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An Ecologically Safe and Socially Just Supply Chain Design for Li-battery

Ying Xue[a], Yazeed M. Aleissa[a], Bhavik R. Bakshi[a]

[a] *William G Lowrie Department of Chemical and Biomolecular Engineering, The Ohio State University, Columbus OH 43210, USA*

Abstract

Global goals like “Net-zero”, “Nature-positive”, and “Socially Just” require human activities to reduce emissions, restore nature, and be socially equitable. This work proposes an approach that includes ecological capacity and social justice requirements to guide engineering decisions and designs. We utilize the supply and demand of ecosystem services to identify the safe and just operating space[1,2]. The ecologically safe space is determined by the multiscale framework of Techno-Ecological Synergy (TES). The degree of overshoot quantifies the absolute environmental sustainability (AES) at the relevant spatial scale[3,4]. For the socially just space, we calculate a minimum threshold of necessary goods and services to meet basic food, energy, and water[5] needs. We demonstrate this approach by a multiobjective supply chain design of Li-battery which minimizes the ecological and social overshoot simultaneously.

Keywords: Safe and Just Space, Absolute Environmental Sustainability, Nature-Based Solution, Supply Chain Design, Multiobjective Optimization

1. Introduction

In the past several years, the COVID-19 pandemic, wildfires, unprecedented heat waves and other extreme natural events reinforced the fact that economic and social structures are untenable without resilient nature. Meanwhile, global goals such as “Nature-positive by 2030”, “Net-zero by 2050”, have been proposed and widely accepted as guidelines for future development. However, achieving these goals must not exacerbate social issues such as poverty, food insecurity, and equity. Hence, the concept of the “Safe and Just Space”[1,2] was introduced, which identifies an operating space for human activities to be within the ecological capacity of the planet and the social threshold where everyone has access to natural resources to meet their basic needs. This requires industry to develop and apply methods for achieving global goals. Due to the concerns of energy and sustainability, the demand for electric vehicles (EV) is growing fast. Li-battery is widely used in EV and its impact is important to the sustainable EV development. This study focuses on designing an ecologically safe and socially just supply chain for Li-battery.

Current sustainability assessment methods such as life cycle assessment (LCA) are useful for quantifying relative sustainability which encourages the reduction of environmental impacts[4]. Environmental sustainability requires human impact to not exceed nature’s carrying capacity[6] but most methods ignore the capacity of nature. Reducing negative impact alone is not enough to get the full recovery of nature by 2050, as envisioned by the “Nature-positive” goal[7]. The idea of absolute environmental sustainability (AES) includes nature’s carrying capacity in sustainability metrics as a reference value. Xue and Bakshi developed a multiscale approach for absolute environmental sustainability assessment (AESA) which encourages “Nature-positive” decisions[4]. Through biophysical models, this techno-ecological synergy (TES) based AES metric quantifies ecosystem services at different spatial scales to identify the ecological threshold with high geographical resolution. Furthermore, Aleissa and Bakshi[3] proposed a quantitative social threshold that aligns with the ecological threshold by using the flow of ecosystem goods and services. The social foundation represents the minimum human demand to meet their basic food, energy, and water needs from that ecosystem service.

This work brings in the concept of AES and social threshold into Li-battery supply chain design under the global goals of "Nature-positive" and "Socially Just". Four main sectors are considered along the supply chain: mining, processing production and packaging. Ecological and social thresholds are quantified at country level for each process using the methods mentioned in the previous paragraph. The ecological and social transgression levels for Li-battery supply chain are minimized simultaneously as design objectives rather than merely constraints. The transgression level is expressed as the ratio of human impact and ecological/social threshold, making it a linear fractional optimization problem. It is first transformed into a linear program through the Charnes-Cooper method and then solved by ε-constraint method. We also show how this framework can contribute to identifying hotspots and future improvement opportunities towards global goals. The major novelties of this work are: 1) A multiscale approach of ecological threshold quantification in supply chain design. 2) Quantifying and incorporating aspects of social justice in supply chain design. 3) Application to global safe and just supply chain design for Li-battery.

2. Methodology

2.1. The Ecological Ceiling

One popular approach for AESA is based on the Planetary boundary (PB) framework. PB framework identifies nine important earth system processes and defines the safe operating space (SOS) for human development[8]. This method downscales the SOS to specific processes/systems based on a sharing principle such as population which provides holistic perspectives but ignores spatial heterogeneity of ecosystems and has high subjectiveness. These shortcomings may be overcome by a multiscale TES approach.

The TES framework is built upon the concept of ecosystem services (ESs). It has been integrated with LCA (TES-LCA) for assessment and process design[9]. Instead of directly downscaling SOSs, the multiscale TES approach quantifies the capacity of ecosystems with biophysical models from different spatial scales, which is illustrated in Figure 1a. Public and private ownerships are considered for ecological threshold partitioning. Private ownership implies that only landowners own the ecosystem services, while for public ownership, ESs belong to every activity inside the region. Figure 1b illustrates a two-scale system (e.g. county and state). Considering a n-scale TES, the generalized mathematical expression of the system's ecological threshold can be expressed as:

$$S_i^{tot} = S_{i,1}^{pvt} + \sum_{j=2}^{J} S_{i,j}^{pub} \prod_{m=1}^{m=j} P_{m+1,m} \quad (1.)$$

Here i represents process i, j represents the j-th scale, m is a dummy variable. S is the ecological threshold, P denotes the sharing principle. In this study Equation (1) will be used to estimate the ecological safe space for each process in the supply chain. For process i the absolute environmental sustainability metric – ecological overshoot (EO_i) is defined in Equation 2 and D_i represents environmental impacts.

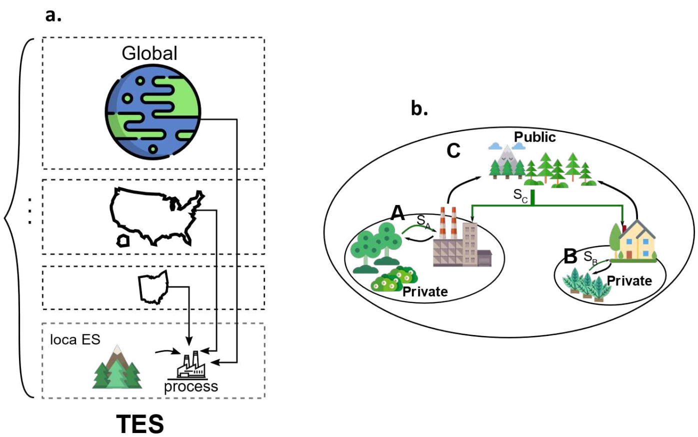

Figure 1. (a) A four level TES example (local, state, country and global). (b) Illustration of public and private ownership of ecosystem supply.

$$EO_i = \frac{D_i}{S_i} \quad (2.)$$

2.2. The Social Foundation

Aleissa and Bakshi[3] define the social threshold as the population's minimum demand (D^{min}) to meet their basic food, energy, and water needs from ecosystem services. This aligns with the UN sustainable development goals of zero hunger, clean water, and energy for everyone, which specify global standards that define the required amount of water, caloric intake, and electricity to sustain human lives[10]. Then, the social threshold can be formulated as the required emissions from food production and electricity generation to meet the energy and caloric intake thresholds for the entire population. The metric of social shortfall (SS) from the social threshold is expressed as:

$$SS_i = \frac{D_i^{min}}{D_i} \quad (3.)$$

After identifying the safe and just space through the ecological and social thresholds, we can use the current level of demand to assess the operating conditions relative to the thresholds. Figure 2 shows the scenarios that arise with the relative demand levels and the other thresholds.

3. Development of Ecologically Safe and Socially just Supply Chains

3.1. General Problem Statement

The approaches described in the previous section will be integrated with LCA, multi-objective optimization for designing a safe and just supply chain. Life cycle environmental impact of each process, from cradle to gate, will be estimated. There are two objectives: the ecological objective is to minimize the ecological overshoot and the social objective is to minimize the social shortfall. Both objectives focus on carbon emissions. The major decision variables are selection of suppliers, location of warehouses, and transportation modes. The provided parameters are a set of suppliers and locations for each process in the supply chain, a set of transportation modes, production capacity, demand for the final product, etc. To simplify this problem, this study mainly focuses on selecting suppliers, in another word finding the most suitable country to produce a specific product from "Nature-positive" perspective.

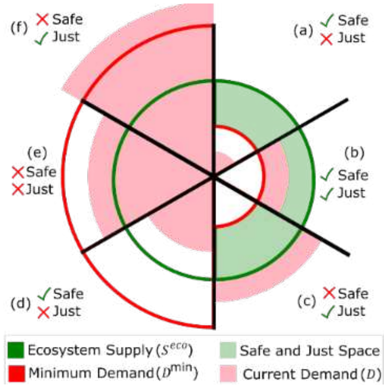

Figure 2. Possible scenarios for the SJS are determined by the current level of demand and the ecological and social thresholds.

3.2. Lithium-battery Supply Chain

Environmental impacts of EVs are mainly from the use phase and battery production. There are different supply chains for battery manufacturing based on the final product and the design application. However, many of these supply chains share similar stages: procurement of raw materials, processing these raw materials into valuable chemicals, production of battery components, and fabrication and packing of the battery cell. Each of these stages has its complex supply chains across the world currently. In this problem, we assume it is a linear supply chain, also products and processes has a one-to-one corresponding relation.

3.3. Supplier Selection

We want to find the optimal set of suppliers that minimize the ecological overshoot and the social shortfall (Equation 2, 3) along the supply chain from the perspective of CO_2 emission. Using these metrics as objectives results in a mixed-integer linear fractional programming (MILFP) problem that can be optimized to minimize a single objective locally at each stage of the supply chain, or to minimize the metrics in terms of the aggregate supply and demands for the entire supply chain. The set of countries (I) and main processes (J) are given. S_i denotes the ES supply (ecological threshold) and D_i^{min} represents the minimum impact to meet human needs in country i ($i \in I$). $x_{i,j}$ and $c_{i,j}$ are both binary variables. $x_{i,j} = 1$ if process j is to be established in country i; 0 otherwise. $c_{i,j} = 1$ when country i can have process j; 0 otherwise. D_i is the demand of ecosystem services (environmental impact). The general form of total emission can be expressed in Equation 4 where g_j is life cycle emission factor (EF) for product j, $e_{j,k}$ is EF for product j in transportation mode k. $Q_{j,k,i,i'}$ and $l_{i,i',k}$ are flow rate and distance from i to i'.

$$D_i = \sum_i \sum_{i'} \sum_j \sum_k g_j Q_{j,k,i,i'} + e_{j,k} Q_{j,k,i,i'} \, l_{i,i',k} \tag{4.}$$

The model formulation for the entire supply chain in this study is shown as below.

$$\min EO = \frac{\sum_i D_i}{\sum_i S_i} \tag{5.}$$

$$\min SS = \frac{\sum_i D_i^{min}}{\sum_i S_i} \tag{6.}$$

$$s.t. \quad x_{i,j} \in \{0,1\} \quad \forall i \in I, j \in J \tag{7.}$$

$$\sum_{i \in I} x_{i,j} = 1 \quad \forall j \in J \tag{8.}$$

$$x_{i,j} \leq c_{i,j} \quad \forall i \in I, j \in J \tag{9.}$$

$$c_{i,j} \in \{0,1\} \quad \forall i \in I, j \in J \tag{10.}$$

The constraint in equation (8) ensures that each process included in Li-battery supply chain is assigned to only one country. Equation (9) makes sure that process j is assigned to country i only when country i can produce that product. Figure 3 shows the results for the optimal supply chains that minimize the ecological overshoot and social shortfall, for both local and aggregate approaches.

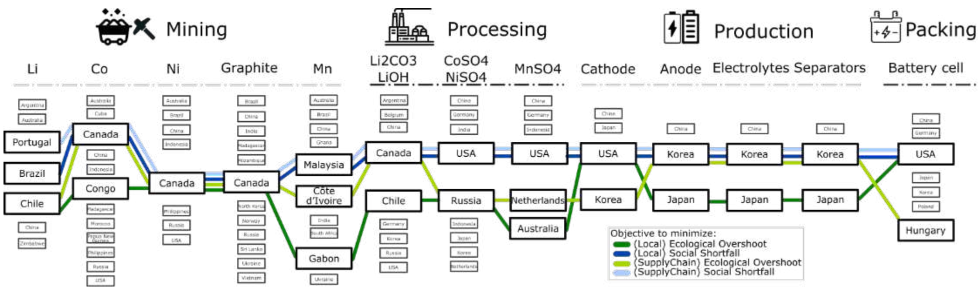

Figure 3. Supply chain results for optimal suppliers' network for the different objectives. For example, minimizing the ecological overshoot at each stage of the supply chain result gives a solution of (Chile, Congo, Canada, Canada, Gabon, Chile, Russia, Australia, South Korea, Japan, Japan, Japan, USA), More details are available in the work of Aleissa[11].

These results represent the best combinations of suppliers in the current market. However, political relations and economic deals, in addition to logistic and transportation constraints, can limit the selection of supplier networks. In addition, single-objective optimization does not reveal information about the interaction with other objectives. Hence, we performed multi-objective analysis and optimization to find the best set of solutions that define the trade-offs between the objectives. We also compare the optimal global supply chains to the current supply chains of Tesla using their limited supplier network[12], as shown in Figure 4.

These results can be used to identify hotspots along the supply chains that affect the performance of the social and ecological objectives. For example, the suppliers for lithium for Tesla performed worse than other suppliers in the market in terms of ecological overshoot. Tesla's recent investment in manganese mines in the United States improved their supply chain social performance but greatly downgraded the ecological performance compared to suppliers from Gabon or Ghana.

4. Conclusions

In this work we demonstrate the necessity of including absolute environmental sustainability and social justice into sustainability assessment and design to achieve the 'Nature-positive' and 'Socially-Just' goals. We propose a method for sustainable supply network design which accounts for nature's capacity and social needs. This method can be tailored to activities at different scales and has been applied to a battery supply chain design. LCA coupled with multiobjective optimization guides the selection of suppliers from ecological and social aspects, and the Pareto curve is obtained showing the trade-off between these two aspects.

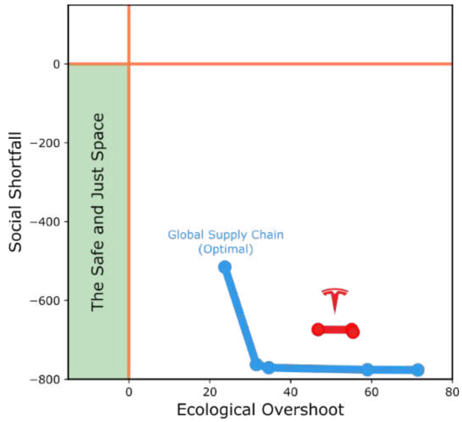

Figure 4. Comparison between Tesla's supply chains and the global optimal supply chains for Li-ion batteries.

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