Some Modeling Challenges in Dynamic Life Cycle Assessment

Kai Lan

Life cycle assessment (LCA) has been a mainstream tool to evaluate the environmental impacts of products, services, and systems. Current LCAs inherently rely on the static basis and commonly fail to include temporal considerations. To better assist in the decision-making for sustainable development, dynamic LCA has been initiated to answer more complex and interdisciplinary questions. As in its initial phase, dynamic LCA faces many modeling challenges that at the same time are meaningful research opportunities. In modeling dynamic LCA, there are several key aspects that need more attention for contribution and close collaboration across the first three phases of the LCA framework.

DOI: 10.15376/biores.19.3.4040-4042

Keywords: Life cycle assessment; Dynamic; Temporal profile; Sustainability

Contact information: Department of Forest Biomaterials, North Carolina State University, P.O. Box 81005, Raleigh, NC 27695 USA; klan2@ncsu.edu

Striving for a sustainable future has become a universally acknowledged goal within our society. In our march towards this goal, a critical agenda involves the development of modeling tools capable of identifying sustainable pathways, quantifying their impacts on both human and natural systems, and assessing our alignment with pre-established objectives. Among efforts being made in this agenda, life cycle assessment (LCA), as one major tool in Industrial Ecology, has been widely and frequently used to evaluate the environmental impacts of products, services, or systems throughout their life cycles. After decades of development, LCA has come to embody a standardized framework with four phases, namely goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. To tackle diverse research questions across varying scales, LCA has been equipped with various methodological approaches, *e.g.*, attributional or consequential LCA, process-based or economic input-output LCA. However, prevailing LCA studies predominantly rely on static data, neglecting the temporal dimension of inputs, outputs, and environmental impacts. This oversight may result in discrepancies in research outcomes. In response to these limitations, dynamic LCA has been promulgated to integrate temporal dynamics into the assessment framework. To conduct dynamic LCA, there are several key modeling aspects to discuss for the considerations of future practitioners.

In conducting the dynamic LCA studies, when defining the goal and scope, it is imperative to delineate the temporal scope (or say the temporal boundary). The inputs from the technosphere (*e.g.*, intermediate products) or biosphere (*e.g.*, CO_2 sequestered from the atmosphere), and outputs (*e.g.*, emissions and products) outside the temporal scope should not be accounted for. A notable challenge arises from potential inconsistency between the temporal scope and the time horizon of LCIA methods. One example is accounting for 20-year life-cycle carbon balances of bioenergy products with 100-year Global Warming

Potential (GWP). Typically, the temporal scope should not exceed the time horizon of the LCIA method; otherwise, it is not plausible to convert the elementary flows outside the time horizon to the impact results. The determination of the temporal scope involves two critical aspects, namely the time length and the starting point, which significantly influence the outcomes. For example, for the time length, a 1-year temporal scope may yield limited differences compared to a static LCA, whereas a 100-year temporal scope with emissions spread over the duration could lead to markedly distinct results from static LCA. The other vital aspect is selecting the starting point. If we imagine a conceptual forest system with 25-year rotations and all harvested biomass combusted for energy, then repeating cycles can be formed with negative CO_2 emissions from the first 25 years (due to biogenic carbon uptake by forest growth) and a pulse Greenhouse Gas (GHG) emissions in the last year (due to combustion). If the temporal scope begins in the first year of the rotation, then the temporal profile shows negative GHG emissions first then followed by a pulse positive emission; if the temporal scope begins in the last part of the rotation, then it will be the opposite way. For dynamic LCA, these two scenarios may result in totally opposite results. Previous studies have debated about different starting points, especially for forest carbon accounting, *e.g.*, carbon debt repayment approach, dividend-then-debt approach.

Upon the defined goal and scope, the next step involves developing a temporal profile of LCI data, or dynamic LCI. Typically, in this step, the foreground data are modeled as dynamic. However, background data (*e.g.*, energy input, upstream burdens of materials) are commonly modeled as static, due to the lack of temporal information in current LCA databases. Future efforts are needed to construct the background data system or databases with temporal considerations, particularly for the background data with high emissions and temporal variations. Another emerging topic in dynamic LCI is prospective modeling that anticipates the future changes or evolution of the human and natural systems. These future dynamics can include, for instance, the evolution of the electricity market mix, the changes of future forest carbon stocks due to emerging wood products or bioenergy demand, the future shift of municipal solid waste generation, or the future penetration of the emerging technologies. Prospective modeling approaches can include integration with simulation models (*e.g.*, Integrated Assessment Models, partial/general equilibrium models), scenario analyses (*e.g.*, parametrized scenarios, Shared Socioeconomic Pathways (SSPs)), and projections based on historical data. The usefulness of prospective modeling lies in its capacity to display possible future systems and elucidate how various actions and activities may impact subsequent outcomes.

Subsequent to the generation of dynamic LCI data, it is then possible to apply dynamic LCIA. In this phase, dynamic LCIA methods are developed and applied to convert LCI data to life-cycle impact results. Amongst the discussion of dynamic LCIA, one of the most important topics is about choosing the time horizon. For example, the common time horizons for GWP by the Intergovernmental Panel on Climate Change (IPCC) are 20, 100, and 500 years. It is anticipated that the adoption of extended time horizons will precipitate increased uncertainties within dynamic LCIA methodologies. Compared to the temporal scope of dynamic LCI data, longer time horizons may dilute the effect arising from the temporal profile of the LCI data. For instance, for a system with a 10-year temporal scope, the differences between dynamic LCA and static LCA results may be more significant under a 100-year time horizon than a 500-year time horizon. Therefore, how to choose the proper time horizon for various impact categories is a challenging, yet significant topic for dynamic LCA.

At present, there exists a notable shortage of standardized methodologies for dynamic LCIA across major impact categories and LCA databases that incorporate a dynamic LCA hierarchy. Though fulfilling these gaps presents considerable challenges, it is imperative for the LCA community to persist in engaging these challenges, to foster interdisciplinary research collaborations, and to confront the increasingly complex and nuanced issues pertaining to sustainability. This continuous engagement is vital for advancing the field of LCA and for addressing the multifaceted challenges of sustainability in a comprehensive manner.