Is Lean Necessarily Green?

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Abstract

In this paper, we investigate the environmental performance of lean supply chains using carbon dioxide emissions as the key performance indicator. Lean is based on the premise that compressing time reveals hidden quality problems and that their resolution leads to more efficient, cost-effective business processes. If time compression always implies lower emissions, then a leaner system is always greener as measured by emissions. If time compression does not always lead to lower emissions, then further changes to the lean system may be required in order to make it greener. We use a simulation model of a generic supply chain as well as two representative examples of supply chains to examine this. Our analysis shows that supply chain emissions are highly sensitive to the frequency and mode of delivery of goods as well as the type and amount of inventory stored at each company. Our results suggest that lean supply chains are not necessarily green, although they could turn out to be green in certain cases. The main impediment appears to be distance. While lean supply chains typically have lower emissions due to reduced inventory levels, the frequent replenishment at every point in the provision stream generally tends to increase the emissions. If a lean supply chain is located entirely within a small region, then it would almost certainly be green from an emissions perspective due to the low levels of inventory and short shipping distances. As distances increase along the supply chain, it is quite possible for lean and green to be in conflict, leading to tradeoffs as well as additional opportunities for optimization.

Keywords: lean; lean and green; supply chains; environmental performance; carbon dioxide emissions

Introduction

Lean manufacturing methods pioneered by Toyota are replacing conventional methods in both manufacturing and service industries. Lean thinking (Womack and Jones 1996) is a systematic approach to developing business processes with the aim of doing more with less while coming as close as possible to providing customers exactly what they want, when and where they want it. It is already the dominant paradigm in manufacturing today, and it is also being applied to supply chains (Jones and Clark 2002); therefore its environmental sustainability impacts are important to understand.

Lean thinking provides a way to: 1) specify value, 2) determine the best sequence for value-creating steps, 3) perform these activities without interruption when a customer requests them, and 4) continually improve the process. Lean processes attempt to eliminate wasteful activities by focusing on time compression throughout the value stream. It is based on the premise that compressing time reveals hidden quality problems, and that their resolution leads to more efficient, cost-effective business processes (Simons and Mason 2003). The techniques of lean logistics (Womack and Jones 2005) extend these ideas to entire supply chains. As the customer "pulls" value by demanding a certain quantity of a product, that information propagates upstream through the supply chain consisting of multiple companies, and the right amount of product moves downstream in the fastest possible time with a minimum of waste. Lean logistics require frequent replenishment of goods in small amounts at every point in the provision stream, as well as the compression of the provision stream in time and distance.

Some researchers have asked if there are limits to the application of lean management thinking in complex supply chains (Cox and Chicksand 2005). They suggest that lean's focus on minimizing waste and passing the benefits onto customers is likely to strategically benefit only the strongest players within the supply chain—those that can exert considerable leverage both upstream and downstream in the chain. We too want to know if such limits exist, although our focus is on the environment.

As lean relentlessly focuses on reducing non-value added time and producing just the right amount of a product as needed, an important question is whether it improves or deteriorates environmental performance. The U.S. Environmental Protection Agency (EPA 2003) has found that lean produces an operational and cultural environment that is highly conducive to waste minimization and pollution prevention, and that lean provides an excellent platform for environmental management tools such as life-cycle assessment and design for environment. But as the EPA also notes, lean (as originally documented by Womack and Jones) does not explicitly incorporate environmental performance metrics, potentially leaving improvement opportunities on the table. As lean implementation pushes manufacturing processes toward the point of lowest cost, does it also push them to the point of optimal environmental performance?

Typical metrics for measuring environmental performance include scrap or non-product output, materials use, hazardous materials use, energy use, water use, air emissions, hazardous waste, and water pollution (EPA 2005). None of these is directly optimized in a typical lean implementation, so it is difficult to know whether a lean process is operating at optimal environmental performance. Value stream mapping, a standard tool in the lean toolkit, examines the time it takes to produce a product and the proportion of that time that is value-added, and provides the basis for optimizing performance over the single dimension of time. But it does not explicitly consider the resources consumed and waste generated in manufacturing a product. To help address this question, Simons and Mason (2002) developed *sustainable value stream mapping* by adding a sustainability metric (supply chain carbon dioxide divided by market weight of product) to the conventional value stream mapping process. Similarly, Karp (2005) advocates adding environmental aspects to value stream maps.

Other additions to conventional value stream mapping include mapping the flows associated with the use of energy, water and materials in order to find hidden sources of waste in the value stream (EPA 2005). The idea is to use these resource flow maps to address environmental questions in parallel with time compression during the development of future state maps. But the maps alone do not automatically reveal the best way to minimize the consumption of these resources. Moreover, it is unclear how an optimal future state map would be developed if a conflict existed between time compression and environmental performance.

The issue of environmental performance becomes even more complicated when entire supply chains are considered. With the rapid increase of long-distance trade, supply chains are increasingly covering larger distances, consuming significantly more fossil-fuel energy for transportation and emitting much more carbon dioxide than a few decades ago. Karp (2005) reports, "as large manufacturers rely on lengthy supply chains the environmental impact of suppliers continue to grow." For example, fruits and vegetables travel over 1500 miles on average within the U.S., and over half of the energy consumption associated with food production is related to transportation (Pirog, Van Pelt, Enshayan and Cook 2001). A basic diet with imported ingredients can consume four times the fossil-fuel energy and emit four times the carbon dioxide compared to domestically produced ingredients (Halweil 2002). Particularly problematic is the growing use of trucks and airplanes at the expense of slower and more efficient trains and ships. The transportation sector already produces a quarter of all energy-related carbon dioxide emissions and these emissions are growing fast at about 2.5 percent annually (Venkat 2003). In the U.K., road transport has been identified as the largest source of carbon dioxide emissions (Mason and Lalwani 2003). Transportation is the fastest growing energy consumer in the European Union with a 47 percent increase since 1985 compared with 4.2 percent for other sectors (Lalwani and Mason 2004).

This has important implications for lean supply chains. To be fair, lean principles call for distances on a supply chain to be as short as possible. But in this age of global trade, very few supply chains can consist entirely of short transportation links. Even if several of the companies on a supply chain can be located close to each other and close to customers (a fairly unlikely scenario at present), raw materials may have to be shipped from other parts of the country or other parts of the world. If the companies are somehow located close to all the raw materials, then finished products may have to be transported to customers living elsewhere. Moreover, the low cost of labor in developing countries is an increasingly important factor in locating parts of the supply chain far from customers in the developed world. The idea of lean location logic (Womack 2003; Womack and Jones 2005) recognizes this and attempts to minimize the total cost of operating a supply chain, albeit without internalizing the environmental costs. It suggests that firms consider locating high-volume manufacturing in low-wage countries that are close to the region of sale, such as Mexico rather than China for the U.S. market.

Currently, however, a typical supply chain is likely to have at least a few moderately long transportation links, making energy use and carbon dioxide emissions due to transportation significant contributors to negative environmental performance. Carbon dioxide emissions closely track the energy used in transportation, so emissions alone can serve as a key indicator of both energy use and pollution in supply chains. While there should be a range of performance metrics to measure the full environmental impact of supply chains, we focus on carbon dioxide emissions in this study.

Carbon dioxide emissions are the primary sustainability metric used by the sustainable value stream mapping referred to earlier (Simons and Mason 2002; Simons and Mason 2003). Sustainable value stream maps show both the time incurred and carbon dioxide emitted at every step in a supply chain. Both time and emissions are classified as value-added, non-value added, and necessary but non-value added. As with any extension of value stream mapping, this poses the problem of optimizing more than one performance metric at the same time (time and emissions in this case). Simons and Mason use examples of food supply chains to suggest that producing food closer to the point of consumption and being more responsive to the consumer will help lead to a win-win situation where time compression and emissions minimization can occur synergistically.

Our investigation of the environmental performance of lean supply chains is motivated in part by the difficulty of knowing whether a particular future state (representing a time compressed supply chain) achieves the lowest possible emissions, especially when distances are significant. If time compression always implies lower emissions, then a leaner system is always greener as measured by emissions. If time compression does not always lead to lower emissions, then further changes to the lean system may be required in order to make it greener, possibly resulting in a tradeoff between lean ideals and green ideals.

In this paper, we use a simple generic supply chain model as well as two representative supply chains examples to show that the environmental performance of supply chains (as measured by carbon dioxide emissions) is highly sensitive to the frequency and mode of delivery of goods as well as the type and amount of inventory stored at each company. While lean supply chains typically have lower emissions due to reduced inventory being held internally at each company, the frequent replenishment at every point in the provision stream generally tends to increase the emissions. On balance, we find that several factors influence the total emissions as a supply chain gets leaner, implying that lean may be green in some cases but not in others. This suggests that optimization of emissions in supply chains is an open problem that may require solutions that are complementary to standard lean techniques.

Methods

Our purpose in this investigation is to develop insights into the emission characteristics of supply chains, including lean and non-lean configurations. We start by developing a simple simulation model of a generic two-stage supply chain using Vensim [2006], a system dynamics modeling package. In this model, emissions are generated by the transportation of goods between the stages and by the storage of inventory within the stages. By varying the order size at each point – which is directly related to the frequency of replenishment and inventory held – we look for an optimal order size at each stage that minimizes emissions. The benefit of a simulation model is that it allows us to easily explore the problem space by varying the parameters and testing the sensitivity of the system to variations in order size. As we will see shortly, such experimentation can provide very useful insights into how emissions can be minimized and whether or not a lean configuration always produces lower emissions than a non-lean configuration. For the purposes of this study, we ignore emissions from the actual manufacturing steps and assume that they are nearly constant. Only the transportation and storage emissions vary depending on the configuration.

We then apply these ideas to two supply chains derived from the literature, and rely primarily on hand-calculations to minimize emissions. One is a manufacturing supply chain that produces windshield wipers for automobiles (Jones and Womack 2002). Transportation emissions are important in this case, but storage emissions are negligible since inventory can be stored at ambient temperature. The second example is a food supply chain (Simons and Mason 2002), where storage emissions are significant because of cold storage requirements.

In order to keep the analysis and optimization as simple as possible, we assume that only the following three road transport options are available in all the cases and do not consider rail, water and air transport (calculations are based on data from Pirog, Van Pelt, Enshayan and Cook 2001):

Table 1: Characteristics of road transport options.

Transport Mode	Maximum Load[1] (kg)	Fuel Type	Specific total CO_2 emissions (g/ton-km)
Heavy-duty Truck	17300	Diesel	62
Midsize Truck	6000	Diesel	122
Light Truck	700	Gasoline	459

For products that require cold storage at each inventory point, we assume that storage emissions are proportional to the weight of the product stored and the duration of storage. We assume a nominal storage emissions rate of 1 g/kg-hour, and then vary it in our simulation experiment to test its sensitivity. Some products may also require refrigerated shipping, which would add to the emissions for each hour of transportation, but we do not explicitly consider this in our study. We also ignore any additional energy use and emissions due to lighting, heating, etc., while goods are in storage.

A Generic Supply Chain

We start with a simple, generic supply chain, as shown in Figure 1. There are two stages, each with inventory storage and an input supply rate. There is also a final delivery output from the second stage, which matches the customer demand. For the purpose of our experiment, we assume an arbitrary, but frequent demand for the final product of 350 kg once every five hours. We assume that each of the supply links is 1000 km long and that full-truck direct shipments are used. We also assume that trucks are used productively on

[1] Excluding container weight.

their return trips and we do not include the return trips in our analysis. None of the material entering the system is wasted as scrap or non-product. None of these assumptions is critical to the general trend seen in the results, but the assumptions simplify the model and allow us to focus on studying the emission characteristics in this initial investigation. The model also provides an option to turn cold storage on or off at each stage in order to study the performance for different types of materials. The actual system dynamics model includes the necessary information flows and decision logic, which we have omitted from Figure 1 for clarity.

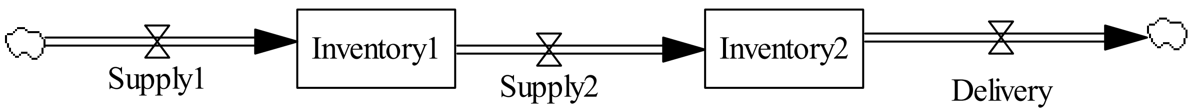

Figure 1. A generic two-stage supply chain depicted as a stock-flow diagram.

A key parameter in the model is the minimum order size at each stage, which determines the frequency at which the inventory is replaced. For example, if the order size at the second stage is exactly 350 kg, then an order for this amount would be placed by the second stage as soon as that amount of product was delivered to the customer. This order would be supplied by the first stage, which in turn would place an order to replenish its stock based on its own minimum order size. If the minimum order size at the second stage is 700 kg, then a replenishment order would be generated after that quantity of the product has been delivered. As the minimum order size increases, the inventory level increases correspondingly and the frequency of replenishment decreases.

In the case of a lean supply chain, the minimum order size would be as close to 350 kg as possible in this example, such that replenishment orders closely follow the delivery patterns. Moreover, both stages in the supply chain would be tightly synchronized (with the same minimum order size) and inventory levels would be very low. Figure 2 shows the total emissions per unit weight of the product as a function of the minimum order size. As the order size increases past 700 kg, it becomes possible to use midsize trucks instead of light trucks, which produce significantly lower emissions for each unit of product delivered as shown in Table 1. If the order size exceeds 6000 kg, then heavy-duty trucks become viable and the emissions drop even more. In the absence of cold storage requirements, it is obvious that emissions will reach a minimum at an order size of just over 6000 kg. In reality, the order size can only take on certain specific values because it must match the full capacity of the truck, unless the truck is efficiently shared by multiple products or companies.

Figure 2 also shows the emissions characteristic when cold storage is required at both stages. As the minimum order size increases, inventory levels also increase and the average time that products are in storage increases. Thus, a large minimum order size would lead to increased emissions from storage, which would have to be balanced against the lower transportation emissions. The cold storage curves – one with the nominal storage emissions of 1 g/kg-hour and the other with 5 g/kg-hour – illustrate this tradeoff, and show that there is likely to be an order size where minimum emissions can be achieved, given the restriction that full-truck shipments must be used. In our example, a midsize truck carrying 6000 kg would provide the best performance for products requiring cold storage, which is also close to the best performance without cold storage. Refrigerated shipping would increase the total emissions and raise both of the cold storage curves to somewhat higher emission levels. Note that the optimal order size is far from the 350 kg required by an ideal lean system. The ideal lean system can certainly achieve minimal emissions by sharing a larger truck, if the logistics can simultaneously handle significant distances and different just-in-time shipping requirements for multiple (possibly lean) product lines and companies.

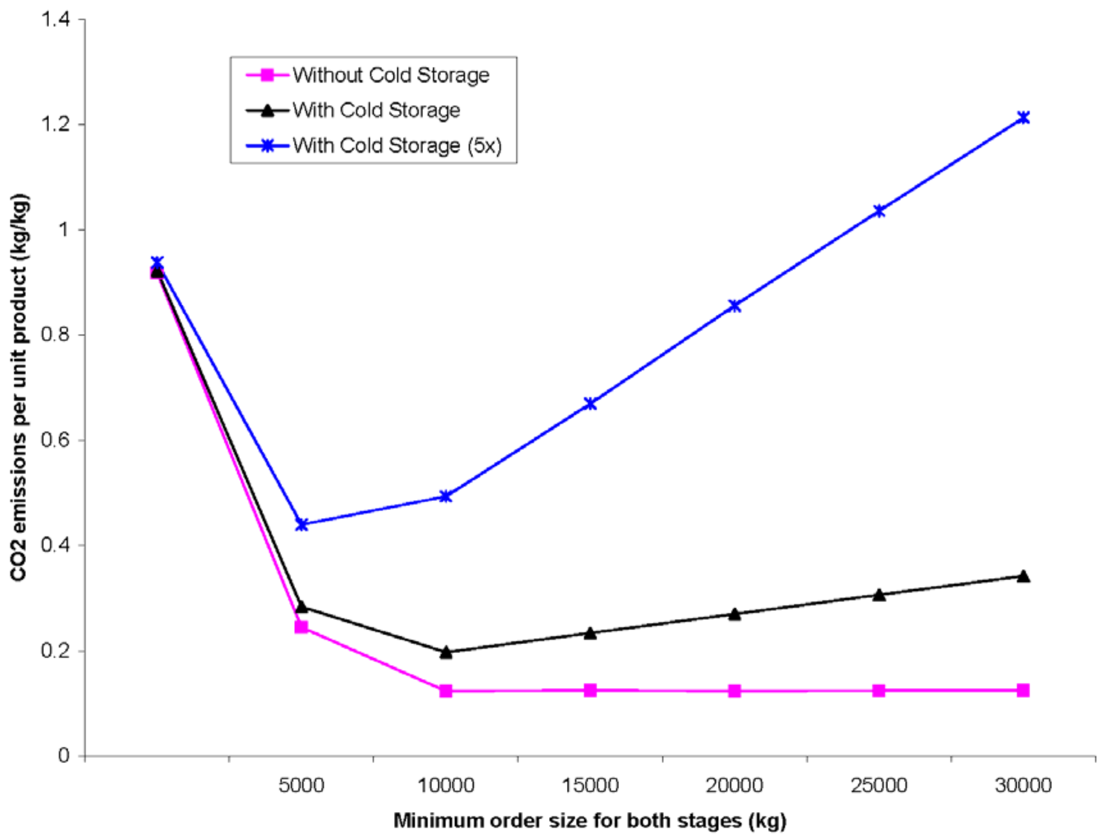

Figure 2. Carbon dioxide emissions for a two-stage lean supply chain with and without cold storage.

Figure 3 shows the emission characteristics of a general two-stage supply chain where each stage has an independent minimum order size and no cold storage requirements. In this case, each stage can be lean or not lean, independent of the other stage. The total emissions per unit weight of the product reaches a minimum for a certain combination of the two order sizes. This analysis suggests that a globally minimum emission level could be achieved – at least theoretically – for a general N-stage supply chain. The optimization could be rather complicated when cold storage requirements are added to various stages.

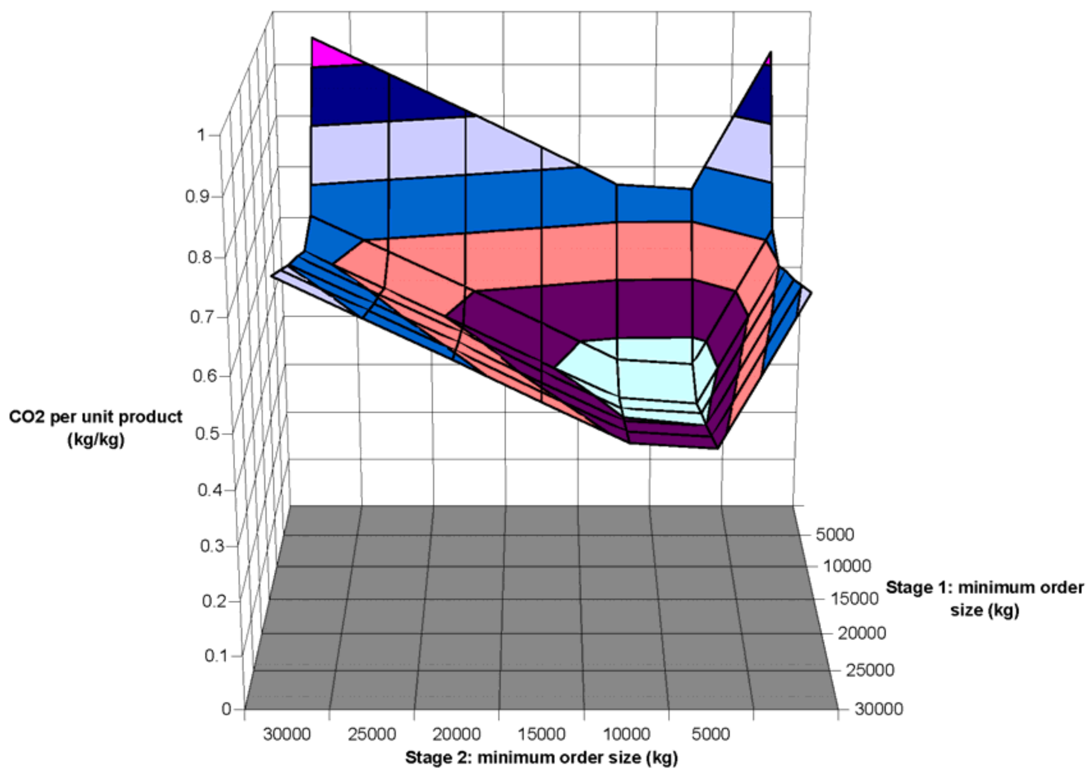

Figure 3. Carbon dioxide emissions for a supply chain with two independent stages.

A Manufacturing Supply Chain

We continue our investigation of supply chain emissions by considering a manufacturing supply chain with significant transportation emissions but negligible storage emissions. We use the example of a windshield wiper supply chain (adapted from Jones and Womack 2002). Figure 4 shows the "current state" map prior to implementing the lean improvements. We have omitted from this diagram most of the numbers that are relevant for lean improvements and instead focused on the distances and batch sizes (same as our order sizes) used for delivery between the stages. Since the original system operates on a batch mode with relatively large order sizes and inventories, we assume that heavy-duty trucks are used for the biweekly deliveries, while midsize trucks are used for the daily deliveries six days per week. This allows us to switch from heavy-duty trucks to midsize trucks in Figure 5 where the biweekly deliveries are replaced by daily deliveries, noting that a heavy-duty truck can carry about three times the load of a midsize truck. All deliveries use full-truck direct shipments and we assume that return trips are productively used for other purposes.

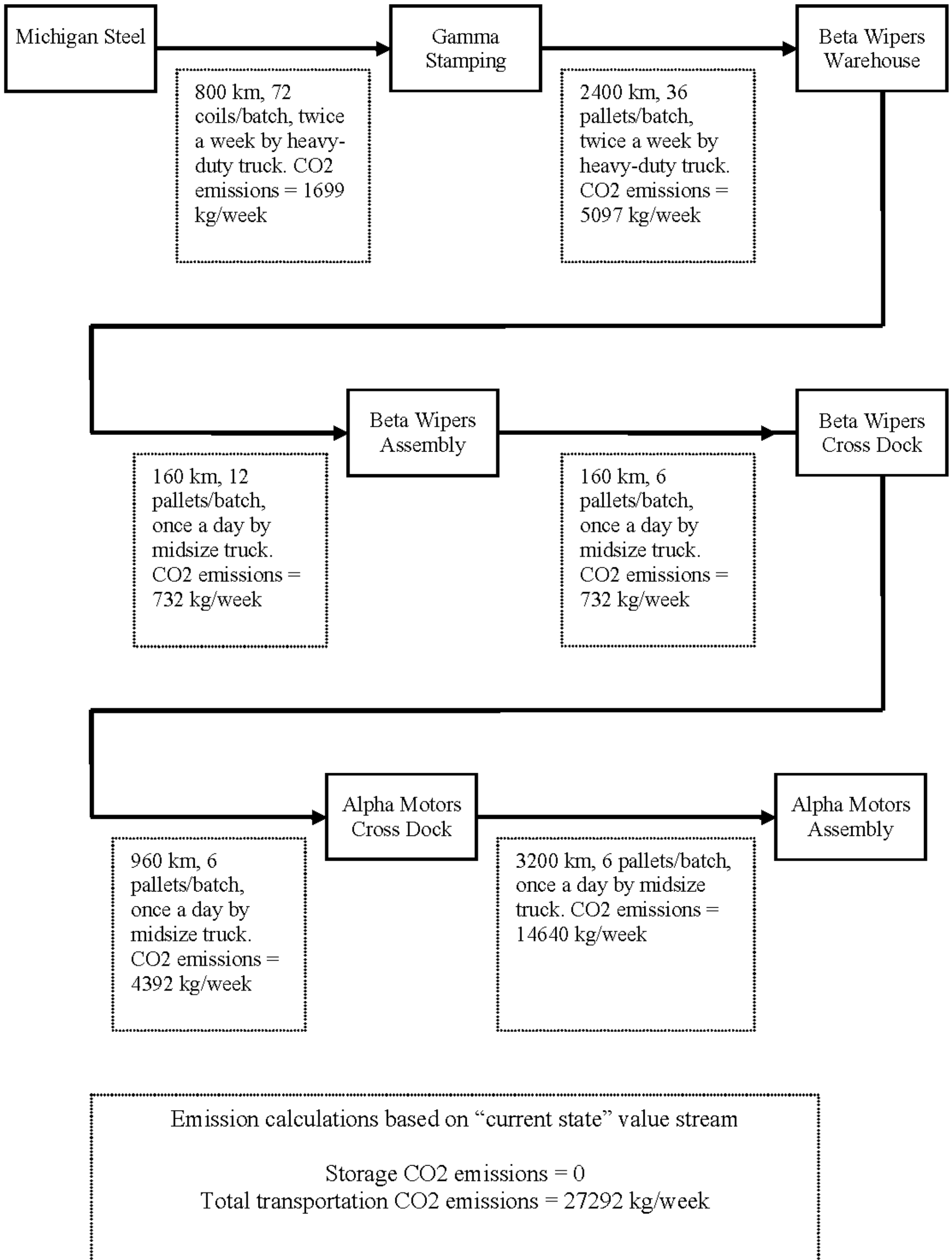

Figure 4. Windshield wiper supply chain: Current state (adapted from Jones and Womack 2002).

Figure 5 shows a future state based on lean principles. While the distances are still large, time has been compressed and just-in-time deliveries of small quantities have been adopted. We still assume full-truck shipments as before, but using smaller trucks, since the large distances and frequent just-in-time deliveries may necessitate dedicated trucks. The total carbon dioxide emissions per week (based on our assumptions) are marginally higher in the future state, suggesting that the lean system is not closer to the point of minimal emissions.

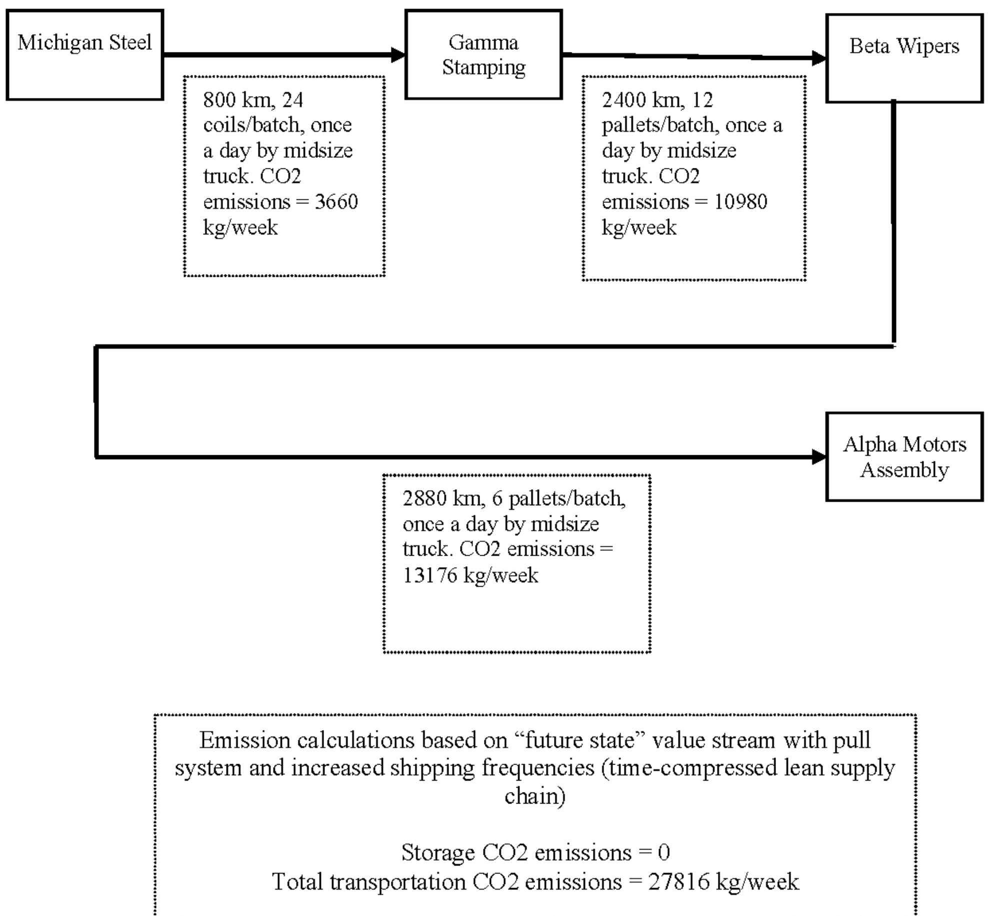

Figure 5. Windshield wiper supply chain: Future state with increased shipping frequencies (adapted from Jones and Womack 2002).

In Figure 6, we illustrate a hypothetical improvement to the emissions characteristic by decreasing all the shipping frequencies and switching to heavy-duty trucks. If the increased inventory can be physically accommodated at each stage in the supply chain, then emissions would decrease to less than half of both the original configuration and the lean configuration. This indicates that a lean approach does not necessarily lead to the lowest possible emissions when distances are large. In fact, lean and green have conflicting delivery requirements in this example.

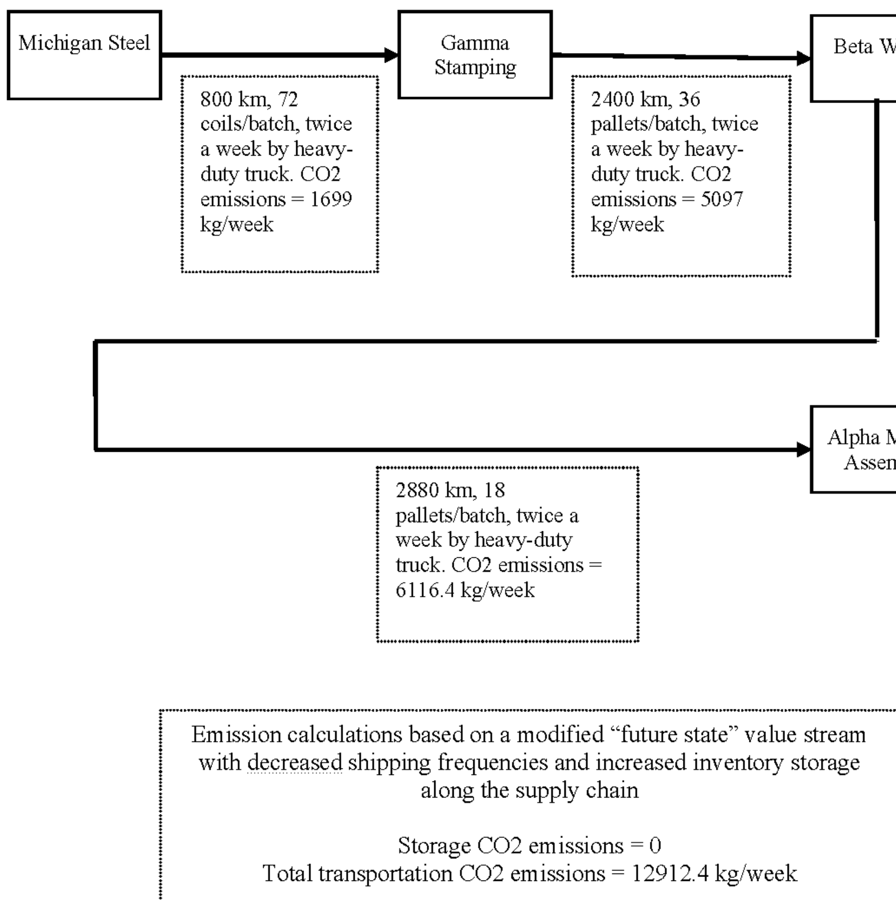

Figure 6. Windshield wiper supply chain: Future state with decreased shipping frequencies and increased inventories.

A Food Supply Chain

Next, we examine the emission characteristics of a generic food supply chain which includes both transportation and cold storage (adapted from Simons and Mason 2002). Figure 7 shows the current state map prior to implementing lean improvements. In this case, emissions are specified for a unit of the final product. Since the emissions data for this example were provided by Simons and Mason in their paper, we have not used the data from Table 1.

Once again, we have focused on transportation and storage emissions, which correspond to the non-value added and the necessary but non-value added emissions. Production emissions, which correspond to the value-added emissions, are not shown in the individual process steps.

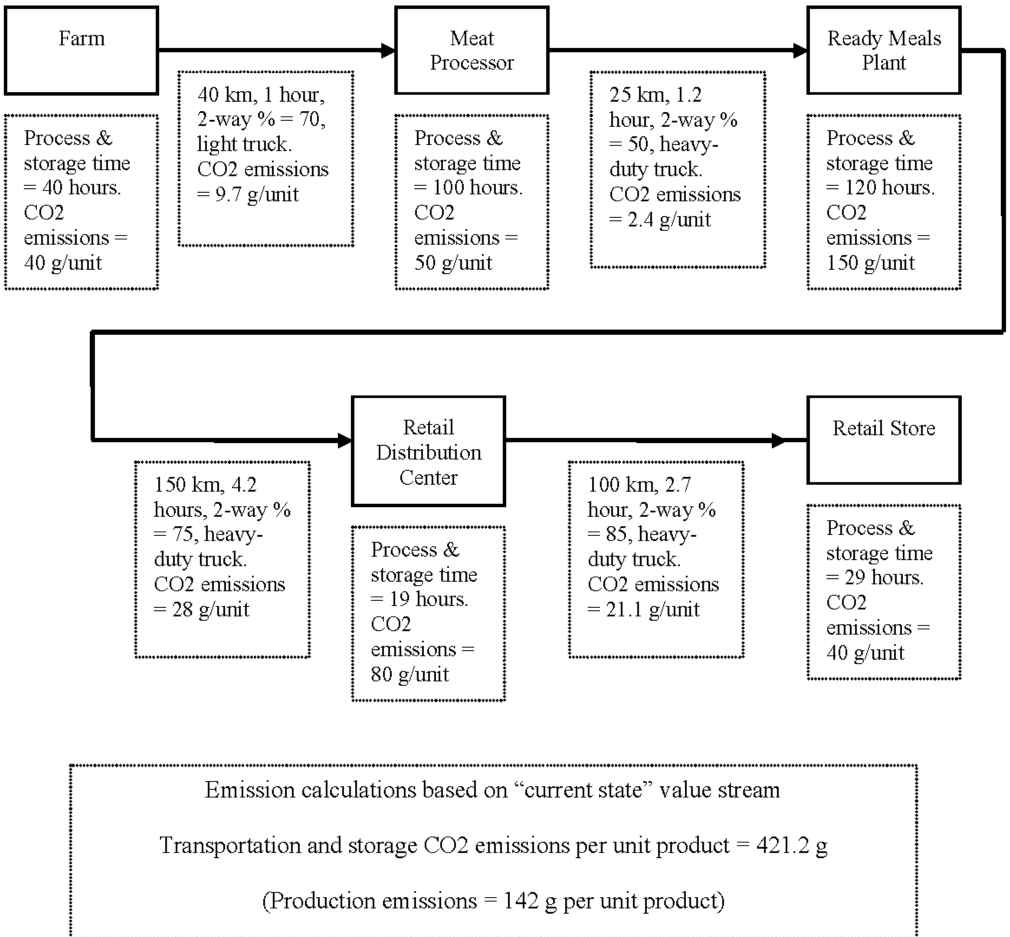

Figure 7. Food supply chain: Current state (adapted from Simons and Mason 2002).

Figure 8 shows a leaner future state with more frequent, just-in-time deliveries from the Meat Processor to the Ready Meals Plant using a light truck. This decreases the cold storage time at the Ready Meals Plant. The net result is that total emissions decrease slightly in the future state. However, all the transportation links in this example are very short, so storage emissions dominate the overall emissions, and any reduction in cold storage is very helpful in reducing total emissions.

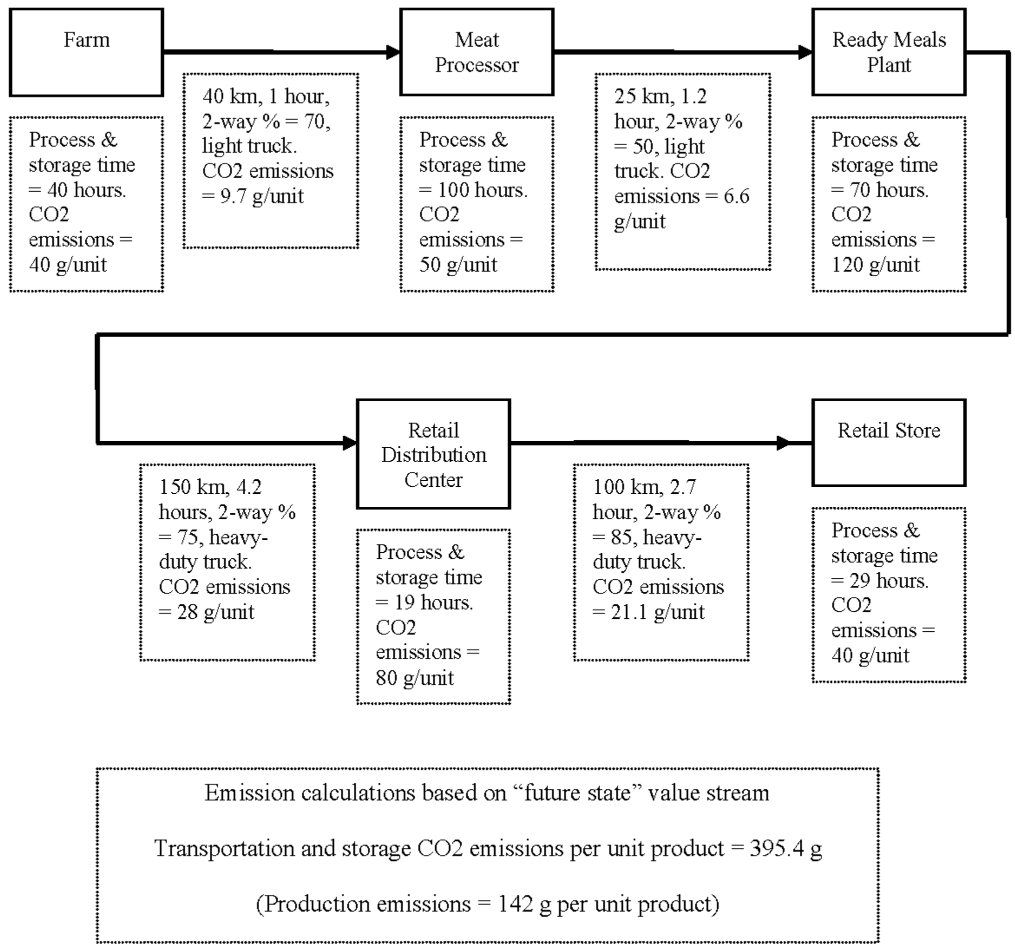

Figure 8. Food supply chain: Future state with more frequent deliveries to the Ready Meals Plant (adapted from Simons and Mason 2002).

As we have argued earlier, short distances are likely to be the exception rather than the rule in today's supply chains. Figure 9 shows how the total transportation and storage emissions vary as a function of the distance between the Meat Processor and the Ready Meals Plant in steady-state, keeping all other things fixed. We ignore any cold storage required during transportation, since this requirement would affect both the current state and future state in nearly the same way on a unit product basis. We see that the future state generates lower emissions only when the distance is less than 200 km, once again suggesting a likely conflict between lean and green when distance increases.

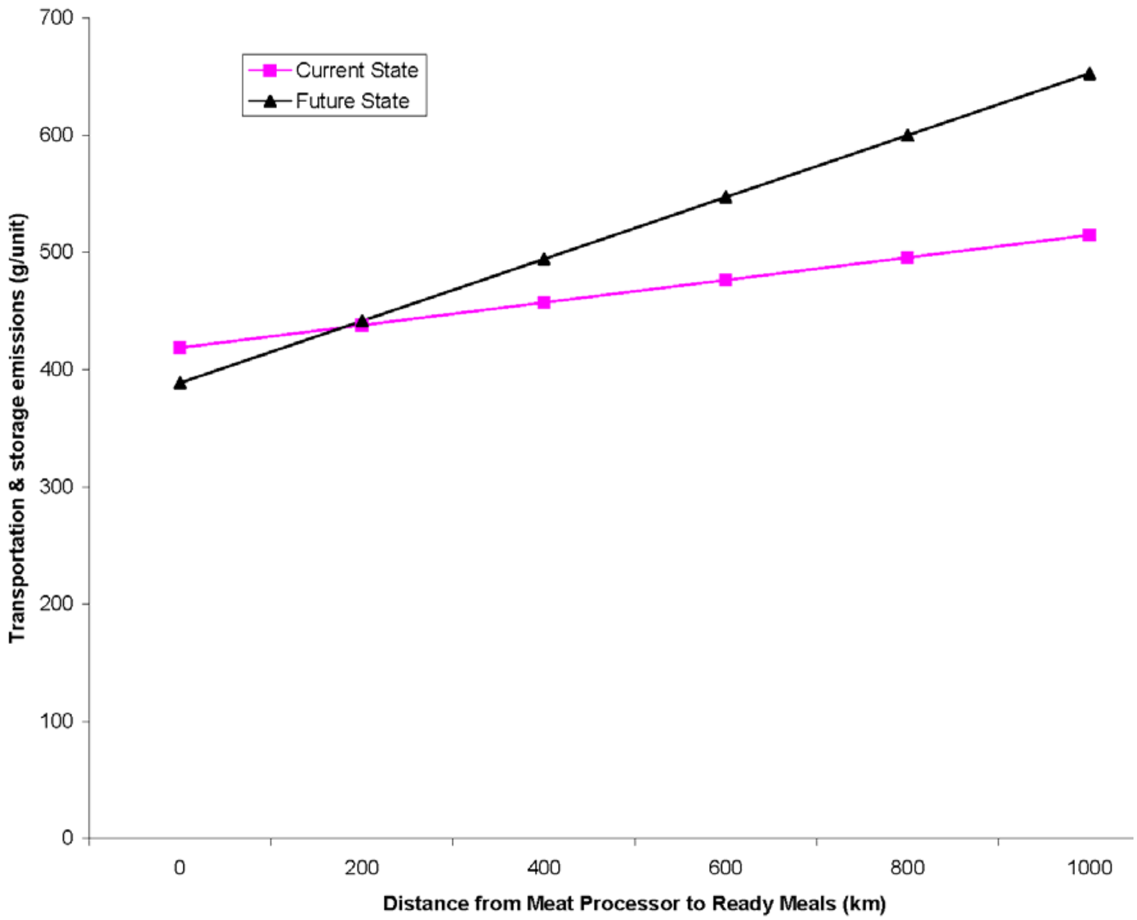

Figure 9. Transportation and storage emissions as a function of distance from Meat Processor to the Ready Meals Plant.

Conclusions

Our goal in this study has been to develop insights into the emission characteristics of supply chains, for both lean and non-lean configurations, using hypothetical and simplified examples. Our analysis of a generic supply chain, a manufacturing supply chain, and a food supply chain all show clearly that lean (or leaner) supply chains do not necessarily reduce carbon dioxide emissions, particularly when distances along the supply chain are significant. When cold storage is not required for a particular product line, emissions depend largely on the transportation mode, and larger deliveries at less frequent intervals all along the supply chain generally lead to the lowest emissions.

When cold storage is required along the supply chain, it is advantageous to keep inventory levels low. But this increases transportation emissions due to more frequent deliveries; consequently, there is likely to be an optimal order size that balances inventory level and delivery frequency.

Our analysis suggests that lean supply chains are not necessarily green, although they could turn out to be green in specific cases. The main impediment appears to be distance. If a lean supply chain is located entirely within a small region, then it would almost certainly be green from an emissions perspective due to low levels of inventory and short shipping distances. As distances increase, it is quite possible for lean and green to be in conflict, which may require additional modifications to the supply chain (perhaps moving it away from the ideal lean configuration) if emissions are to be minimized. Thus, minimizing carbon dioxide emissions in supply chains is likely to involve tradeoffs between lean principles and green principles. Another way for lean supply chains to minimize emissions is by using more efficient transport modes, such as heavy-duty trucks in our examples, and sharing the trucks with other product lines and companies in order to use their full capacity. But the logistics of just-in-time deliveries could become quite complicated when large distances and multiple product lines are involved.

This study represents a first step toward a systematic understanding of supply chain emissions and how they might be optimized. Although we have not proposed any specific optimization methods other than comparing different configurations of a supply chain through simulation and hand-calculation, we have shown that it is indeed possible to minimize supply chain emissions.

We should emphasize once again that we have focused exclusively on carbon dioxide emissions as an environmental performance indicator in this study. A broader range of performance metrics will be needed to measure the full environmental impact of supply chains, which may highlight some of the direct benefits of lean supply chains. The next steps in our research are to empirically validate the ideas and insights from this study using a set of real-world supply chains and to develop optimization methods for minimizing emissions in complex supply chains.

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