Models for Sustainability

Yuan Yao

As one of the major methodologies used in the modeling of sustainability, Life Cycle Assessment (LCA) is widely used to evaluate the environmental impacts of emerging technologies and to enhance decision making towards sustainable development. However, most of the current LCA models are static and deterministic. More insights could be generated when LCA models are coupled with higher-resolution techniques in a prospective fashion. Instead of trying to accurately predict the future, the purpose and value of integrated prospective models are to explore the boundaries of possibility and to shed light on directions that can lead to sustainable pathways. The biggest challenge is to determine the appropriate model resolution so that both big-picture insights and critical details are included. This challenge is hard to address, especially for interdisciplinary models that try to incorporate more than one dimension related to sustainability. However, improvements can be made continually through efforts from a growing population of interdisciplinary researchers.

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

Achieving a sustainable future is the ultimate goal of our society, but how to achieve it is still an open-ended question. Great efforts have been made to develop models capable of evaluating the environmental impacts of different human activities and to identify suitable pathways toward a more sustainable future. A typical example is the development of an emerging research area Industrial Ecology (IE), which specifically models interactions between industrial processes and the environment through approaches such as Life Cycle Assessment (LCA), material flow analysis, and systems analysis.

As a major method used in IE, LCA has been used by a wide range of communities for decision making. A recent trend is to use LCA in Research Development and Deployment (RD&D) for identifying early-stage research that can contribute to the sustainable development of the society (Quadrennial Technology Review 2015). Lots of LCA work has been performed for emerging technologies in different sectors, such as bioenergy and biomaterials, next-generation manufacturing, and renewable electricity. These LCA studies have aimed at comparing the environmental impacts of new technologies with conventional ones and showing the potential benefits that can be realized by emerging technologies.

However, most of the current LCA studies are static and deterministic. In other words, they do not model temporal changes or consider a variety of uncertainty resources, which may lead to different results. For example, the results from an LCA study for a biorefinery based on present techno-economic parameters may deviate significantly from a real plant 10 years later. So now, a critical question that arises is, "*How can one develop credible models to inform decision making for a sustainable future*?"

Someone may argue that the question itself is paradoxical, as prospective models could not be validated by reality until we reach the future. However, the purpose of a good prospective model is not to predict the exact future but to show the possibilities and to shed light on directions that can lead to a more sustainable pathway. The work done by the International Energy Agency (IEA) on energy decarbonization is a great example (IEA 2015). By comparing the projections of energy system deployment at different scenarios, IEA identified those key technologies that can make huge differences on limiting average global temperature increases, such as electrification of the end-use sector and aggressive adoption of renewable energy. More importantly, such results can highlight the actions that people could do today to facilitate and accelerate the transition to a sustainable future. Although IEA's work is rather macro-economic modeling than LCA, the concepts of such prospective models are useful for LCA communities to think about how to develop better models to inform decision making for the future.

To enable more robust and credible projections of emerging technologies, LCA should be integrated with higher-resolution modeling techniques, such as techno-economic modeling, process simulation, and system dynamics. Unlike a traditional LCA model in which the inputs are inventory data collected from industrial processes or generated through simulation models, the integrated LCA model allows input of technical parameters directly, such as feedstock mixes, products yields, operational conditions, and different process configurations. Then the uncertainty and possible temporal changes related to key parameters could be added and used to simulate the potential outcomes in a prospective fashion. Readers are referred to references (Yao *et al.* 2015; Huang *et al.* 2016) for examples of developing an integrated model to enable life-cycle projection of emerging technologies through integrated LCA models.

The challenge here is to determine a suitable level of resolution to solve different types of problems. An over-simplified model, or say a model with a low-resolution level, tends to fail, as many key factors may be ignored. For example, it is unrealistic to assume that a green technology (*e.g.*, bio-based water bottles) will be accepted by customers immediately on the basis of its having been identified as a "sustainable product". Modeling the impacts of such an emerging technology in the future will require rigorous models that consider many factors related to technology penetration and customer acceptance. On the other hand, the high resolution of complex models that incorporate all the details from the micro- to macro- level does not guarantee the success, because big-picture concepts and insights may be lost in such a "detailing" process.

This challenge is hard to address, especially for models that try to establish the bounds of possibility for the future and to guide current RD&D process toward sustainability. As sustainability is a broad area that has multiple dimensions (economic, environmental, and social), it is easy to add higher-resolution models to one dimension but not to all of them. Some critical details may also be lost when trying to couple models from different disciplines. However, these challenges should not stop the development of interdisciplinary models, which could be gradually improved through increasing participation of interdisciplinary researchers.

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