investigate recent developments, current challenges, and future perspectives in the LCSA literature. According to the review, a high number (40%) of LCSA studies are from the environmental science discipline, while contributions from other disciplines such as economics (3%) and social sciences (9%) are very low. On broadening the scope of analysis, 58% of the studies are product-level works, while 37% quantified the impacts at national level and achieved an economy-wide analysis, and only 5% of the studies were able to quantify the global impacts of products using LCSA framework. Furthermore, current applications of LCSA have not considered the rebound effects, feedback mechanisms, and interrelations of the system of interest sufficiently. To address these challenges, we present a complete discussion about the overarching role of systems thinking to bring tools, methods and disciplines together, and provide practical examples from the earlier studies that have employed various system-based methods. We discuss the importance of integrated system-based methods for advancement of LCSA framework in the following directions: (1) regional and global level LCSA models using multi-region input-output analysis that is capable of quantitatively capturing macro-level social, environmental, and economic impacts; (2) dealing with uncertainties in LCSA during multi-criteria decision-making process and expert judgments in weighting of LCSA indicators; and (3) integration of system dynamics modeling to reveal complex interconnections, dependencies, and causal relationships between sustainability indicators.

**Keywords:** life cycle sustainability assessment; systems thinking; multi-region input-output analysis; system dynamics; uncertainty; triple bottom line sustainability accounting

## 1. Introduction

Life Cycle Sustainability Assessment (LCSA) is an interdisciplinary framework for integration of models rather than a method itself, and therefore there are many opportunities for integration of tools and methods to improve the applicability of LCSA [1,2]. Until now, practical use of LCSA in sustainability science and engineering is limited and this framework still continues to evolve within the scientific community [3,4]. The EU's 6th Framework program-funded Coordination Action for Innovation in Life Cycle Analysis for Sustainability (CALCAS) aims to overcome the limits of current Life Cycle Assessment (LCA) methods by presenting two mechanisms such as deepening and broadening to further advance the life-cycle sustainability modeling [5,6]. According to Guinée [7] and Guinée and Heijungs [8], broadening of LCSA can be accomplished by including environmental, social and economic aspects and enlarging the system boundary from a micro-level (process-based) to macro-level (economy-wide) analysis. Additionally, to deepen the LCSA framework, there is a need for considering the dynamic relationships among the LCSA parameters and analyzing the causality mechanisms between the system parameters, such as economic, social and environmental metrics [9].

There are still many unaddressed questions related to broadening and deepening of LCSA [5]. In a research on concept, practice and future directions for LCSA [10], the major shortcomings of LCSA framework are listed as: (a) lack of understanding the mutual dependencies and complex interactions among the sustainability indicators; and (b) reductionist approach and myopic view by looking at the Environmental LCA (E-LCA), Social LCA (S-LCA), and Life Cycle Costing (LCC) assessment results separately. In a recent work concentrating on the challenges and future of LCSA framework [7], extending the system boundary of LCSA from a micro to macro level analysis, dealing with complex dynamic relationships between social, economic and environmental indicators, integration of more quantitative social indicators, dealing with uncertainties, and developing scenario-based decision support tools for multi-criteria decision making are listed among the most critical challenges. Similar critical and futuristic viewpoints are also presented in a work conducted by Cucurachi and Suh [11]. The researchers also concluded that LCSA should further evolve into a tool for a comprehensive quantitative sustainability assessment by using a wide range of socio-economic indicators, embracing causal relationships, and focusing on uncertainties in LCA results during the multi-objective decision-making. According to the aforementioned points that address critical issues for the future LCSA, broadened and deepened LCSA should definitely go beyond a snapshot (isolated and without consideration of temporal aspect) of sustainability assessment based on the environmental, economic and social sustainability analysis of products or process [10]. Therefore, LCSA needs to be further developed using systemic approaches dealing with uncertainties, concentrating on stakeholder involvement in multi-criteria decision-making, focusing on causal dynamic relationships between the pillars of sustainability.

## 2. Literature Review

According to the literature review ("Life Cycle Sustainability Assessment" in either title, abstract, or keywords for time span between 2000 and 2017, accessed on 10 January 2017 in Scopus database), there is a lack of cohesion between associated disciplines, which is one of the most important barriers against addressing the aforementioned research needs and challenges. Figure 1 shows the percentage of papers related to LCSA from different disciplines. Although there is a growing interest in LCSA frameworks, LCSA studies are limited to certain disciplines. A high number (40%) of LCSA studies are from the environmental science discipline, while contributions from other disciplines such as economics and social sciences are very low (see Figure 1). Furthermore, only 56 studies out of 109 studies found in the literature were applied works, while the rest are either qualitative or review studies. Because this study investigates the issues related to applications of LCSA, we investigated the works that are applied though a case study and didn't include the qualitative papers in our literature review analysis.

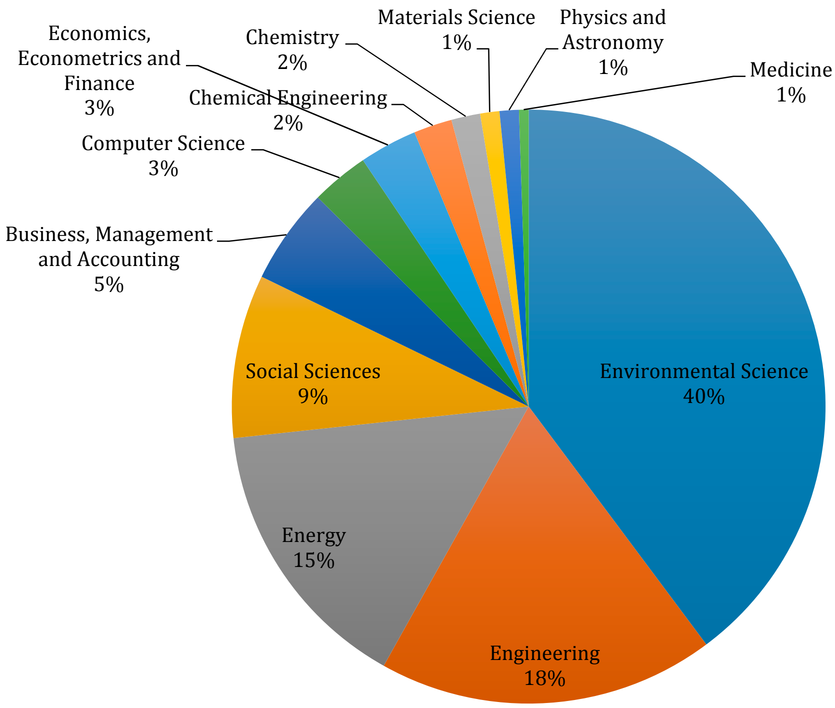


**Figure 1.** Percentage of peer-reviewed journal and conference papers (LCSA references from the bibliometric analysis of Scopus databases on "Life Cycle Sustainability Assessment" in either title, abstract, or keywords for time span between 2000 and 2017, accessed on 10 January 2017).

Applications of LCSA studies are classified based on three dimensions of improvement in LCSA in accordance with Guinée et al. [1]: (1) broadening of impacts from environmental impacts only to inclusion of economic and social indicators; (2) broadening the level of analysis from product level to economy-wide and global analyses; and (3) deepening the assessment mechanism by inclusion of scenario assessment, rebound effects, feedbacks and interconnections, multi-criteria decision-making/stakeholder involvement, and uncertainty analysis. Among the 109 studies, 56 studies presented an application of LCSA with various case studies, while great majority of the other studies focused on specific methodological aspects of LCSA and few conducted a literature review on certain aspects of LCSA.

According to bibliometric analysis, 58% of the studies (33 studies) are product-level works, while 37% of the studies quantify the impacts at national level and achieved an economy-wide analysis. On the other hand, only three studies were able to quantify the global impacts of products using LCSA framework. These three studies present an application of a new socio-economic indicator to measure geopolitical supply risks of materials of products [12,16,34]. Although the method proposed is a useful indicator that provides important insights for geopolitical risks, it relies on the first layers of supply chain outside of a country investigated. In other words, the proposed method considers the first layer of the multi-stage supply chain (outside of a country) as applied in the bilateral trade data analyses. This drawback might cause underestimation of impacts, which is known as truncation error [67]. Although encompassing the entire supply chain can be very challenging using process-level data, there are methods, such as hybrid input-output life cycle assessment, which are capable of capturing the impacts associated with the entire supply chain and can eliminate the truncation error (cut-off error) [68–71]. As an alternative method, use of multi-regional input-output modeling can help cover the entire global supply chain and eliminate the truncation error. The recent applications of this method are discussed in Section 3.1 as a possible way to broaden the scope of the LCSA. According to the literature review, all studies covered environmental dimensions of sustainability, while only one study did not include economic dimensions and four studies did not consider social dimensions in their LCSA application. This finding shows that almost all applications of LCSA studies achieved the first dimension of improvement in LCSA as broadening of indicators (impacts): inclusion of social and economic dimensions in addition to the environmental impacts. Although there might be other studies quantifying or assessing economic, social, and environmental impacts of goods, products, or services, these studies were not investigated. This is a drawback of the bibliometric analysis relying on the definition of LCSA, while ignoring the other studies encompassing these three dimensions with different methods than LCSA. Some other issues found in the literature are the inconsistency between indicator selection, challenges in quantification of social indicators, and assigning weight (prioritization) of different indicators. These challenges and some applications of LCSA studies addressing these challenges are presented in Section 3.1.

Literature analysis in deepening of LCSA showed that 46% of studies adopted scenario/policy assessment. Seventeen studies conducted uncertainty analyses for their LCSA results and 38 studies applied multi-criteria decision making or stakeholder involvement in LCSA. On the other hand, only two studies utilized a complete systems thinking approach encompassing feedback mechanisms and interconnections (indirect effects, the dynamic relationships among social, economic, and environmental dimensions, market mechanisms, etc.) among the system of interests. Such mechanisms are important because they can take into account system effects and consequences choices and policies proposed. For instance, a large-scale bioenergy production may affect the food supply, social structure (employment in different sectors), food prices, land use, and other indicators important to society, economy, and the environment. There were also no studies analyzing rebound effects in LCSA. These findings showed that deepened mechanisms are not sufficiently covered in the LCSA community.

Addressing LCSA challenges can only be achieved using transformative and systemic approaches through involvement across disciplines [72]. In a recent study, Marvuglia et al. [73] proposed a conceptual framework through integrated computational methods calling for dynamic system modeling and involvement of stakeholders in multi-criteria decision-making. The authors present an important attempt to facilitate cooperation between scientists from different disciplines under the umbrella of a life-cycle sustainability analysis. However, until now, these challenges are mostly mentioned in conceptual studies rather than empirical works [1,3,4,8,53,72,74–76]. The practical examples and use of integrated methods and approaches are still less studied and limited to a group of researchers as stated in Table 1. Future direction for developing methods and tools should help the scientific community to move from approaches based on isolated disciplines towards inter/trans-disciplinarity and a holistic/systematic perspective in order to address emergent issues related to sustainability problems [77]. In this regard, systems thinking plays a crucial role to assist this move.

**Table 1.** Bibliometric analysis of applied LCSA studies in between 2000 and 2017.

| ID# | Author and Year | Year | Broadening Indicators | | | Broadening Boundary (Scope) | | | Deepening | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Environmental | Economic | Social | Product-Level | National | Global | Scenario/ Policy Assessment | Rebound Effects | Interconnections and Feedbacks | MCDM/ Stakeholder Involvement | Uncertainty |
| 1 | Gemechu, E.D., Sonnemann, G., Young, S.B. [12] | 2017 | ✔ | ✔ | ✔ | | | ✔ | | | | | |
| 2 | Ren, J., Ren, X., Liang, H., Dong, L., Zhang, L., Luo, X., Yang, Y., Gao, Z. [13] | 2016 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | ✔ |
| 3 | Van Kempen, E.A., Spiliotopoulou, E., Stojanovski, G., de Leeuw, S. [14] | 2016 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | |
| 4 | Sou, W.I., Chu, A., Chiueh, P.T. [15] | 2016 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | ✔ |
| 5 | Helbig, C., Gemechu, E.D., Pillain, B., Young, S.B., Thorenz, A., Tuma, A., Sonnemann, G. [16] | 2016 | ✔ | ✔ | ✔ | | | ✔ | | | | | |
| 6 | Azapagic, A., Stamford, L., Youds, L., Barteczko-Hibbert, C. [17] | 2016 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | ✔ | ✔ |
| 7 | Onat, N.C., Kucukvar, M., Tatari, O. [18] | 2016 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | ✔ | | ✔ |
| 8 | Gumus, S., Kucukvar, M., Tatari, O. [19] | 2016 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | ✔ | ✔ |
| 9 | Touceda, M.I., Neila, F.J., Degrez, M. [20] | 2016 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | |
| 10 | Pizzirani, S., McLaren, S.J., Forster, M.E., Pohatu, P., Porou, T.T.W., Warmenhoven, T.A. [21] | 2016 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | |
| 11 | Onat, N.C., Kucukvar, M., Tatari, O., Egilmez, G. [9] | 2016 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | ✔ | | |
| 12 | Luu, L.Q., Halog, A. [22] | 2016 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | | |
| 13 | Onat, N.C., Kucukvar, M., Tatari, O., Zheng, Q.P. [23] | 2016 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | ✔ | ✔ |
| 14 | Climaco, J.C.N., Valle, R. [24] | 2016 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |

**Table 1.** *Cont.*

| ID# | Author and Year | Year | Broadening Indicators | | | Broadening Boundary (Scope) | | | Deepening | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Environmental | Economic | Social | Product-Level | National | Global | Scenario/ Policy Assessment | Rebound Effects | Interconnections and Feedbacks | MCDM/ Stakeholder Involvement | Uncertainty |
| 15 | Kalbar, P.P., Birkved, M., Nygaard, S.E., Hauschild, M. [25] | 2016 | ✔ | ✔ | ✔ | | ✔ | | | | | ✔ | ✔ |
| 16 | Galán-Martín, Á., Guillén-Gosálbez, G., Stamford, L., Azapagic, A. [26] | 2016 | ✔ | ✔ | ✔ | | ✔ | | | | | ✔ | |
| 17 | Moslehi, S., Arababadi, R. [27] | 2016 | ✔ | ✔ | ✔ | ✔ | | | | | | | |
| 18 | Atilgan, B., Azapagic, A. [28] | 2016 | ✔ | ✔ | ✔ | | ✔ | | | | | ✔ | |
| 19 | Huang, B., Mauerhofer, V. [29] | 2016 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | | |
| 20 | Onat, N.C., Gumus, S., Kucukvar, M., Tatari, O. [30] | 2016 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | ✔ | ✔ |
| 21 | Dong, Y.H., Ng, S.T. [31] | 2016 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 22 | Gencturk, B., Hossain, K., Lahourpour, S. [32] | 2016 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | | ✔ |
| 23 | Steen, B., Palander, S. [33] | 2016 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 24 | Gemechu, E.D., Helbig, C., Sonnemann, G., Thorenz, A., Tuma, A. [34] | 2016 | ✔ | ✔ | ✔ | | | ✔ | | | | | ✔ |
| 25 | Luu, L.Q., Halog, A. [35] | 2016 | ✔ | ✔ | ✔ | | ✔ | | | | | | |
| 26 | Wagner, E., Benecke, S., Winzer, J., Nissen, N.F., Lang, K.-D. [36] | 2016 | ✔ | | | ✔ | | | | | | | |
| 27 | Kalbar, P.P., Karmakar, S., Asolekar, S.R. [37] | 2016 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | ✔ |
| 28 | Keller, H., Rettenmaier, N., Reinhardt G.A. [38] | 2015 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | |
| 29 | De Luca, A.I., Iofrida, N., Strano, A., Falcone, G., Gulisano, G. [39] | 2015 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | ✔ | |
| 30 | Ren, J., Manzardo, A., Mazzi, A., Zuliani, F., Scipioni, A. [40] | 2015 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | ✔ |
| 31 | Yu, M., Halog, A. [41] | 2015 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 32 | Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., Hewage, K. [42] | 2015 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | |

**Table 1.** *Cont.*

| ID# | Author and Year | Year | Broadening Indicators | | | Broadening Boundary (Scope) | | | Deepening | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Environmental | Economic | Social | Product-Level | National | Global | Scenario/ Policy Assessment | Rebound Effects | Interconnections and Feedbacks | MCDM/ Stakeholder Involvement | Uncertainty |
| 33 | Peukert, B., et al. [43] | 2015 | ✔ | ✔ | ✔ | ✔ | | | | | | | |
| 34 | Stamford, L., Azapagic, A. [44] | 2014 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | ✔ | |
| 35 | Akhtar, S., Reza, B., Hewage, K., Shahriar, A., Zargar, A., Sadiq, R. [45] | 2014 | ✔ | ✔ | | ✔ | | | | | | ✔ | |
| 36 | Martínez-Blanco, J., et al. [46] | 2014 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 37 | Kucukvar, M., Gumus, S., Egilmez, G., Tatari, O. [47] | 2014 | ✔ | ✔ | ✔ | | ✔ | | | | | ✔ | ✔ |
| 38 | Lu, B., Li, B., Wang, L., Yang, J., Liu, J., Wang, X.V. [48] | 2014 | ✔ | ✔ | ✔ | ✔ | | | | | | | |
| 39 | Onat, N.C., Kucukvar, M., Tatari, O. [49] | 2014 | ✔ | ✔ | ✔ | | ✔ | | | | | | ✔ |
| 40 | Onat, N.C., Kucukvar, M., Tatari, O. [50] | 2014 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | | |
| 41 | Kucukvar, M., Noori, M., Egilmez, G., Tatari, O. [51] | 2014 | ✔ | ✔ | ✔ | | ✔ | | | | | ✔ | ✔ |
| 42 | Valdivia, S., Ugaya, C.M.L., Hildenbrand, J., Traverso, M., Mazijn, B., Sonnemann, G. [52] | 2013 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 43 | Pesonen, H.-L., Horn, S. [53] | 2013 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 44 | Wood, R., Hertwich, E.G. [54] | 2013 | ✔ | ✔ | ✔ | | ✔ | | | | | | |
| 45 | Ostermeyer, Y., Wallbaum, H., Reuter, F. [55] | 2013 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 46 | Foolmaun, R.K., Ramjeawon, T. [56] | 2013 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | ✔ | |
| 47 | Vinyes, E., Oliver-Solíæ, J., Ugaya, C., Rieradevall, J., Gasol, C.M. [57] | 2013 | ✔ | ✔ | ✔ | ✔ | | | | | | | |
| 48 | Manzardo, A., Ren, J., Mazzi, A., Scipioni, A. [58] | 2012 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | ✔ |
| 49 | Stamford, L., Azapagic, A. [59] | 2012 | ✔ | ✔ | ✔ | | ✔ | | ✔ | | | | |
| 50 | Traverso, M., Finkbeiner, M., Jørgensen, A., Schneider, L. [60] | 2012 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | |

**Table 1.** *Cont.*

| ID# | Author and Year | Year | Broadening Indicators | | | Broadening Boundary (Scope) | | | Deepening | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Environmental | Economic | Social | Product-Level | National | Global | Scenario/ Policy Assessment | Rebound Effects | Interconnections and Feedbacks | MCDM/ Stakeholder Involvement | Uncertainty |
| 51 | Traverso, M., Asdrubali, F., Francia, A., Finkbeiner, M. [61] | 2012 | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ | |
| 52 | Menikpura, S.N.M., Gheewala, S.H., Bonnet, S. [62] | 2012 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | |
| 53 | Nzila, C., Dewulf, J., Spanjers, H., Tuigong, D., Kiriamiti, H., van Langenhove, H. [63] | 2012 | ✔ | ✔ | | ✔ | | | | | | ✔ | |
| 54 | Schau, E.M., Traverso, M., Lehmannann, A., Finkbeiner, M. [64] | 2011 | ✔ | ✔ | ✔ | ✔ | | | | | | | |
| 55 | Moriizumi, Y., Matsui, N., Hondo, H. [65] | 2010 | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ | ✔ |
| 56 | Zhou, Z., Jiang, H., Qin, L. [66] | 2007 | ✔ | ✔ | | ✔ | | | | | | ✔ | |

*Why Systems Thinking and How It Relates to LCA?*

A system is defined as "an interconnected set of elements that is organized in a way that achieves something" [78]. In other words, a system must have elements, interconnections, and function or purpose, which can be found in any products (goods and services), assessed using the LCA approach. Furthermore, the LCA itself is a system-based tool since it aims to track environmental impacts of products (systems) through its complex global supply chains (systems). In this sense, the LCA approach deals with systems that are nested within systems. Like LCA, LCSA is a system-based tool and deals with systems of systems with much broader and deeper considerations (revealing macro-level impacts, consideration of social, and economic impacts, and taking into account underlying mechanisms). These aspects require LCSA practitioners and researchers to adopt systems thinking, which is defined as the ability to see the parts of bigger mechanisms, recognizing patterns and interrelationships, and restructuring these interrelationships in more effective and efficient ways. According to the literature review on LCSA, there is a strong need for systems thinking perspectives and how it can be adopted towards coping with the challenges in LCSA. Hence, in this study, the overarching role of systems thinking is highlighted as a catalyzer of harmonizing tools, methods, and disciplines. The authors first explain the importance of "systems thinking" and present example applications for possible methodological approaches that can be used for advancing the current LCSA framework in the following directions: (1) regional and global level LCSA models using multi-region input-output analysis capable of capturing macro-level social, environmental, and economic impacts quantitatively; (2) dealing with uncertainties in LCSA during multi-criteria decision-making process and involving expert judgments in weighting of LCSA indicators; and (3) integration of system dynamics modeling to reveal complex interconnections, dependencies, and causal relationships between sustainability indicators.

## 3. Systems Thinking as a Catalyst for Harmonizing Tools, Methods, and Disciplines

Addressing the research gaps in the LCSA framework requires the adoption of system thinking. Although LCA and LCSA frameworks are both system-based approaches, meaning they allow us to track impacts over supply chains and basic relationships among the processes involved, they lack the understanding of interconnectedness and feedback relationships among different system elements (disciplines, processes, services, products, their surrounding environment, and their relationship with sustainability impacts). While there are studies highlighting the importance of use of integrated system-based tools [72,79,80], most of the applications do not consider the causal and feedback relationships. Systems thinking can allow us to improve our ability to understand elements (processes, indicators, sub-systems), their interconnections, ask "what-if" questions about possible future impacts, and provide a better basis for practitioners and the scientific community towards redesigning systems (products, processes, supply chains, services, etc.). Adopting systems approach and life cycle thinking are crucial to deal with wicked problems of sustainability [81]. Integration of systems thinking methods and tools can redefine the role of LCA by bringing its scope beyond "quantification/interpretation of the sustainability impacts" to a domain where causal relationships among different indicators and sub-systems are revealed and to a solid base for system improvement. Such approaches have been widely applied in ecological, socio-ecological, and socio-technological systems research [82,83]. As the LCSA framework proposes a broader and deeper perspective, harmonization of these methods/tools/disciplines to address more complex problems is inevitable and necessary. In this regard, an outlook of the existing system-based tools and their recent applications, challenges, and possible future directions for LCSA framework is discussed in the following sections.

### *3.1. Broadening the Object of Analysis: Revealing Macro-Level Impacts Using Single and Multi-Region Input-Output Analysis*

Almost all case studies using LCSA focused on the "broadening of impacts" dimension rather than "broadening of system boundary" of analysis focusing on macro level impacts of production and consumption at national and global economy level. Obviously, with a globalized economy, while consumption of products takes place in some parts of the world, manufacturing and consumption occur in different parts of the world. However, the scope of the traditional LSCA studies is predominantly at product level and does not address macro-level impacts and cannot capture a majority of upstream impacts due to narrowly defined system boundaries (the cutoff criteria) [51,84,85]. To promote sustainable consumption and production policies and to understand the social, economic and environmental effects of consumption, there is a dire need to capture whole life cycle sustainability impacts across international supply chains. The importance of consideration of all indirect supply chain-related impacts (is also called economy-wide macro-level analysis) within the LCSA framework is emphasized in the Guinée et al. [1] as "inter-related global sustainability issues require more comprehensive approaches in which the macro-level impacts (economy-wide, or global) covering entire supply chain is essential to reveal sustainability impacts of products, services, or systems". This is because process-based models involve a limited number of processes without tracing the entire supply chains of products, and the inclusion or exclusion of processes is decided on the basis of subjective choices, which create the so-called system boundary problem [67,86,87]. Past studies on the environmental footprint of sectors also showed that process-based models suffer from significant truncation errors, which can be of the order of 50% or higher [70,88,89].

At this point, Input-Output (IO) based LCA models provide a top-down analysis using sectoral monetary transaction matrixes considering complex interactions between the sectors of nations' economy [90–93]. Guinée et al. [1] emphasized the importance of the IO analysis for the future of LCSA and discussed the necessity of system-based sustainability assessment methods including hybrid LCA and IO LCA. In addition, Jeswani et al. [71] also discussed the importance of combination of IO analysis with LCA to create hybrid life cycle models in order to capture intra-sectoral flows on the meso-level LCSA. Although the applications of IO-based LCSA studies are not abundant in the literature, a handful of papers addressed the importance of extended system boundaries for the LCSA. For example, Wood and Hertwich [54] discussed the comprehensive scope of IO analysis in LCSA for socio-economic assessment. In response to the current research gaps related to comprehensive LCSA methods, Kucukvar et al. [51] built the first hybrid LCSA in which IO-based LCSA along with compromise programming methods used for a multi-criteria decision analysis of warm-mix and hot-mix asphalt mixtures. In other work, Onat et al. [49] and Tatari et al. [94] demonstrated usefulness of using IO analysis for quantification of social, economic, and environmental impacts for LCSA of residential and commercial buildings. In addition, Onat et al. [50] constructed a hybrid LCSA model combining process-based and IO-based approaches for LCSA of alternative vehicles in the United States.

Although single-region IO models are used in previous studies to enlarge the system boundary of LCSA to national economy, Multi Region Input–Output (MRIO) models can be a better modeling approach in the estimation of life-cycle impacts of production and consumption at global scale. Although the majority of previous LCSA studies using IO analysis were case studies focusing on sustainability impacts of products or processes in a single country [95], a MRIO analysis is critical for taking into account the role of international trade [96,97]. This is important since the majority of countries are open economies and life-cycle sustainability impacts of products are found in the geographical boundary of multiple countries [98,99]. A recent study also emphasized that significant proportion (64%) of total environmental, social and economic impacts stem from international trade [100]. Owing to the importance of growing global trade, MRIO models have become a widely discussed topic and they are used for regional and international policy making in environmental impact analysis [101,102]. Currently, there are a number of initiatives aimed to compile large-scale global MRIOs such as Externality Data and Input–Output Tools for Policy Analysis (EXIOPOL), Global Trade Analysis Project (GTAP), World Input–Output Database (WIOD), Global Resource Accounting Model (GRAM), and EoRA [103–106].

MRIO databases (e.g., EoRA, EXIOBASE, GRAM, WIOD and GTAP) are extensively used in order to capture the role of international trade for a holistic environmental footprint analysis. For example, some studies include carbon, water, and ecological land footprints of households [107,108], consumption and production [85,109], international trade [110], transportation [111], and nations [112,113]. Although these MRIO databases are extensively utilized for analyzing the regional and global environmental impacts, the integration of MRIO analysis with LCA is often limited. As a first empirical study, Wiedmann et al. [114] developed a two-region hybrid IO model to avoid truncation that can lead to erroneous rankings of LCA results. The researchers presented a case study showing usefulness of hybrid LCA for accounting the indirect greenhouse gas emissions of energy technologies in the United Kingdom (UK). In other work, Malik et al. [115] built a hybrid LCA for measuring the direct, as well as indirect energy and carbon impacts of production of bio-crude from algal resources, and used a global multi-regional LCA approach. The authors used a detailed MRIO table developed in the Industrial Ecology Virtual Laboratory for Australia consisting of 19 Australian regions and 344 industry sectors [116]. Hertwich et al. [117] also constructed a hybrid LCA model using the EXIOBASE database as a global MRIO database. The researchers analyzed the environmental impacts and resource requirements of different low-carbon electricity generation technologies for several electricity production sectors such as wind power, solar power, hydropower, and gas-and coal-fired power plants with carbon dioxide capture and storage. In a recent work, Ward et al. [118] developed a hybrid LCA model that allows estimating carbon dioxide impacts of new process technologies. The researchers utilized three global MRIO databases such as EXIOBASE, GTAP and WIOD and compared the LCA results using each MRIO database separately. However, the applications of above-mentioned MRIO-based LCA studies are mostly bounded by ecological, energy, carbon and water footprint categories for nation's production and consumption activities. Among the 56 case studies reviewed, the majority of studies used a detailed process-based LCSA (P-LCSA). A few studies used an IO-based hybrid LCSA analysis in order to extend the system boundary of analysis to economy level. However, there is no empirical work found among the case studies, which conduct a global MRIO analysis to broaden the system boundary to the global economy.

### *3.2. Broadening the Scope of System Boundary and Indicators: Triple Bottom Line Sustainability Accounting*

To broaden the scope of LCSA indicators, triple bottom line (TBL) is used as an accounting framework, which integrates the three pillars of sustainability: society, environment, and economy [119]. Over the past decade, the interest in TBL accounting has been growing in industry, nonprofit organizations, and governments. In the literature, a few researchers have broadened the scope of indicators and system boundary simultaneously using an IO analysis, which is capable to quantify not only environmental pressures, but also social and economic impacts at macro level [120,121]. For example, the "Balancing Act" study is the first empirical study on macro level sustainability assessment of sectors using a TBL approach. The researchers from the Integrated Sustainability Assessment (ISA) research group at the University of Sydney analyzed the environmental, economic and social impacts of Australian manufacturing and service sectors based on 10 macro-level sustainability indicators [120]. Similarly, the research team at the University of Central Florida utilized an IO analysis to build the first comprehensive TBL sustainability assessment framework of the U.S. economy. In their model, the Carnegie Mellon University Green Design Institute's EIO-LCA tool [69] is extended with additional socio-economic and ecological land use indicators for a complete TBL sustainability analysis. The researchers used gross operating surplus (GOS), gross domestic production (GDP) and imports for economic indicators: income, tax and injuries for social indicators; and water, energy, carbon and land footprint for environmental indicators [122].

In addition to the abovementioned studies focusing on sector-specific TBL analysis, several researchers used over 40 indicators to broaden the LCSA framework with additional indicators. On the other hand, a few studies found in the literature used a combined application of IO analysis and LCSA. For instance, Kucukvar et al. [51] built an IO-based hybrid LCSA model based on

16 sustainability indicators and analyzed the TBL sustainability impacts of road construction from hot-mix and warm-mix asphalt mixtures in the United States. Among the environmental indicators, water, energy, carbon, and land footprint, hazardous waste and toxic releases are quantified. GOS, GPD, Tax, Import, Income and injuries are considered socio-economic indicators. In a recent work, Onat et al. [50,123] utilized a holistic IO method for quantification of macro-level economic, social, and environmental impacts of alternative passenger vehicles. Among socio-economic indicators, the researchers used various socio-economic indicators such as human health, income, injuries, government tax, employment at various skill levels, emission cost, and profit, GDP and import. Among LCSA studies, the Sustainable Industrial Systems research group from the University of Manchester used a vast number of social, economic and environmental indicators. The researchers primarily used a process-based LCSA framework for the life cycle sustainability impacts of electricity production in U.K. In addition, scenario-based analysis is also conducted to see the long-term socio-economic and environmental implications of electricity generation policies [44,124]. Similarly, Traverso et al. [60] built a process-based LCSA model and life cycle costing is used for economic impact analysis of sustainability assessment of the assembly step of photovoltaic (PV) modules production. Among the social sustainability indicators, number of workers, worker's gender type, and average wage rate are considered. However, the authors concluded that there are still challenges for a useful application and the selection of social LCA indicators and how to set weights for determining the importance of life cycle sustainability indicators. To that end, most of the studies reviewed tried to broaden the scope of indicators rather than the scope of system boundary using IO analysis and/or hybrid LCA approaches.

### *3.2. Deepening the Assessment: Revealing Dynamic, Causal, and Trade-Off Relationships*

The goal of LCA is to assess the environmental impact of products from a system perspective and to identify possible improvement strategies [125,126]. Developing strategies to improve the environmental, social, and economic performance of a product cannot be realized with an isolated evaluation of impacts in these different domains as system-of-interest, considering the fact that environment, society, and economy are interconnected and affect one another [9]. For instance, if goods or services become cheaper due to improved efficiency, meaning an improved environmental performance, a consumer may benefit from these products more often and eventually may have a greater environmental impact or offset the potential environmental impact reduction [127]. This feedback from the system-of-interest is called rebound effect and it mainly represents the interconnection between the system-of-interest (product), economy (LCC), and the environment. There are also indirect effects that cannot be captured with traditional LCA approaches. For example, biofuels can have indirect land use change offsetting the environmental benefits [128]. Capturing indirect effects requires a proper boundary definition and an understanding of the underlying mechanism causing the indirect effect [129–131]. LCA relies on cause-effect relationships in the environment and focuses on understanding the environmental consequences of actions [125]. However, traditional cause-effect relationships can be misleading and insufficient for explaining indirect effects as the complexity of a system increases [132]. Such static approaches cannot capture the major relationships between the system-of-interest (product, process, service, sector, etc.) and its surrounding environment (social, economic, and environmental systems interacting with the system-of-interests). Understanding system behavior, revealing the dynamic and causal relationships are essential to be able to, not just to predict, but envision the future impacts and redesign systems by determining major factors malfunctioning systems [78]. System dynamics (SD) modeling philosophy is one of the most suitable methods for achieving such objectives since it helps defining the multi-dimensional causal relationships, potential delays, and feedback mechanisms quantitatively [133–135]. Hence, integration of SD to LCSA framework can advance the LCSA as a decision-support tool and provide a better foundation for effective policy making. In this regard, Onat et al. [9] developed a SD model to analyze sustainability impacts of alternative vehicle technologies. For the first time, SD methodology is integrated to LCSA framework to broaden (economy wide assessment, inclusion of social and economic parameter) and deepen (interconnections, dynamics, feedbacks) the assessment. Life cycle sustainability impacts of alternative vehicle technologies are analyzed from a systems perspective by considering dynamic and causal relationships among transportation sector, economy, and the environment. Figure 2, the causal loop diagram, shows these major relationships among the system parameters (sub-models). The study provided important findings and showed how SD can be utilized to provide a better understanding of underlying mechanisms within the system of interest and its TBL impacts. The proposed model is composed of four comprehensive sub-models with one being the system-of-interest (transportation system) and its triple bottom line impacts (sub-models of the environment, economy, and society). These four major sub-models contain smaller sub-models such as public welfare, human health, employment, GDP, vehicle ownership cost, $CO_2$ emissions and climate change, particulate matter formation (PMF), photochemical oxidant formation (POF), population, travel need, and on-road fuel efficiency. In total, twelve causal loops (causal mechanisms) are identified and their relationships are mathematically presented. These loops represent the feedback relationships among the main parameters of the model. They have either reinforcing or balancing effect and the total feedback impact depends on their relative strengths over time compared to one another. In other words, reinforcing and balancing loops cancel each other at varying degrees and whatever remains is the total feedback effect. In this system, feedback impacts are smaller compared to other impacts from exogenous drivers (impacts coming from outside of the defined system boundary) such as economic and population trends, greenhouse gasses from rest of the economy and world. Although a significant behavioral change is not observed resulting from feedback impacts, there might be cases where the system behavior changes significantly due to feedback impacts. The study provides the first empirical application and methodological framework for advancement of LCSA as it addresses most of the current research gaps in the LCSA literature. For more detailed information please see Onat et al. [9].

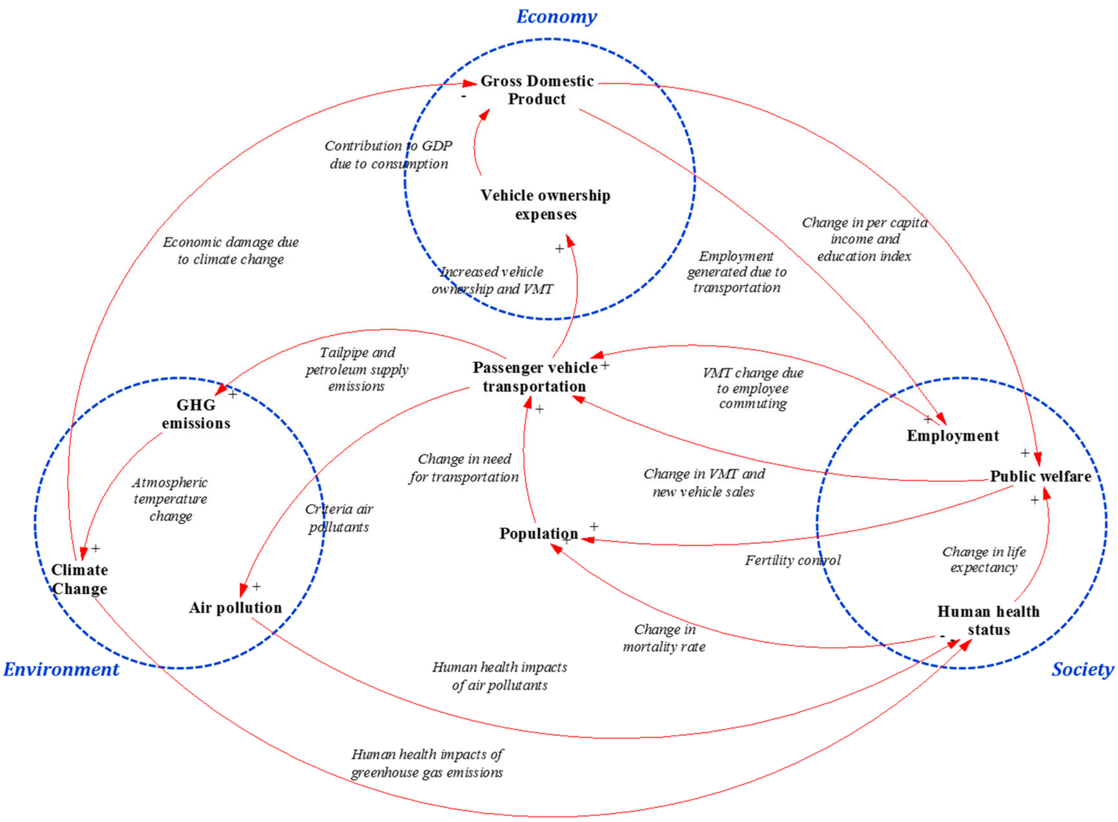


**Figure 2.** Causal loop diagram of the model.

Considering that LCSA framework deals with various dimensions—economy, environment and the society—integration of multi-criteria decision support tools is becoming crucial to provide a very critical guidance to LCA practitioners [11,71]. LCSA considers positive impacts such as social and economic (e.g., employment, profit, economic value added), as well as negative impact such as the associated environmental pressures (e.g., toxic emissions, waste, land use). When we try to make decisions on the sustainability of products, unwanted environmental burdens and socio-economic benefits easily become conflicting objectives. Therefore, multi-criteria decision making (MCDM) approaches have become a very robust and necessary approach for such circumstances, being able to overcome issues associated with such tradeoffs. MCDM methods are highly useful and practical for decision-makers to involve a full range of social, economic and environmental indictors for an integrated sustainability assessment [71]. At this point, there are several important challenges in MCDM such as how to assign weights and aggregate the indicator results [7,47,136,137]. A limited number of researchers have focused on the MCDM and integrated expert weighting for sustainable product selection based on LCSA results [60,138,139]. In the literature, applications of MCDM methods combined with LCA results are abundant; however, few studies applied MCDM methods for dealing with multiple criteria, expert judgments, and uncertainties in LCSA [58,140]. To give some examples, Onat et al. [23] used a combined application of multi-criteria optimization and an IO-based hybrid LCSA. The researchers used a compromise programming as a tool for MCDM and applied their method for optimum vehicle allocation problem based on 16 macro-level sustainability impacts. Expert weighting and scenarios analysis are used for an integrated decision-making. The authors also concluded that the proposed method could be used as a practical decision-making platform when deciding which type of product to promote given each alternative's comparative and conflicting environmental, economic, and social impacts. In another work, Onat et al. [30] developed an IO-based hybrid LCSA model using several macro-level social, economic, and environmental indicators. The LCSA results are then combined with Intuitionistic Fuzzy Sets and Technique for Order-Preference by Similarity to Ideal Solution (TOPSIS) approaches [30]. In their work, an intuitionistic fuzzy set method is utilized to determine the weights of each social, economic and environmental metric based on inputs from expert judgments. The scenario-based Intuitionistic Fuzzy MCDM and TOPSIS methods are utilized to rank the life cycle sustainability performance of alternative passenger vehicles. The research also used Life Cycle Sustainability Triangle (also used in Traverso et al. [60]) in order to reflect the sensitivity of expert weighting in multi-criteria decision-making based on LCSA results. In other work, Kucukvar et al. [51] used a compromise programming to solve the multi-objective optimization problem, which has the tradeoffs between environmental and socio-economic indicators. The researchers built their optimization model upon LCSA results to determine the optimal asphalt pavement allocation strategy for a functional unit of 1 km pavement using sustainability weights ranging between 0 and 1. The researchers used several weighting scenarios for LCSA indicators and used a Monte Carlo simulation technique in order to deal with possible uncertainties in LCSA results. Kucukvar et al. [47] developed the first fuzzy-based MCDM model applied for the ranking of best pavement design. The authors used a double layer fuzzy decision-making method, which assigns weight for each life cycle phase as well as considers uncertainties in life cycle sustainability performance of alternatives. In their research, the authors used linguistic terms such as "very good", "good", "very bad", etc. to deal with uncertainties in final LCSA results. Overall, the aforementioned studies represent the recent application of LCSA and MCDM as well as scenario-based group decision making considering expert judgments and uncertainties in environmental, economic and social impact categories.

## 4. Challenges and Future Directions

There are various challenges associated with abovementioned tools and their application within the LCSA framework. First, the selection of indicators remains as a challenging point of LCSA framework. According to the literature review, a great majority of LCSA (52 out of 56) studies focused on the "broadening of impacts" dimension. However, it is critical to note that economic and social impacts are still limited to a few indicators. For instance, economic impacts are mostly calculated using the LCC analysis that fails to capture the full dimension of economic sustainability [54,141]. Several other key financial indicators such as gross value added, profit, import dependency, levelized cost, profit, etc. can be used to extend the depth of the economic analysis [59,89]. So far, the applications of social indicators are also not studied sufficiently. S-LCA is still in its infancy and the applicability of S-LCA is highly limited due to data needs, difficulties in data quantification, and subjective nature of the social indicators. In recent works, some important social indicators such as human health impacts, employment, accidents and safety, public acceptance, life expectancy, public welfare and equity are used quantitatively in S-LCA of energy and transportation systems [9,44,49], and these quantitative indicators can be improved and applied to other LCSA studies, as well. In addition, SETAC and UNEP are continuously working on establishing a framework for the inclusion of socio-economic impacts and convert current E-LCA into a triple-bottom-line sustainability assessment model. At this point, applications of S-LCA are becoming the main challenge due to data availability and lack of standard methods and tools to gather product specific social impacts data [52,142,143]. A recently developed social hotspot database contains country- and sector-based statistical data to screen potential hotspots at a macro level and to provide detailed social assessments about the value chain [142]. The Roundtable for Product Social Metrics is also trying to address these concerns and to develop a harmonized method through a collaborative approach. Further, indices like the Social Progress Index [144] and the Sustainable Neighborhoods for Happiness Index [145], and measures of social capital [146] and social cohesion [147] serve as potential measures for S-LCA models. Ultimately, efforts exist to identify a set of standardized S-LCA indicators grouped under workers, consumers and communities such as child labor, safety, well-being, etc. S-LCA can also be used to analyze the extent to which human well-being, both subjective (e.g., happiness, life satisfaction) and objective (e.g., health, biostatistical measures of stress), are promoted while supporting social, ecological, economic, and cultural sustainability [148].

Second, global MRIO databases are mostly used for environmental analysis, and there are no research efforts employing recently developed MRIOs for a global LCSA. However, MRIOs can be a superior method for extending the scope of LCSA framework from a regional economy to global economy. At this point, the sector resolution in global multiregional Supply-Use tables continues to be one of the top challenges hindering a wide adoption of MRIOs in LCSA studies. The findings of recent studies also showed that disaggregation of IO data are superior to aggregating environmental data in determining IO multipliers and minimize uncertainties [149,150]. Therefore, recently developed MRIOs such as EXIOBASE, GTAP, WIOD, and EoRA should be improved using high country and sector resolution MRIO data and even more intra-country regional detail. Especially, the EXIOBASE covers the 27 EU member states as well as 16 non-EU countries with rest-of-the-world accounts, distinguishing 200 products, 163 industries, a dozens of environmental impact categories, as well as several socio-economic indicators (e.g., employment and income based on skill groups). The EXIOBASE contains more detailed sector and product accounts to disaggregate product and industry totals [151], therefore it is suitable for the product and/or sector level global LCSA analysis. Especially, the THEMIS, which is a hybrid input-output model developed from the EXIOBASE, can provide an important base for a global life cycle environmental, economic and social impacts of new products and technologies based on impact of human health, social well-being, prosperity, natural environment and exhaustible resources[117]. Another high-resolution MRIO database that can be a powerful tool is currently under development and the researchers from the Stockholm Environment Institute (SEI) are working on development of the Input-Output Analysis Tool (IOTA), which is a hybridized version of MRIO analysis. This model includes 236 regions of production, 57 economic sectors and various environmental footprint categories and sustainability indexes [152]. If IOTA would be extended with socio-economic metrics and a high-resolution input-output data, this newly developed MRIO tool can also be used to conduct a global LCSA considering micro and macro level impacts.

Third, global MRIO databases are powerful tools to broaden the scope of LCSA to global analysis. However these databases are subject to uncertainties related to data year, collection process and differences in establishing IO tables of national economies. Most of the MRIO databases are using old datasets based on the 2000s. With an exception, some databases such as EoRA and WIOD provide time series data; however most of these MRIO databases do not have enough sector resolutions, which make them unsuitable for a detailed hybrid LCSA. Among these MRIOs, there is an ongoing research on developing a time series Supply-Use MRIOs for the period between 1995 and 2014 [153]. Once it becomes available, the EXIOBASE 3 can be an excellent tool to conduct a time-series global LCSA at global scale. Overall, the use of MRIO databases might result in significant uncertainties in LCSA results. To minimize such uncertainties, one suggested method is to make comparisons between different MRIO databases [96,150,154]. As an alternative method, the authors suggested an uncertainty analysis of economic input–output relationships and environmental intensity vectors that can improve the validity of the result presented in MRIO studies. In this regard, developing stochastic Leontief matrix and pollution intensity vectors remains as an important future work that needs a great effort for data collection and analysis. To determine the standard deviations of multipliers, Lenzen et al. [149] discussed the importance of considering the stochastic variation of whole MRIO system using Monte Carlo techniques. In order to maintain and increase the credibility of proposed system-based life cycle decision-support tools (IO analysis, hybrid IO LCA, MRIO LCA, system dynamics, etc.), the researchers need to develop these tools transparently (replicable) and deal with uncertainties associated with data and assumptions.

While integration of SD modeling can be very helpful to understand dynamic complexity and the system as a whole, it brings different challenges and uncertainties. Because such LCSA applications aim to include additional mechanisms such as relationships among different sub-systems (e.g., rebound and feedback effects), spatial and temporal variations etc., results are highly sensitive to assumptions made [155]. Although such assumptions are very influential in traditional LCA approaches [156], any additional step towards increasing the boundary brings additional uncertainties. These additional uncertainties are mostly related to formalization of the nexus between social, economic, and environmental sub-systems interacting with the system-of-interest (the system assessed). Although methods such as Exploratory Modeling Analysis [18,157] and reliability theory [158], and viability theory [159] might be helpful to address uncertainties, the major source of uncertainties are the assumptions made when mathematically defining dynamic relationships among system parameters (especially in further parts of the system). Overcoming this challenge requires further attention from the scientific community and in-depth research about how things affect each other. One well-known example of such efforts is the Dynamic Integrated model of Climate and the Economy (DICE) model [160]. The DICE model provided a basis for understanding how economy and climate can affect each other. Similarly, there is a strong need for models defining relationships between parameters (indicators) of environment-economy-society. Such models can exponentially contribute to the future LCSA as researchers can integrate these small models, modify these in accordance with their system-of-interest, and create new models to investigate life cycle sustainability impacts of various products. This can be a model library containing models explaining specific relationships among parameters from different domains such as how increased per capita income effect public welfare, how human health status influences population dynamics, how mobility affects consumption of a particular product, and how equity affects human well-being. In fact, all of these are parts of a bigger picture and can be brought together when trying to address complex issues. In a world where everything is connected, quantification of impacts separately and isolating each from the bigger system can mislead our decisions about products, services, or goods. Therefore, systems thinking play a vital role to bridge different systems, disciplines, and methods.

A strong understanding of systems thinking is essential for the LCA community as well as decision-makers from industries and government organizations. According to the theory of bounded rationality, stakeholders including industries, government organizations, and researchers make reasonable decisions based on the information they have [161,162]. However, none of these stakeholders have perfect information, especially about more distant parts of the system [78]. Hence, decisions about products/policies are made with limited or delayed information, and causes discrepancies between goals and perceived present conditions. Furthermore, "systems thinking" is mostly discussed among systems thinkers with less emphasis on applicability or usefulness to those outside the circle (industries, organization, different disciplines in scientific community). Thus, a need exists for systems-thinking teaching and learning research to support LCSA models. System-based solutions are mostly problem or context-specific. Therefore, they usually cannot be applied to other domains without an understanding of systems language and the systems in a new domain [163]. Although bringing out examples of context-specific solutions are quite helpful and can be learned from, the overarching role of systems thinking as a catalyst to harmonize methods, and disciplines cannot be realized without developing a common systems language within and beyond the scientific community. Development of a common system language might be one of the most important challenges for advancement of LCSA as addressing complex issues certainly requires harmonization of methods, tools, and disciplines.

## 5. Conclusions and Perspective

There is strong need for a shared understanding of the inherent interconnectedness and complexity of sustainable development. In this regard, developing a common system language for harmonization of various tools, methods, and disciplines is essential for addressing challenges related to LCSA as well as the UN's sustainable development goals. Integrated modeling approaches can help to clarify and articulate the interconnected system of goals and to analyze and inform key policies, programs and projects for their impact on sustainable development goals [164]. Integrating MRIO databases and SD modeling, along with quantitative social and economic indicators, has a strong potential for addressing current challenges of LCSA as well as UN's sustainable development goals.

No matter how sophisticated/advanced the models, approaches, or frameworks we apply, the goal should not be foreseeing the future exactly, which is unrealistic considering the immense sea of uncertainties. It rather should be envisioning the future and bringing it into being [78]. A prerequisite condition for realizing the future is a better understanding of mechanisms and further parts of the systems, and how these link to our intended objectives. For instance, do we envisage a world supporting our current objectives of production and consumption, or do we envisage a world where all humans are offered an opportunity to thrive? Such questions might also guide life cycle models. In this regard, we need to generate basic knowledge of dependencies among critical sustainability indicators. A better understanding of systems thinking in LCSA framework can be turned into a knowledge generation mechanism with positive impact on sustainability science and can pave the way for standardized set of sub-models (smaller compact models) explaining major and basic relationships among sustainability impacts. Such knowledge generation mechanism can help dissemination of the LCSA framework and increase the applicability/usefulness to those outside the circle and can bridge different disciplines. On the other hand, expecting adoption of stronger systems thinking and practice in LCA can still be early for industry, since internalization of life cycle thinking has not been fully adopted outside of academia. Sending humans to the moon in the 60s was realized when the integration across disciplines and systems are accomplished [11]. Similarly, as most of the technological inventions, systems of systems, are built upon its preceding systems, starting to create interdisciplinary system dynamics models explaining the basic relationships among the sustainability indicators (impacts), processes, services, and products can lead to creating better assessment tools for advancement of LCSA.

**Author Contributions:** Nuri Cihat Onat conducted the literature review, synthesis, and analysis. Nuri Cihat Onat wrote discussions related to deepening of LCSA framework (e.g., systems thinking, system dynamics, uncertainty, etc.) and future perspectives. Murat Kucukvar analyzed the literature review findings and wrote discussions related to broadening the LCSA framework (multi-regional input-output modeling, use of input-output modeling to quantify social and economic impacts, etc.) and contributed to writing of all sections. Anthony Halog contributed to conclusions, future perspective and provided insightful feedbacks for all sections. Scott Cloutier contributed to the parts related to S-LCA and methods and perspectives for accounting well-being/happiness indicators for S-LCA. All authors contributed to each section of the paper at different degrees.

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