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Authors
Reich-Weiser, Corinne
Dornfeld, David

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A discussion of greenhouse gas emission tradeoffs and water scarcity within the supply chain☆

C. Reich-Weiser*, D.A. Dornfeld

Laboratory for Manufacturing and Sustainability, Mechanical Engineering, University of California, Berkeley, CA, 94720-1740, United States

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ABSTRACT

Supply-chain greenhouse gas emissions and water scarcity are investigated as important components of sustainable manufacturing systems and a different impact reduction approach is suggested for each metric. Greenhouse gas emissions have a global impact regardless of emission location, which allows for supply-chain tradeoffs, whereas water scarcity is a local measure that is useful in predicting the long-term sustainability of a manufacturing location. Using publicly available data, greenhouse gas supply-chain tradeoffs are shown to exist between transportation distances, transportation mode, and regional electricity mix. This study sets the groundwork for designing and implementing reduced impact supply-chain networks.

1. Introduction

The manufacturing sector is a significant contributor to environmental damage and resource use [1]. This has potential long-term implications if resources are overused and our air, water, and soil are altered irreversibly. Because of this, manufacturing researchers have investigated the resource consumption and health risks associated with specific manufacturing processes [2–6] and factory operations [7–9]. These studies have been vital to sustainable manufacturing research and they provide insight on the impacts of specific processes and factories. However, it is also important to see the larger supply-chain picture given that the supply chain can account for a quarter of the total manufacturing costs [10], and is likely to contribute to environmental costs as well.

Previous environmental supply-chain work has focused on the importance of environmental supply-chain research and investigated methods and metrics to reduce environmental impacts. Durham [11] highlighted the need for environmental management of the entire manufacturing cycle. O'Brien [1] argued that industry had to play a pivotal role in ensuring sustainable development in society. Zhou et al. [12] investigated ways to incorporate sustainability considerations into the economic decision-making process with the use of an analytic hierarchy process, where weighting factors were used to determine a single metric that was then minimized across the supply chain. Weaver et al. [13] discussed the potential re-structuring of paper producer locations based on recycling collection sites, virgin pulp producer locations, and customer locations. Westkamper et al. [14] argued the need for a sustainable manufacturing strategy and discussed several approaches for life-cycle management and its application in sustainable manufacturing. Daniel et al. [15] focused on supplier location relative to how local weather and geographic conditions (humidity, rainfall, airflow) affect the fate and transport of emissions to the environment.

While the previous environmental supply-chain research has provided much-needed insight in this growing area, it has generally neglected the critical issue of regional water scarcity and the straightforward greenhouse gas (GHG) tradeoffs possible between electricity and transportation emissions. This paper focuses on these two areas not only because they are critical to current climate change concerns [16] and offer quick opportunities for insight using publicly available data, but also to demonstrate two approaches to reducing environmental impacts across both forward and reverse supply chains.

Water scarcity is a local measure that is useful in predicting the long-term sustainability of a manufacturing location [17]. Furthermore, water scarcity tradeoffs are not always possible between regions. For example, a drought in the United States is not impacted by someone in England conserving water; however, the US drought could have an impact if people in England consume less of a product that is manufactured in the drought area, or if that manufacturing moves to a new location. Therefore, water scarcity by location should be considered piece-wise by the supply-chain designer [17].

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* Corresponding author.
E-mail addresses: corinne@me.berkeley.edu (C. Reich-Weiser), dornfeld@me.berkeley.edu (D.A. Dornfeld).

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Alternatively, because GHG emissions lead to global climate change [16], considering GHG emissions across the entire life-cycle (including materials extraction, manufacturing, transportation, use, and end of life) allows for tradeoffs and reductions that might otherwise not be apparent. For example, some GHG related supply-chain tradeoffs could exist between regional energy mix variations, resource availability (materials, water, transport, infrastructure), labor (cost, societal requirements), policy (regulatory, political), and available technologies. While further work is needed to understand the specific impact of each of these variables on emissions, this paper focuses specifically on the previously unconsidered GHG tradeoffs between transportation and electricity. GHG emissions from electricity and transportation can be estimated using publicly available data allowing for a rough-cut supply-chain design analysis to be performed. This preliminary approach can be followed with specific data collection to finalize decisions as necessary, which saves time as certain options are eliminated quickly and areas requiring further analysis can be quickly determined.

Both water and GHG data allow a manufacturer to be risk averse and potentially reduce costs. Knowledge of GHG emissions in the supply chain allows a producer visibility into vulnerabilities associated with the increased price of GHG emissions as well as an opportunity to reduce this risk. On average, GHG emissions within the supply chain of products and services purchased by industry are three times greater than direct emissions from industry [18]; however, many corporations are satisfied measuring only direct and electricity related emissions. A recent article in the Wall Street Journal discussed Dell Computer's attempt to become 'carbon neutral' despite failing to measure or offset their upstream supply-chain emissions. This is particularly surprising considering that "Dell officials estimate[d] that the emissions produced by its suppliers and consumers each amount to about 10 times the footprint Dell has defined for itself" [19].

Similarly, knowledge of regional water scarcity allows a producer to predict cost increases and act to ensure their long-term sustainability. Water is a crucial part of many manufacturing processes, as well as necessary for human health; however, water resources around the world are being depleted and availability is expected to shift as climate change progresses [20,16,21,22]. China, as an example, is currently facing a threat of water shortage. There, the water table is dropping at a rate of over a meter a year, indicating a loss of non-renewable water resources [23]. For industries planning to continue or install in China, the possibility of drought is well worth considering.

The incorporation of supply-chain considerations into manufacturing environmental analysis follows four of the five basic rules for a manufacturing wedge technology as outlined by Dornfeld et al. [24]. A wedge technology is one that is both scalable and offers a net environmental benefit when implemented. The goal is to produce enough wedges that global warming emissions can be stabilized or reduced over time. The rules can be paraphrased as follows: (1) the life-cycle environmental impacts of the wedge technology cannot exceed the environmental savings of its implementation; (2) the technology must be applicable at the lowest level in the supply chain; (3) the environmental impact and cost must be calculated in terms of basic and appropriate metrics; (4) societal, economic, and environmental concerns must be considered; and (5) an accompanying analytical tool or methodology is needed. Rules 1, 2, 3, and 5 are satisfied by supply-chain environmental assessment as discussed in this paper. Rule 4 could be satisfied, but is not yet, by considering the human rights and labor laws of specific manufacturing countries in the supply chain.

This paper is organized as follows. First, an overview of life-cycle assessment methodologies is presented. Then a discussion of regional water scarcity and GHG emissions from electricity and transportation is given. Finally, a case study to illustrate the potential for further work on GHG supply-chain tradeoffs is presented.

2. Life-cycle assessment

Environmental life-cycle assessment (LCA) is necessary to determine the environmental impacts associated with a process, product, or service. LCA is generally described as a systematic analysis of the material flows associated with every stage of a product's existence throughout materials extraction, manufacturing, distribution, use, and end of life; however, in practice, any number of these stages might be left out of the analysis.

The ISO 14040 series of standards define LCA guidelines and establish four stages to an LCA: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation of results [25].

The first step is to determine the goal and analysis boundary. A boundary is defined by the pre-determined set of activities to be analyzed within the product's life-cycle. The boundary can be set to include all manufacturing operations, a factory, a machine-tool, or a geographic region. For certain environmental metrics it is necessary to determine the total impact associated with a product or service globally. This is the case for GHG emissions as they contribute to global climate change regardless of the emission location, and insight can be gained from a global perspective. However, a global assessment is not necessarily appropriate for a metric such as water, because the total water use associated with a product's manufacture across multiple locations provides no indication of regional environmental damage from overuse. For the case of water, a "gate-to-gate", or region-specific, analysis is most appropriate.

The second step to an LCA, inventory analysis, is arguably the most time-consuming, where detailed data collection is required across a range of processes to obtain a complete picture of environmental impact [25]. Life-cycle inventories can be obtained using one of three general methodologies: process LCA, input–output LCA, or a hybrid combination of process and input–output.

Process LCA is the most common method for inventory analysis. Process LCA consists of methodically analyzing material flows at every stage of the life-cycle to understand precise consumption and emission values. In many cases, the work of previous researchers on certain materials or processes is included to complete the analysis. For situations where the desired analysis boundary is finite, as it will be for water consumption, a process approach must be utilized. However, when a comprehensive supply-chain analysis is desired, process LCA has a boundary definition problem. This is because a supply chain is inherently infinite (every step of the supply chain creates demands), and every component of a system simply cannot be accounted for by the LCA practitioner, given time and cost constraints.

Alternatively, the Economic Input–Output LCA (EIOLCA) method is a boundary-less approach to LCA. EIOLCA utilizes economic input–output tables and industry environmental data to construct a database of environmental impact per dollar of production in a given industry [26,27]. There is a large setup cost in creating the EIOLCA database; however, it is relatively straightforward to use once in place as financial data can be mapped to EIOLCA data directly. This method solves the boundary problem of process LCA because the economic input–output tables capture the interrelations of all economic sectors; however, input–output LCA has the problem of providing only aggregate industry level data.

In this paper, a hybrid of process and input–output LCA is utilized to demonstrate GHG emission tradeoffs, because it is more efficient and comprehensive than process LCA while being more specific than input–output results alone [26]. The EIOLCA data in this paper is utilized from a free online database provided by Carnegie Mellon University [28] and then augmented with specific electricity and transportation GHG data from previous researchers. While the numbers presented here are imperfect, they are reasonable estimates that allow for supply-chain tradeoff arguments to be presented.

3. Water scarcity

Water scarcity may be present currently, come about through climate change, or be created through the overuse of resources. As producers make decisions about where to source goods or where to locate new factories, understanding where water scarcity could lead to increased costs or political turmoil will be critical for risk mitigation. In many cases water consumption many occur without the user realizing they are tapping into non-renewable sources and depleting reserves, making an understanding of the regional water patterns critical to long-term success.

Future scarcity from overuse (or pollution) can be approximately predicted by looking at current water consumption rates along with renewable water availability. The renewable water amount is what could be consumed annually, on average, without depleting underground aquifers, lakes, and rivers. If water is being consumed at an annual rate that is greater than the renewable water availability, then non-renewable water sources are being consumed, and there is a future risk of scarcity. Regions with a strong renewable resource today may generally provide the best opportunity for long term availability.

Data from the United Nation's Aquastat database [29] can be used to see if there is any current scarcity or risk of scarcity in a region. For example, Fig. 1 illustrates an estimate of the renewable water resources for a variety of countries, with consumption of water by households, agriculture, and industry disaggregated [29]. Note that these values give no indication of seasonal or historical variability, and applying a safety factor might be appropriate. The "available internal renewable water" indicates what is remaining of the renewable water given current rates of consumption. From these results we see that water-intensive manufacturing processes might be well suited to somewhere like Brazil or Canada, whereas Egypt is already overusing its resources. Korea, Germany, and Spain have numbers that might be low enough to be very fragile as climate change progresses or given seasonal fluctuations.

Given this approximate information about remaining renewable water resources in a certain region, a producer or buyer can evaluate multiple locations. This regional estimate should be followed with a specific evaluation of water resources at the potential site location. Along with multiple other supply-chain and location-specific factors, this provides an additional data point on risk and cost mitigation.

Note that unlike GHG emissions, water scarcity cannot be optimized across the supply chain. Water use in a location with scarce resources is not comparable to use in a location with plentiful resources, and water use in one location cannot be traded for greater savings elsewhere. For these reasons, a regional rather than global life-cycle approach is suggested for water scarcity.

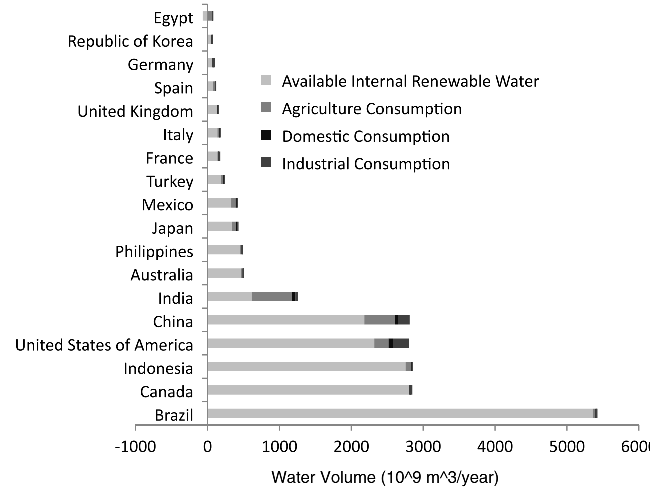

Fig. 1. Internal renewable freshwater resource availability and consumption by country [29].

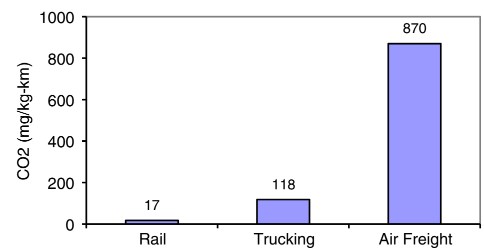

Fig. 2. Freight transportation average life-cycle CO_2 emissions [31].

4. Greenhouse gas emissions

GHG emissions have grown in importance over the past decade as researchers and consumers recognize the threat of climate change. As a result, manufacturers are already seeing a price on carbon in certain locations, and it is expected that carbon will have a price more broadly in the future.

GHG emissions contribute to climate change regardless of where they are emitted [16]; thus it is reasonable to trade emissions in one location for emissions elsewhere. Similarly, it may be reasonable to slightly increase emissions at one point in the supply chain if it means they can be more dramatically reduced elsewhere.

To enable this type of tradeoff analysis within the supply chain, electricity and transportation emission values are summarized below. Electricity and transportation are chosen as variables to trade off as they can be significant factors in supply-chain GHG emissions [30], and can be approximated with publicly available data. GHG emissions are calculated in terms of their 100-year global warming potential (GWP) in CO_2-equivalents (CO_{2eq}) as given by the IPCC [16].

4.1. GWP of transportation

The GHG emissions of freight transportation can be normalized by either the cargo's weight or the cargo's volume. In this analysis the weight-based approach is chosen. While the volume transported may determine how many vehicles are required for transportation, the weight will directly impact fuel efficiency [31]. Additionally, a weight-based approach assumes that the packing efficiency is maximized and provides a baseline of impact.

Carbon dioxide (CO_2) data from Facanha [31] is used as an estimate of total GHG emissions for rail, trucking, and air freight [31]. Air freight was found to have the highest CO_2 emissions per kg transported a km (Fig. 2). Facanha conducted a comprehensive life-cycle analysis of CO_2 emissions, and found that combustion emissions of CO_2 accounted for approximately two-thirds of the total transportation life-cycle GHG emissions [31].

These results can be taken into account along with the strategic advantages that one transportation mode might offer over another, such as flexibility, timeliness, security, risk, reliability, and service. Air freight is the fastest and most flexible transportation mode; however, it is the least environmentally friendly and the most costly. An optimal choice of transportation has the minimum environmental impact while still meeting needs. These types of tradeoffs must be carefully weighed by planners when considering where to locate facilities and how to transport items between them.

4.2. GWP of electricity generation

Although the electricity required to manufacture a product may not vary significantly between locations (except due to

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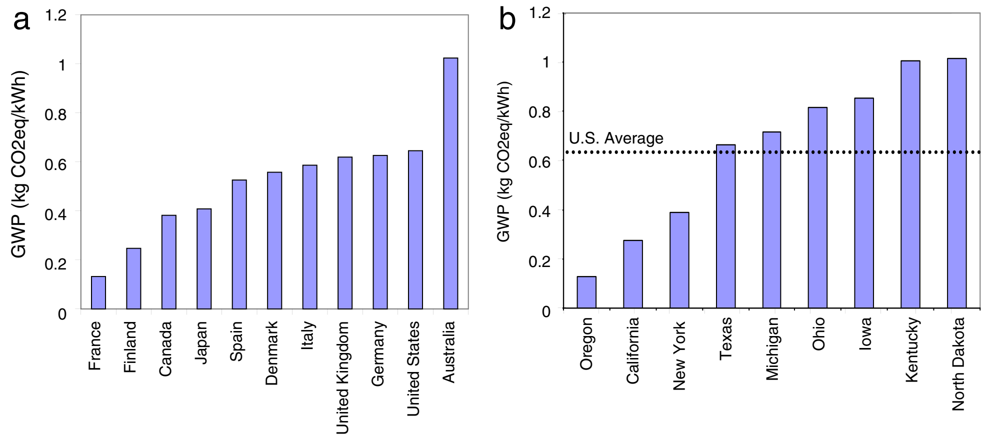

Fig. 3. Global warming potential (a) per kWh of electricity consumed [33] and (b) of electricity in US states [36].

technological or climate variations), the GHG emissions from electricity generation may differ dramatically.

The environmental impact of electricity generation is dependent on electricity distribution efficiencies, energy conversion efficiencies, and the mix of technologies producing electricity. For example, fossil fuel electricity generation varies in its direct GWP from 0.96 kg CO_{2eq}/kWh for coal to 0.60 kg CO_{2eq}/kWh for natural gas [32]. These variations effect the environmental impact of a kWh used in each location.

To further illustrate this variability, Fig. 3(a) shows the GWP for electricity generation in countries with available data through the EcoInvent database [33]. France has the lowest GHG emissions per kWh because 78% of their electricity generation is nuclear and 12% is from renewables such as wind, solar, and hydro electricity [34]; Germany, on the other hand, derives 27% of its electricity from nuclear generators and 10% from renewables, with the remainder coming from the burning of fossil fuels [35].

Similarly, regional differences within a country can produce variations in the GHG emissions per kWh of electricity demand. This is seen in Fig. 3(b), for a sample of states within the United States. Again, depending on the energy mix within each state, the emissions vary substantially.

4.3. Case study

As a theoretical exercise to understand GHG tradeoffs between transportation and electricity mix, consider the GWP of manufacturing a generic American automobile, as discussed by Zhang et al. [37]; this vehicle is worth $ 23480 and weighs 1532 kg. Consider that this vehicle can either be manufactured in Detroit, Michigan and then sent by truck to the consumer, or manufactured locally to the consumer.

An estimate of the US supply-chain GHG emissions for automobile manufacturing can be determined from the "Automobile and Light Truck Manufacturing" sector of Carnegie Mellon's 1997 input–output life-cycle assessment database [28]. By inputting the value of Zhang's generic American vehicle to the database, it is seen that manufacturing had a GWP of approximately 15,000 kg CO_{2eq} in 1997, of which 4400 kg were caused by the power generation and supply sector. The power generation and supply sector is based on the average US electricity mix, which can be scaled to Michigan's electricity mix using the values in Fig. 3(b); the new total emissions for the baseline of manufacturing in Michigan is approximately 15,500 kg CO_{2eq}/kWh. This same scaling procedure is used to estimate total emissions for manufacturing the vehicle in California, Texas, Ohio, or Kentucky. In this example, it is assumed that the entire supply chain is located either in Michigan or at the customer site.

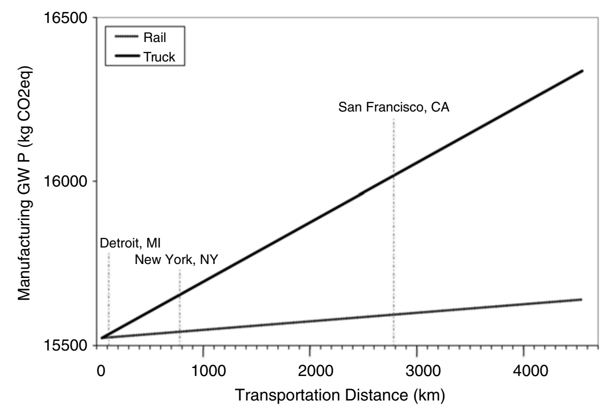

Fig. 4. Incremental GWP of transport (base of 15,520 kg CO_{2eq} for assembly in Detroit, MI).

For comparison, trucking emissions are added to the Michigan manufacturing baseline to approximate manufacturing in Michigan and trucking the vehicle to California, Texas, Ohio, or Kentucky (Fig. 4).

Results are given in Fig. 5, where the difference between manufacturing locally and manufacturing in Michigan are shown. Because California and Texas have an energy mix with a GWP/kWh that is less than that of Michigan, GWP is saved by manufacturing locally in these states. On the other hand, Ohio and Kentucky both have an energy mix with a GWP/kWh that is greater than that of Michigan, which is not offset by reduced transportation; therefore, if possible, it is better from a GWP point of view to manufacture in Michigan and truck to these states.

Note the assumption here that manufacturing in each state consumes the average mix. While it is always better to know the actual electricity mix used by a manufacturer, this data is often difficult to obtain across the supply chain, and approximate data allows for decisions to be made in the absence of more specific data.

5. Conclusions

The importance of incorporating GHG emission and water scarcity considerations into supply-chain assessments has been discussed. Water has been described as an important risk factor for supply-chain design decision making. GHG tradeoffs between transportation and electricity mix have demonstrated the potential for future work on supply-chain GHG optimization.

Based on the considerations and tradeoffs highlighted in this paper, a set of guidelines to ensure a successful supply-chain analysis are:

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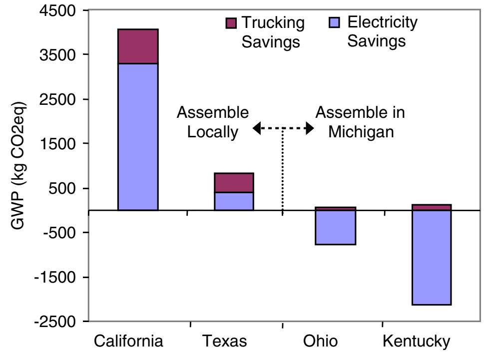

Fig. 5. Savings realized by assembling a vehicle local to the consumer in each state.

1. Potential supplier and manufacturing locations must be known along with the resource (materials, water, energy) availability and infrastructure at each potential location. Location choice is shown to affect water availability, and the emissions associated with transportation and electricity consumption.
2. The resource requirements of each manufacturing stage must be quantified (modeled) for comparison.
3. Important tradeoffs between transportation cost, flexibility, and environmental impact must be understood. The optimal mode of transportation is one with minimal impact while still meeting logistical requirements. Air freight is found to have the highest GHG emissions and energy consumption per kg transported a km.

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Corinne Reich-Weiser is a Ph.D. candidate at the University of California-Berkeley in the Laboratory for Manufacturing and Sustainability. She is researching the optimization of supply-chain environmental impacts using appropriate metrics and hybrid life-cycle assessment techniques.

David Dornfeld is the Will C. Hall Family Chair Professor of Engineering and he directs the Laboratory for Manufacturing and Sustainability (LMAS) at the University of California-Berkeley. His research and teaching interests include sustainable manufacturing, precision manufacturing, and sensor technology.