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Supply Network Design and Product Environmental Performance

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Executive Summary for Public

Current research suggests that a product's impact on the physical environment is largely determined by the environmental impact of production and transportation processes that extract and process raw materials and manufacture products. In order to make better decisions about how to design products and supply networks, we need to understand how the supply network that makes the product impacts the environmental performance of the product. The goal of this study was to address the research question: Do different configurations of a product's supply network yield different environmental performance? We posit that the different configurations of supply networks cause it to be more or less difficult to optimize in both design and operation, thus impacting environmental performance.

We tested our hypothesis by extracting and analyzing data from the Ecoinvent life cycle inventory database. We found empirical support that products that have more interconnected supply networks also have smaller carbon emissions related to their processes. This suggests that when products and their corresponding supply networks are more interconnected and dependent upon one another, there is more opportunity for collaborative design and optimization and thus improved environmental performance.

The practice of life cycle analysis is a common practice in industry, yet it has not been used to study the issue of process choice in manufacturing strategy. Our work fills a void in the academic literature by proposing a theory of how the structure of a product's technology network might impact its environmental performance We will also be the first study to empirically test the link between process structure and sustainability.

Project Motivation

Various pressures are causing consumer good manufacturers to work to improve their products' environmental performance. Companies improve product sustainability through practices such green purchasing (Grankvist and Biel 2007), environmentally-conscious manufacturing (Florida 1996); recycling and remanufacturing (Guide Jr and Wassenhove 2001; Pagell, Wu, and Murthy 2007), design for the environment (Kleindorfer, Singhal, and Van Wassenhove 2005), environmental management systems (Melnyk, Sroufe, and Calantone 2003), and eco-labels and environmental product declarations (Nicholls and Opal 2005).

Life cycle analysis, or LCA (Allenby 2000; Baumann and Tillman 2004; Heijungs and Suh, 2002) is particularly useful for facilitating sustainability-focused product innovation. LCA details the environmental and technological inputs and outputs that constitute the manufacture of a given product, and includes activities from the very beginning of the value chain (e.g. material extraction) to the very end (e.g. product disposal or recycling) (ISO 14040:2006). As product life cycle research accumulates, it is increasingly clear that a product's supply chain (or more accurately, its supply network) often accounts for a significant amount – or even the majority – of the product's environmental footprint across its life cycle. For example recent LCA studies of computers suggest that more energy is required for the production than for the use of a computer over its lifetime (Williams, Ayres and Heller 2002; Krishnan, Williams and Boyd 2008). Thus, while LCA research has concentrated on identifying the particular technologies, materials, and production methods that lead to better or worse environmental performance, it has ignored the question of whether the structure of a product's supply network has any relationship to its environmental performance.

Conversely, within the discipline of supply chain management, there is a rich literature on supply network design (e.g. Lee and Billington 1992; Beamon 1998; Sabri and Beamon 2000; Talluri and Baker 2002). Researchers have analyzed how facilities, transportation, inventory, information, and other network decisions should be used together to develop and support a firm's competitive strategy while maximizing profits across the supply chain (Chopra and Meindl 2001). Typically, supply network design decisions also include performance metrics such as cost, customer responsiveness, activity time, and flexibility (Beamon 1998) in relation to product and process architecture information. However this literature has yet to explore the link between supply network structure and environmental performance. Given that LCA studies highlight the significant environmental impact of most supply network operations, it is critical to understand how decisions made about the supply network might impact a product's environmental footprint.
Thus the goal of this study is to address the research question:

How does the technical configuration of a product's supply network impact its environmental performance?

We posit that the different configurations of supply networks cause it to be more or less difficult to optimize in both design and operation, thus impacting environmental performance.

There are challenges in empirically addressing this research question. Because of the many physical- and design-related factors that ultimately determine a product's environmental impact, one likely needs a large sample study in order to observe the effect of supply network design amidst the other numerous effects. Because of supply network complexity and lack of visibility (Choi et al. 2001; Pathak, Day, Nair, Sawaya and Kristal 2007; Choi and Dooley, 2009), however, only small case studies of real supply networks have been accomplished. Thus we argue that a product's LCA model, or "technology network", can be used as a surrogate for its supply network. A product's technology network is resultant from LCA and details the unit manufacturing processes that constitute the product's life cycle from material extraction to end-customer delivery. Because a large number of products have publically available LCAs and thus technology networks, use of LCA data allows us to perform a large sample quasi-experiment linking technology network structure and environmental performance.

Our study contributes to theory by being the first to test the link between supply network structure and environmental performance. The work contributes to a network-theoretic view of production, and demonstrates how supply network decisions impact a product's environmental footprint.

Theory and Hypotheses

Background

The study of supply network design research is rooted in research concerning manufacturing strategy and process choice – that is, how production steps are located, connected and coordinated. Several case studies find empirical evidence of their being relationships between the configurations of products and their processes (St. John and Young 1992; Vickery et al 1993; Cleveland 1989), while Safizadeh, Ritzman, Sharma and Wood (1996) found that process choice is by and large related to product customization and competitive priorities.

Supply chain researchers have pointed out that companies strategically consider the overall design of their respective supply network, particularly the supply chain's structural characteristics (Choi and Hong 2002). Specifically, such design issues as the distance of production facilities from a market and the degree of production facility utilization and efficiency have important performance implications (Fisher 1997; Randall & Ulrich, 2001). The latter includes the question of outsourcing decisions and supplier location. That is, companies have to consider economies of scale when outsourcing and selecting suppliers so as to balance the pooling of inventory, shortening of lead-time, and maintaining of delivery requirements.

Researchers have also examined the relationship between product architecture and the design of production systems (Ulrich 1995; Schilling & Steensma, 2001). Researchers are interested particularly in product modularity as more industries adopt modular designs to manage mass product customization and fast time-to-market requirements (Fine 1998). Modular architectures have a one-to-one mapping from product function to physical components and have a strong influence on supply network architecture (Novak and Eppinger 2001). For instance, Sturgeon (2002) found that modular product designs in the electronics industry induce a modular production network, resulting in the emergence of large contract manufacturers who manage sub-tier suppliers on a turnkey basis. Modular supply networks exhibit low proximity among its actors, each with autonomous managerial and ownership structures, and are not vertically integrated (Fine 1998; Voordijk, Meijboom, and de Haan 2006). Such networks have important hub-type characteristics (Dhanaraj and Parkhe 2006). Additional supply chain activities such as production planning and control, distribution and logistics are significantly affected by the actual underlying structure of the network (Beamon 1998).

Research thus shows that product architecture and managerial decisions influence the design of supply networks. While the above studies explore product design choices and their impact on outsourcing decisions, the consideration of production process choices associated with suppliers is largely absent. In addition, there is little discussion of the supply network structure and design beyond the tier-one or tier-two manufacturer (Choi and Hong 2002). Yet the entire supply network influences performance (Slack and Lewis 2007), including metrics of cost, customer responsiveness, activity time, and flexibility (Beamon 1998).

Product architecture and the subsequent supply network structure also have environmental implications. Most work on the subject focuses primarily on product architecture and its effect on reuse. Life cycle analysis is rarely considered. For instance, Newcomb et al. (1998) evaluated design configurations with respect to function, service, and post-life issues. In the manufacturing sector, Krikke et al. (2004) found modular product design to benefit recycling and reuse of products. Specifically, companies like HP and Xerox incorporate modularity in their environmental strategy to reduce waste and facilitate a closed-loop supply chain – where subcomponents are sorted, disassembled, recycled or remanufactured.

In sustainability and supply chain management, researchers and practitioners have begun to question the impact of supply network structure on the environmental performance of companies and the overall supply chain. In food and agriculture sectors, for instance, food safety concerns force managers to consider traceability issues – and invariably supply network design choices – to improve supply chain transparency (Roth, Tsay, Pullman and Gray 2007; Pagell and Wu 2008). In the recent sustainable agriculture movement, more consumer demand for local food production and distribution (Pollan 2008) has raised interest in how production location choice impacts the environment and various stakeholders, including growers, food workers, consumers and the community where food products are produced.

In addition, industrial ecology research (Frosch and Gallopoulo 1989) has focused on designing eco-industrial parks where companies try to optimize the production processes in such a way that companies can share materials and energy as production inputs. In this case, supply network design has considered co-location between companies – even in different industries – to better utilize natural resources.

Pooled and Sequential Interdependency in Supply Networks

Because there is directional flow in how suppliers align with one another via their input-output production relationships, this can be represented as a directed network. That is, each supplier is a node in the network, and a directed connection between nodes A and B means that the output of supplier A is the input to supplier B.

Figure 1 provides an example of a small portion of a hypothetical supply network. Cheese (a final product) is produced by assembling whey, milk powder, and manufactured butter – along with adding energy – in the form of specific production steps. Similarly the whey is made from spring barley, which requires fertilizer as an input to grow.

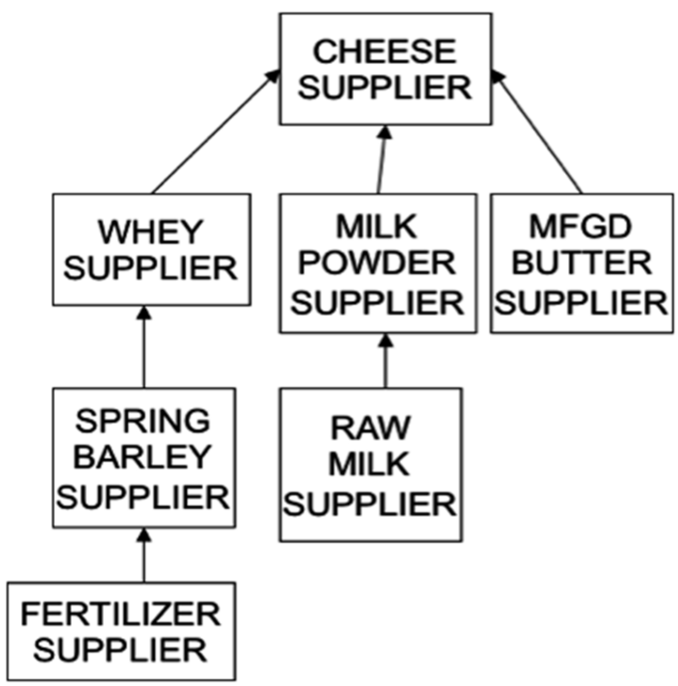

Figure 1 Partial supply network for cheese production

One can see that suppliers may either directly depend on one another because they are in sequence (e.g. whey and spring barley suppliers), or may only depend on one another indirectly because they are not adjacent (e.g. spring barley and milk powder suppliers). Suppliers that depend on one another must coordinate both the content and timing of what they do; suppliers that are not directly connected may or may not be coordinated, but clearly any additional coordination beyond required dependencies comes at a cost.

It is often noted that a supply network's primal level is the triad; a dyad alone does not constitute a network other than in a trivial sense (Choi and Dooley, 2009). Thus in discussing the structure of such networks, it is worthwhile to consider how three suppliers might be configured.

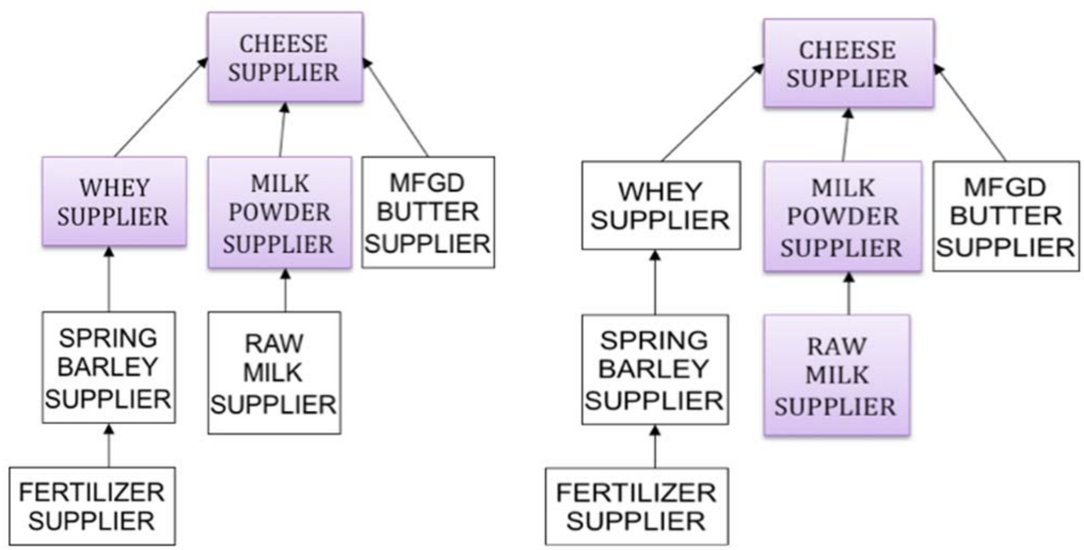

Figure 2 Pooled and Sequential Interdependencies in a Supply Network

Figure 2 shows the two ways in which a supply triad could be arranged. On the left, whey, milk powder, and cheese suppliers are related to one another via pooled interdependencies; while on the right, cheese, milk powder, and raw milk suppliers are related to one another via sequential interdependency. Pooled interdependency requires that the supplier acting as a sink (e.g. cheese) play a coordinating role for the two upstream suppliers that may not otherwise be coordinated (e.g. whey and milk powder suppliers). By contrast, in sequential interdependencies the manufacturer acts as a sink and coordinates only with the single upstream supplier. From the viewpoint of the "cheese production" node, pooled interdependency leads to managing two inputs, while sequential interdependency leads to only managing one input.

In general, supply networks that are truly configured as continuous supply chains, which in the extreme have only sequential interdependency, are more cost effective and efficient because they involve the management of fewer inputs. The converse of sequential interdependency is a supply network with high degrees of pooled interdependency, placing large management loads on certain suppliers, and thus increasing cost and decreasing efficiency. Even if the pooled interdependency represents redundant suppliers (e.g. two suppliers of the same component), there is still increased cost and decreased efficiency, but with the advantage of flexibility and resiliency. Thus, whether a supply network is more sequential-interdependent or pooled-interdependent has important implications for resource efficiency and network performance.

We shall operationalize the amount of pooled interdependency in a supply network by measuring its degree of centralization. Centralization is a concept in graph theory (i.e. network analysis) that measures the extent to which the network is a hub network, with all nodes disconnected except for their connection to a single hub node (Wasserman and Faust 1994). Figure 3 depicts two supply networks, one with extreme pooled interdependence with high centralization, and one with extreme sequential interdependence with low centralization. These two supply network archetypes can be thought of as corresponding to process-dimension extremes in Hayes and Wheelwright's (1979) product-process matrix, although at a higher level of analysis. Thus we have developed a rigorous and novel way of measuring a fundamental property of manufacturing process structure. We shall now summarize what the effects of centralization are on manufacturing performance, in order to better understand how it might impact environmental performance of the product.

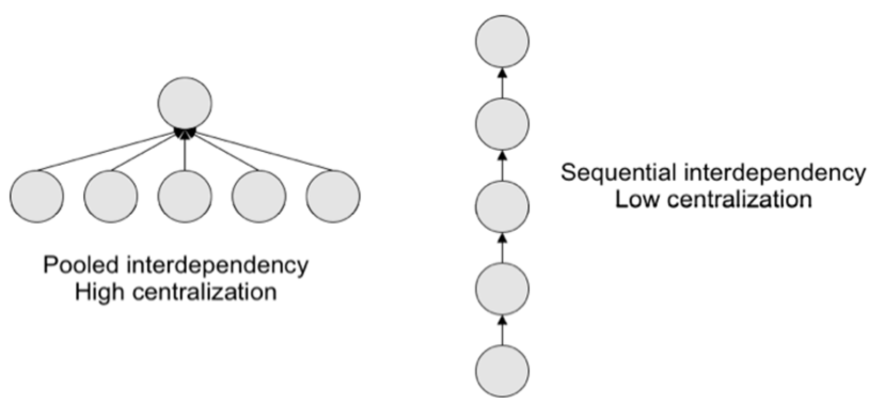

Figure 3 Supply network archetypes and centralization

Supply networks with higher centralization (i.e. pooled interdependence) will tend to have relatively more set-ups, be more labor intensive, and have less automation than more continuous, sequential networks, ceteris paribus. The Dell laptop production supply network described by Friedman (2005) in the popular book *The*

World is Flat offers a simple illustration of the pooled supply network process. Dell purchases different components from various electronics contract manufactures and assemble the final products in one of its factories. The Dell factory serves as the final parts consolidation and assembly point. In this case, the suppliers have their own production set-ups, and workers at Dell's final assembly line carry out a series of labor-intensive tasks.

Hypothesis

When harmful substances are released into air, water, or soil, human health and ecosystem quality and human may suffer. For example, carbon dioxide and other green house gases increase global warming potential, which in turn creates more drought-stricken areas and impacts the health of people dependent on those water sources. In general, we can think of human health and ecosystem quality as largely impacted by processes of "emission", including those from energy use. Resource use is largely driven by processes of "extraction" of precious materials, forests, fossil fuel, etc. We shall now argue that centralized supply networks increase emissions and extractions, and thus decrease environmental performance.

The literature on process design confers that more centralized (e.g. job shop) networks have more setups, more labor intensity, and less automation. According to Wheelwright and Clark (1992), this corresponds to a less mature technological state, resulting in lower product and process efficiencies. This means, fundamentally, that more inputs—more emissions and extractions—are required per unit of output desired.

Centralized supply networks are more likely to have disaggregation, leading to more organizations being engaged in the value chain, and this has two effects. First, disaggregation has spatial implications—supplier and buyer organizations rarely co-locate. Thus a more centralized network is likely to involve more transportation, which in turns causes more emissions (from burning of fossil fuel) and more extractions (of fossil fuel). Second, disaggregation causes increased variation in operating procedures and innovation patterns, and decreased economies of scales for management control systems. Thus we expect disaggregation to lead to more variable and less effective environmental management systems and strategies; in turn leading to less resource efficiency as seen by more emissions and more extractions. Thus we propose:

> *H1: The greater the level of centralization in the supply network, the more CO2 emissions associated with the product.*

Methodology

In LCA one must first define midpoint and endpoint categories in order to group and aggregate the various possible environmental effects of a process or activity (ISO 14040:2006). We shall focus on the most commonly reported aspect of a supply chain's environmental performance, namely, its CO2 (or carbon) emissions. CO2 emissions are the most dominant form of emissions that lead to green house gases, which in turn are linked to climate change which has significant adverse impacts on ecosystem quality, biodiversity, and human health (Russo and Fouts 1997). Also note that most CO2 emissions come from energy use, thus CO2 emissions are also linked to depletion of fossil fuels (Heijungs and Suh 2002).

Unfortunately there are significant challenges to empirically test these hypotheses. As stated above, because there are so many physical and design factors that ultimately determine a product's environmental impact, a large sample study is needed in order to observe the effect of supply network design amidst the many other effects. Because of supply network complexity and lack of visibility, however, only small case studies of real supply networks have been accomplished (Pathak et al., 2007).

Thus, in order to devise a large sample test, we argue that a product's LCA model, or "technology network", can be used as a surrogate for its supply network. A product's technology network is resultant from LCA and details the unit manufacturing processes that constitute the product's life cycle from material extraction to delivery to the customer (ISO 14040: 2006). A technology network does not depict organizational boundaries and suppliers but rather depicts unit production processes and how they are interconnected. A unit process is a discrete activity that converts environmental and economic inputs into corresponding outputs. For example, the transportation of material from one point to another is a common unit processor; as is the application of energy and material to form new material through industrial production, or the consumption of energy used by the product during consumer usage.

In our study the unit of analysis is a product's technology network comprised of unit processes as so identified by the EcoInvent database. The EcoInvent database is probably the most used life cycle inventory in the world, having been developed over a number of years by a broad coalition of stakeholders. From their website (www.ecoinvent.org): "The EcoInvent Centre, also known as the Swiss Centre for Life Cycle Inventories, is a joint initiative of institutes and departments of the Swiss Federal Institutes of Technology Zürich (ETH Zurich) and Lausanne (EPFL), of the Paul Scherrer Institute (PSI), of the Swiss Federal Laboratories for Materials Testing and Research (Empa), and of the Swiss Federal Research Station Agroscope Reckenholz-Tänikon (ART). The EcoInvent Centre was and is supported by Swiss Federal Offices."

The EcoInvent database contains over 4,500 unit manufacturing processes, organized into various product categories. For example, "construction wood" is a type of "wood", and within construction wood there are eight unit processes represented: softwood or hardwood that is either round wood, industrial wood, air dried, or kiln dried.

While the testing of our hypotheses only involves statistical regression, significant sources of variation exist. Specifically, there are a multitude of reasons why the environmental impact of one unit process (e.g. beef production) might differ from another (e.g. chicken production); the effect of the technology network structure, if it is present, is not likely to be large compared to these other sources of variation. We have two strategies for dealing with this problem. First, with a large sample size even the smallest effect can be detected and found to be statistically significant because of the power associated with very large sample sizes. Second, we will do comparisons within product categories. Thus, from our example above, if air-dried softwood tends to have a more centralized technology network than kiln dried softwood, this effect would be more directly seen in a comparison of the two. For example, the comparative model for human health will be as follows:

$$H_{ij} = \beta_{0j}^{H} + \beta_{1}^{H} C_{ij} + e_{ij}^{H} \quad (1)$$

$$\beta_{0j}^{H} = \gamma_{00}^{H} + \gamma_{01}^{H} Z_{j} + u_{0j}^{H} \quad (2)$$

$$\beta_{1j}^{H} = \gamma_{10}^{H} + \gamma_{11}^{H} Z_{j} + u_{1j}^{H} \quad (3)$$

where,
H_{ij} = CO2 emissions of product *i* in category *j*
C_{ij} = Technology network centrality of product *i* in category *j*
Z_j = Characteristic of product category *j* (network characteristic or otherwise)

In equation 1, the effect of centrality *C* for product *i* in category *j* varies within product category, thus the subscript *j* for β_1. This centrality effect is estimated for each product category, along with base human health values in β_0; this isolates within a product category the centrality effect from other influences. Subsequently, the base β_0 and centrality β_1 effects among product categories are explained in equations 2 and 3, respectively; thus allowing for higher-level understandings as to why human health changes among product categories.

The value of *C* (centrality) is operationalized as the fraction of triads in the technology network that exhibit sequential interdependency minus the fraction of triads that exhibit pooled interdependency. The former is defined as a triad where any given node only has at most one in-coming connection and one out-going connection, and the latter as a triad where at least one node has two in-coming connections. A triad census of each network is performed to calculate the statistics.

Network Analysis
We constructed a network analysis system as show in Figure 4 below. As described previously, unit process level information in ecoinvent database is represented in the form of a 4193x4193 matrix with associated weighted contributions between

the multiple unit processes. This enabled us to treat the data as a directed adjacency matrix where the rows act as inputs to the unit processes represented by the columns. We extracted technical networks from this matrix using the Social Network Analysis and iGraph packages of R. We encountered an interesting problem while investigating some basic network properties such as density and transitivity of the technical networks. Specifically, we found negligible variances in these measures across our sample of 4193 technical networks. We had to take an alternative approach where we built technical networks at different depths.

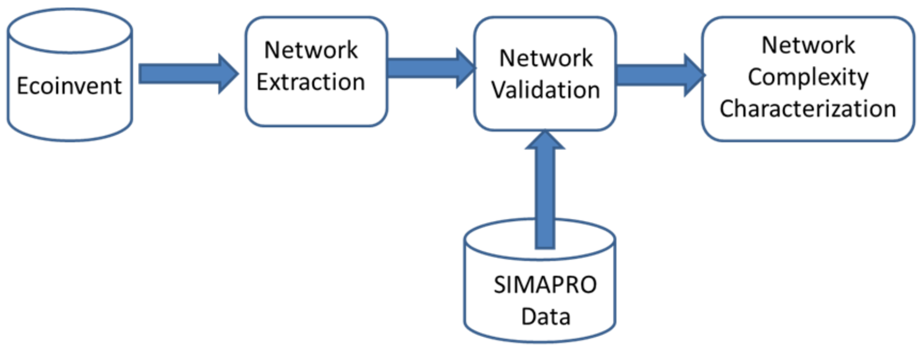

Figure 4: Network analysis system architecture

For example, we would take the first unit process and only develop a network consisting of its first tier inputs and the cross connections between these tier 1 inputs (if any). We would not consider any inputs to the tier one unit processes themselves. We then computed the network metrics mentioned above for all the unit process networks at depth 1. The average density at depth 1 was 0.221 with a variance of 0.017 and an average transitivity at depth 1 of 0.228 with a variance of 0.044. We systematically repeated the process for increasing depths to identify the level at which the variability disappears between the technical networks. At depth 2 the variance for density and transitivity was 0.004 and 0.006 respectively. At depth 3 and depth 4 the variance reduces to 0 up to three decimal places. Thus, a conclusion could be drawn that a certain basic unit processes such as electricity or energy feed into majority of the remaining unit processes forming a cloud like network structure ("common core"). Consequently, we employ technical networks at depth 1 and 2 for subsequent analysis.

In Figure 5, we show a sample network extracted using the R-packages. Some of the networks were manually validated with network illustrations of Ecoinvent technical networks created by SIMAPRO which is a third party LCA software. SIMAPRO does not analyze the networks in a graph theoretic sense. Instead it renders a tree based network illustration that can be manually matched up against the network rendered using our system.

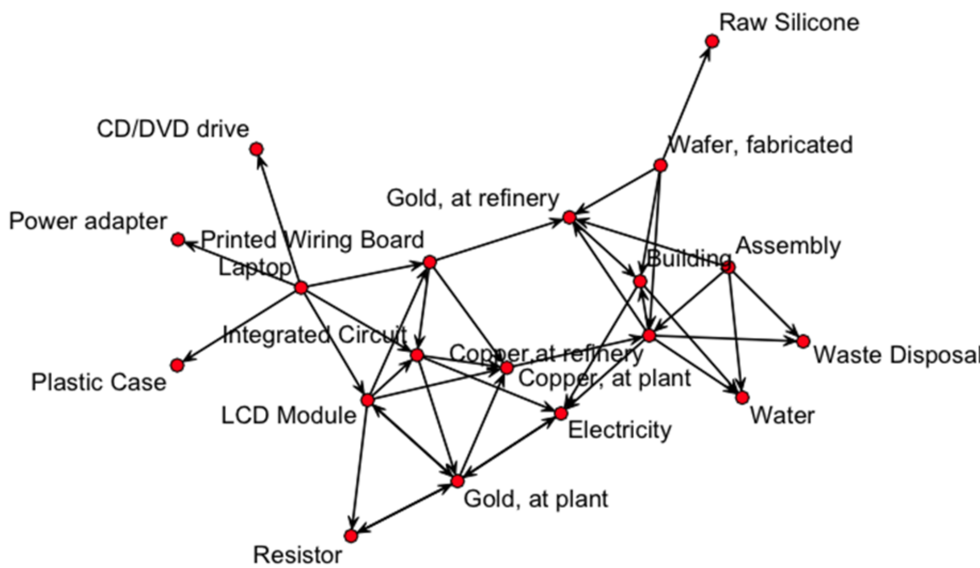

Figure 5: Sample technical network, Laptop Computer at Plant

Centrality Calculations

We use a triad based approach to calculate a centrality score C_i for each of the 4193 unit process technical networks. Theoretically, as we illustrate in Figure 6, there are 16 possible triadic forms possible with three nodes as suggested in the social networks literature (Freeman, 1997; Wasserman and Faust, 1994). Out of the 16 possible forms four triads are incomplete triads and we ignore them. The value of C_i is calculated on the remaining 12 forms. As shown by equation 4, we operationalize C_i as the fraction of triads in the technology network that exhibit sequential interdependency minus the fraction of triads that exhibit pooled interdependency. The former is defined as a triad where any given node only has at most one in-coming connection and one out-going connection, and the latter as a triad where at least one node has two in-coming connections. A triad census of each network is performed to calculate the statistics.

$$C_i = \left(\frac{Total\ pooled\ triads}{Total\ number\ of\ complete\ triads} - \frac{Total\ sequential\ triads}{Total\ number\ of\ complete\ triads}\right) \times 100 \qquad (4)$$

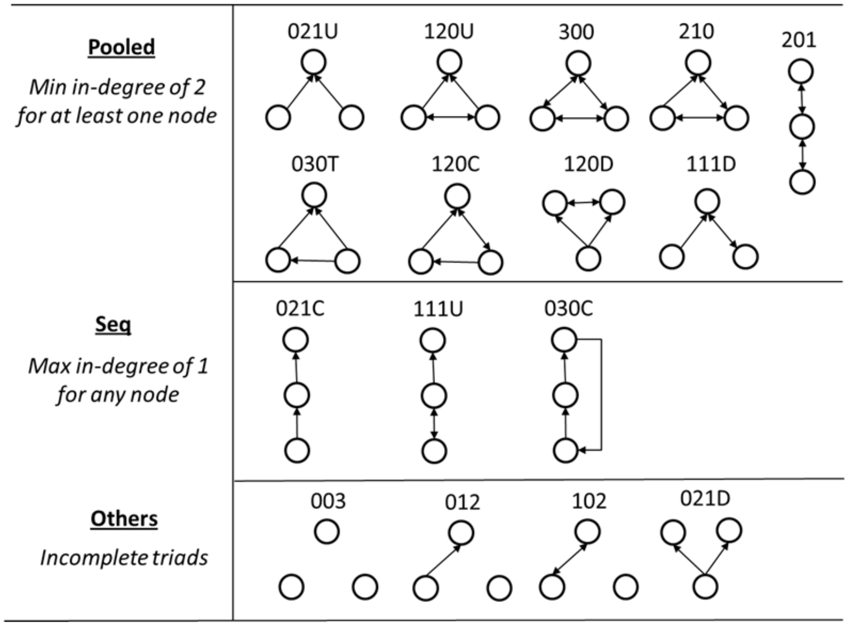

Figure 6: Pooled versus sequential triad classifications

In Figure 7 we summarize the triad centrality scores of the depth 1 and depth 2 unit process networks. The higher the centrality score, the higher is the percentage of pooled triads. For depth 1 networks, one would expect that pooled triads would be significantly higher than sequential triads. As seen in Figure 8, we observe that pattern in our results, providing face validity to our analysis. More interestingly, for depth 2 networks, as shown in Table 1, 15% of the unit processes are more sequential (C score <0). Out of this 15% about 13% are marginally more sequential than pooled with about 2% being definitely more sequential. On the other hand about 63% of unit processes are marginally more pooled than sequential (between 0% and 5%) while about 26% of the unit processes are pooled (C score >5%).

Table 1: Triad centrality score summary for depth 2 networks

Triad Centrality Score	Frequency	Percentage of total networks
<-25%	3	0.07
<-10%	24	0.57
<-5%	39	0.93
<0%	543	12.95
>0%	3363	80.21
>5%	714	17.03
>10%	356	8.49
>25%	10	0.24

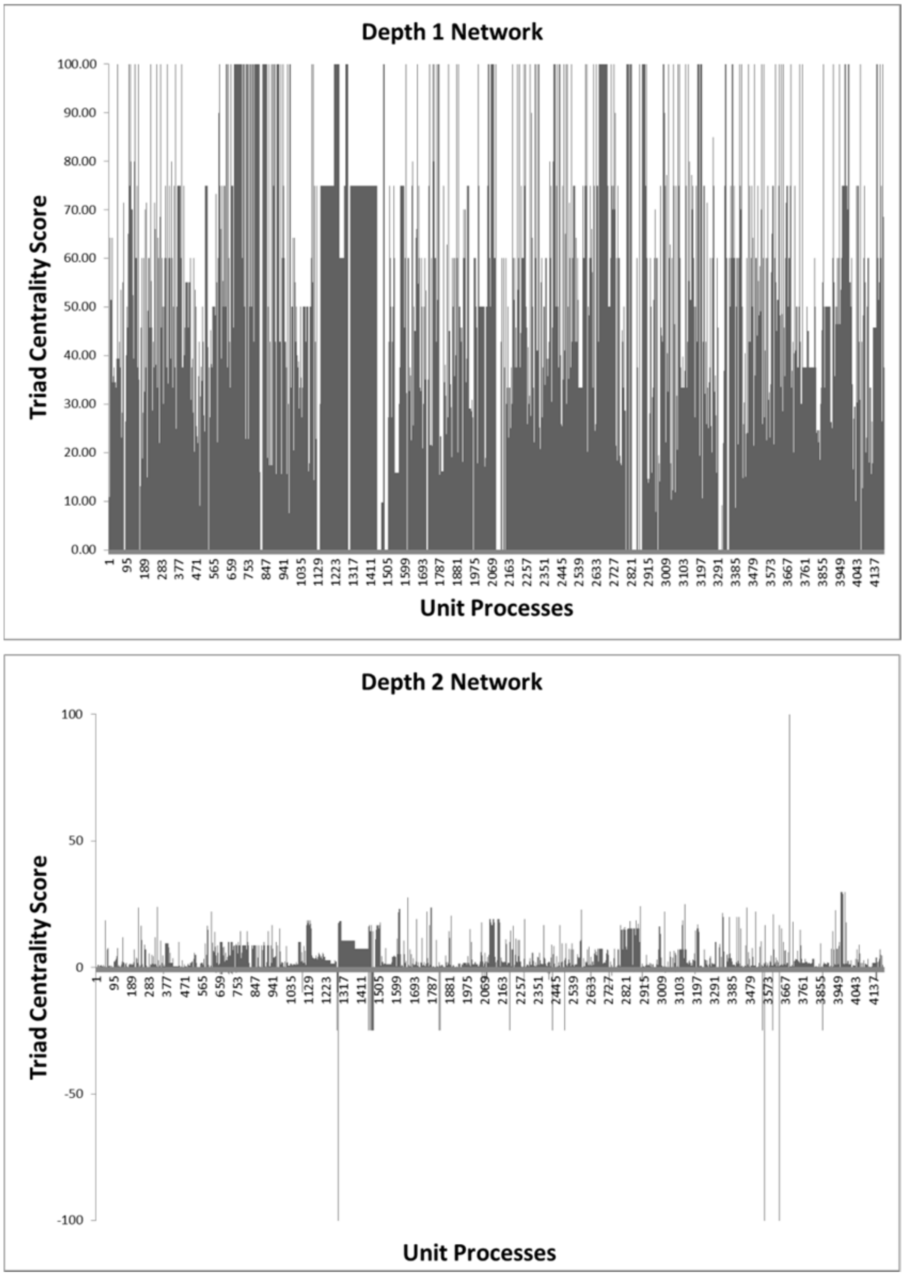

Figure 7: Triad centrality scores for depth 1 and depth 2 networks

Results and Discussion

The results discussed here are preliminary. We are continuing to refine data analysis, but we have confidence that the general results presented here will remain stable as we improve our modeling of the data.

First we characterize the network of extracted data. The size of the extracted networks varied greatly, with the average network having 65 nodes (see Figure 8). The data indicate perhaps three “clusters” of typical networks, some with approximately 30 nodes, some with 50 nodes, and some with over 100 nodes. Variation in size indicates variation in underlying complexity.

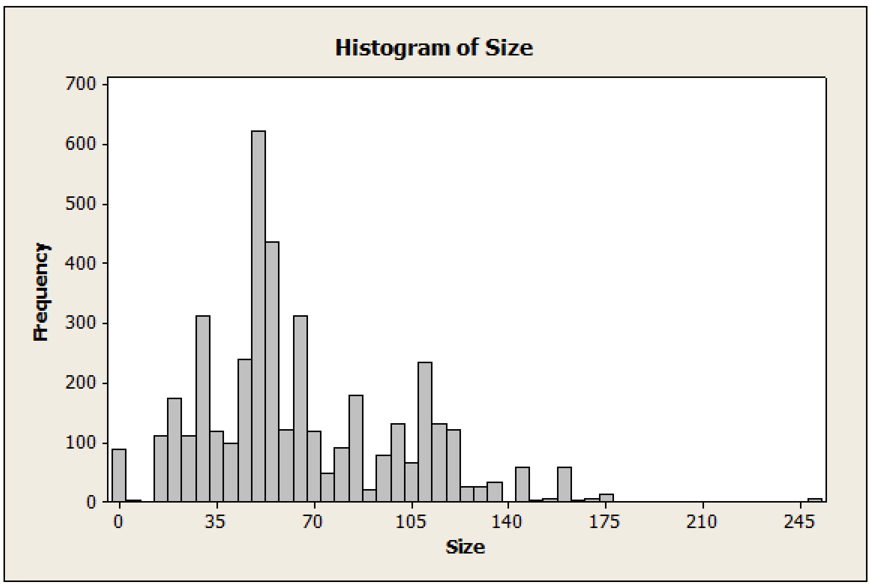

Figure 8 Distribution of network size for depth=2 networks

As compared to network size, the diameter of the network (Figure 9) indicates how close nodes are to one another. As diameter increases, processes become distant from one another and opportunities for optimization decrease. As with network size, we can see considerable variation, indicating underlying variation in the complexity of the networks.

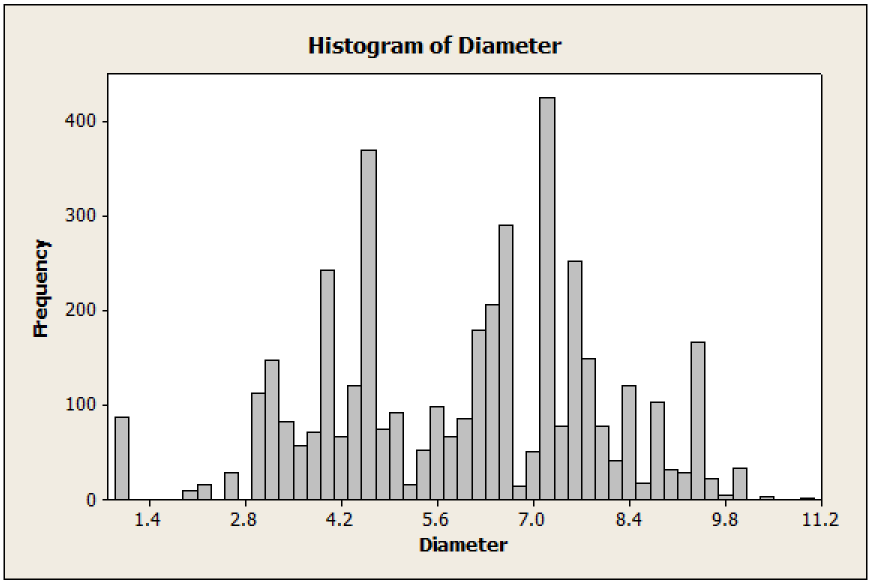

Figure 9 Distribution of network diameter

Finally, the distribution of network densities (see Figure 10) indicates that the networks are relatively spare, i.e. only a small percent of the possible connections are present. Coupled with the previous data, it indicates networks that are relatively sparse.

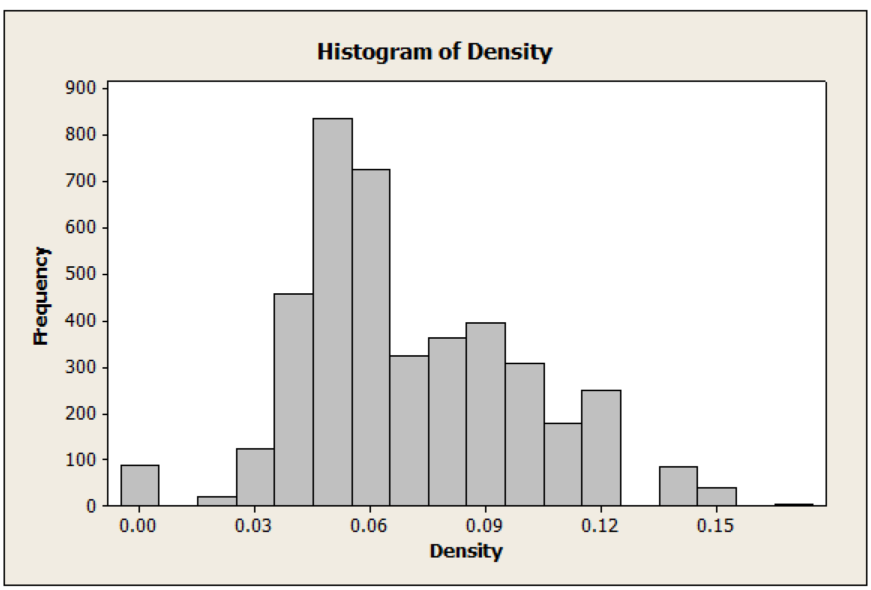

Figure 10 Distribution of network density

Next, we tested the hypothesis. We operationalized centralization as the difference between the percent of triads that are indicative of a pooled archetype minus the percent indicative of a sequential archetype, as defined in Figure 6.

- The correlation between the pooled index and carbon emissions is -0.016 and is not statistically significant.
- When using regression models that take into account the impact of other factors, including control factors, the parameter is estimated as negative and statistically significant (beta = -0.41, t-value = -5.13, p-value < 0.001). This means that pooled networks have lower emissions than sequential networks, ceteris paribus.

In summary, the data rejects our original hypothesis. We had posited that sequential networks would tend to minimize the number of upstream and downstream processes that any given process has to consider during its design and operation, which makes it relatively easier to find optimal solutions. What we found instead was that greater connectivity leads to lower emissions—that connectivity represents an *opportunity* for efficiency and optimization, *not a constraint* towards those ends.

There are several theories that support this alternative logic, i.e. that more connectivity in a supply network may lead to better performance. One such theory is Stuart Kauffman's NK (or rugged landscape) model (Kauffman, 1993). The NK model was developed as a model to explain phenomena in evolutionary biology, but has since been applied to the general area of technology evolution. In the model, N represents the number of design parameters available to the system and K is the average connectivity between them. The optimum performance of systems where K=0, i.e. all elements of the system act independently, is not as large as the optimal performance for small values of K (e.g. 2, 4), meaning that systems with some degree of interaction between components are able to achieve better optimal designs because they are able to take advantage of synergies and complementarities.

From a theoretical perspective, our study is the first to examine the link between supply chain and process architecture and environmental outcomes. Besides the impacts of decisions made at the unit process level, the overall architectural choices that are made can make it relatively easier or more difficult to optimize the design of a product supply chain. The study is one of only a few studies that have operationalized the concept of a supply network and undertaken empirical investigation. The study is the first to extend supply network theory into the realm of sustainability issues. From a practical standpoint, our study suggests that product designers and supply chain managers should encourage architectures that create opportunity for shared optimization, as in reality such a designs can perform better that designs that emphasize independence of operations.

Project Outcomes

The following outcomes are associated with the project.

Conference Presentations
Pathak, S., Mackenzie, C., Kull, T., Rabinovich, E., Dooley, K., and Wu, Z (2011). The missing link: Connecting the structures of products' technological process networks to their environmental performance, presented at *Decision Science Annual Meeting*, Boston, MA.

Publication Plans
We plan to submit three journal papers from the study:

- Journal of Industrial Ecology – Meta-analysis of LCA networks
- Journal of Operations Management – Process complexity and environmental outcomes
- Journal of Supply Chain Management – A network perspective on industrial accidents in complex supply chains

Faculty Development
This project significantly developed the research interests and capacity of its team members in the area of sustainability. For three of the six faculty involved, this was their first project in sustainability, and they have pursued interests in this topic in other projects since this one began. Two of the six faculty are assistant professors, so this grant has helped establish their careers and future grant-seeking. Finally, for five of the six, this was their first NSF grant.

Student Development
A Supply Chain Management Ph.D. student was supported for their first two years of their program on this grant. Unfortunately the student had to leave the program due to family reasons.

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