Embedding fundamental models of technological alternatives within a hybrid inventory for multi-scale life cycle design

Rebecca J. Hanes, Bhavik R. Bakshi

Life cycle assessment is a method wherein production systems at steady state are represented and analyzed using linear models. The matrix form of inventory analysis represents each process with a vector of inputs and outputs, generally derived from empirical data and representing a weighted average of production technologies that are implemented in a given region. The total inventory is calculated using linear algebra or linear programming [1, 2]. In order to perform this calculation, the elements of the process vectors must be fixed and scale linearly, requiring the linearizing assumptions that processes are at steady state and there are no economics of scale [3]. These assumptions simplify the inventory calculation but also limit the amount of detail on production technologies that can be included in the inventory. The majority of production technologies involve non-linear relationships between the input and output amounts as well as economies of scale. Representing these technologies with simple linear models is adequate in a purely assessment-oriented application where the steady-state assumption is valid; however, for applications in which the practitioner wishes to examine the effects of changes in the production system on the total inventory, the linear models lead to inaccurate and unrealistic representations of the production technologies. In particular, both consequential LCA and design applications are problematic with current LCA methods. A consequential LCA study examines the effect of changes made within the life cycle on the total inventory [4]. The lack of economies of scale in the inventory as well as the possibility of non-linear relationships between processes in the life cycle restricts the focus of such studies to changes in the functional unit rather than in the life cycle itself [5]. The utility of LCA in design applications is similarly restricted. With current methods, LCA can only be applied to design problems that involve a process or process system with a pre-determined life cycle [6]. Design decisions within the primary process system can be investigated, but the effect of decisions within the life cycle cannot be captured.

We propose several advances to current LCA methods that enable a hybrid inventory to be used as a tool for life cycle design, in which processes and production technologies within the life cycle are designed along with the primary process system. Suh's integrated hybrid life cycle inventory (IHLCI), used as the starting point for this work, combines a technology matrix compiled via process analysis with an economic input-output (EIO) model [7]. We replace the standard linear technology matrix, which is generally square or made square via partitioning allocation or system expansion, with a rectangular choice-of-technology (RCOT) model in order to represent several alternative production technologies that may each be used in the life cycle [8, 9]. An optimization approach to the inventory calculation is applied in order to select the best combination of production technologies according to some criteria. We capture alternatives within each production technology by using vector functions derived from fundamental models of the production technologies instead of the conventional linear models to represent processes in the inventory. The vector functions model process inputs and outputs as dependent on variables within the process that represent alternative configurations of the production technology. Because these vector functions may or may not be linear, non-linear programming rather than the conventional linear algebra or linear programming is used for the inventory calculation. The combination of the RCOT model and

fundamental production technology models enables a single inventory to capture the effects of technological alternatives and other changes made within the life cycle: the inventory can be used effectively in both life cycle design and consequential LCA applications.

We demonstrate the proposed hybrid inventory with a life cycle design problem involving a toy production system. Optimal designs are obtained using both the proposed approach and the conventional linear approach. We show that by designing the life cycle while considering decisions made within the production technologies, a better environmental optima can be found compared to the linear approach.

References

[1] Reinout Heijungs and Sangwon Suh. *The computational structure of life cycle assessment.* Kluwer Academic Publishers, 2002.

[2] Adisa Azapagic and Roland Clift. Linear programming as a tool in life cycle assessment. *The International Journal of Life Cycle Assessment*, 3(6):305–316, 1998.

[3] J.B. Guinèe, M. Gorrèe, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, H. de Buijn, R. van Duin, and M.A.J. Huijbregts. *Life cycle assessment. An operational guide to the ISO standards.* Kluwer Academic Publishers, Dordrect, 2002.

[4] BP Weidema. *Development of a method for product life cycle assessment with special references to food products (summary).* PhD thesis, PhD thesis, Technical University of Denmark, Lyngby, Denmark, 1993.

[5] Gerald Rebitzer, Tomas Ekvall, R Frischknecht, D Hunkeler, G Norris, T Rydberg, W-P Schmidt, Sangwon Suh, BP Weidema, and DW Pennington. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment international*, 30(5):701–720, 2004.

[6] Brett Alexander, Geoff Barton, Jim Petrie, and Jose Romagnoli. Process synthesis and optimisation tools for environmental design: methodology and structure. *Computers & Chemical Engineering*, 24(2):1195–1200, 2000.

[7] Sangwon Suh. Functions, commodities and environmental impacts in an ecological–economic model. *Ecological Economics*, 48(4):451–467, 2004.

[8] Faye Duchin and Stephen H Levine. Sectors may use multiple technologies simultaneously: the rectangular choice-of-technology model with binding factor constraints. *Economic Systems Research*, 23(3):281–302, 2011.

[9] Faye Duchin and Stephen H Levine. The rectangular sector-by-technology model: not every economy produces every product and some products may rely on several technologies simultaneously. *Journal of Economic Structures*, 1(1):1–11, 2012.