Title

Environmental decision making: supply-chain considerations

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ABSTRACT

Water use, energy use, and global warming potential (GWP) are investigated to assess the environmental impact of the manufacturing supply-chain in the interest of developing sustainable manufacturing systems. Because a major component of the supply chain is transportation, four methods of transportation are investigated: shipping, rail, trucking, and air freight. Additionally, location-specific manufacturing considerations such as water scarcity, resource availability, and energy mix are discussed. Finally, a tool is introduced to enable the visualization and computation of manufacturing supply-chain environmental impacts. This information enables decision making for designing and implementing sustainable supply-chain networks.

INTRODUCTION

The manufacturing sector is a significant contributor to environmental damage and resource use. This is especially true and problematic with the development of a global economy where resource scarcity and resource consumption are not limited by borders. The long-term implications of overusing resources and altering our air, water, and soil have led manufacturing researchers to investigate methods to reduce the environmental impact of manufacturing.

For example, in metal cutting research, Roman *et al*. [2006] investigated the water and energy consumption of industrial cleaning processes, Jayal *et al*. [2004] investigated the relative health risks associated with mist versus flood cooling, Clarens *et al*. [2006] worked to reduce the needed volume of metal working fluids in cutting processes, and Filipovic *et al*. [2005] studied dry cutting techniques.

In these previous environmental analyses, the primary focus has been on low-level process and factory activities. Figure 1 shows important metrics for three levels of manufacturing, each one of which contributes to resource consumption and environmental impact; however, top-level supply-chain activities have been rarely considered. The supply-chain can account for a quarter of the total manufacturing costs [Askin *et al*., 2002], making it likely to contribute to environmental costs as well. Incorporating the supply chain into environmental analyses will both expand the understanding of manufacturing environmental impact and enable the reduction of environmental damage through informed decision making.

Assessing the true impacts of the supply chain is generally very complex, where the supply chain is characterized by supplier locations and the transport of goods between them. Today, a product assembled in one location can be comprised of many components from literally all over the world. After assembly, the product is shipped to distribution and eventually the consumer.

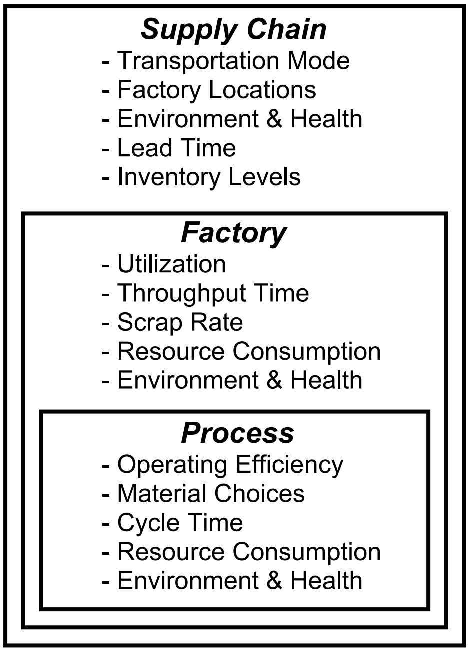


FIGURE 1. CRITICAL CONSIDERATIONS AT EACH MANUFACTURING LEVEL

For the discussion of supply chain environmental impacts in this paper, three specific environmental metrics – water, energy, and global warming potential (GWP) – are used. Unlike other metrics (e.g. eco-toxicity, acidification potential, and particulate emissions), these three metrics are of particular relevance to societies' current energy and climate change concerns [IPCC, 2007]. Water and energy use are straightforward metrics of consumption indicating inputs to manufacturing; however GWP is an emissions metric indicating the manufacturing outputs. GWP combines gaseous emissions that trap heat in the atmosphere into a single metric, which is given in units of CO_2 equivalents (CO_{2eq}), or the amount of CO_2 that would have an equivalent effect as the emitted greenhouse gases.

Both energy and GWP metrics ought to be considered in terms of their life-cycle impact (including materials extraction, manufacturing, transportation, use, and end of life); however, water consumption is a regional rather than life-cycle concern. Water consumption that exceeds renewable resources is problematic; however, water consumption in one-location does not impact the water supply elsewhere. For example, a drought in North Carolina is not impacted by someone in England conserving water. Alternatively, the drought in North Carolina can be impacted if people in England consume less of a product that is manufactured in North Carolina, or if that manufacturing moves to a new location. For this reason, water scarcity is discussed as an important metric when choosing a manufacturing location and as a complimentary metric to water use.

The incorporation of supply chain considerations into manufacturing environmental analysis follows 4 of the 5 basic rules for a manufacturing wedge technology as outlined by Dornfeld *et al*. [2007]. 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 lifecycle 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) environmental impact and cost must be calculated in terms of basic and appropriate metrics (4) Societal, economic, and environmental concerns must be considered (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.

In this paper, the key components of supply-chain assessment are discussed. As shown in Figure 1, five important supply chain considerations are listed; however decisions about the first two affect the remaining three – transportation mode and location directly impact the supply chain's environmental impact and flexibility (influencing lead times and inventory levels) – and will be the focus of this paper. First, methods to calculate the environmental impact of four transportation modes are outlined: trucking, waterway transport, air freight, and rail. Next, some location dependent environmental factors are discussed: water availability and energy mix. Finally, a tool is introduced that utilizes the methods presented and a case study is presented to illustrate supply chain tradeoffs.

METHODOLOGY

The following methodology is utilized for the comparison of transportation modes and manufacturing location alternatives.

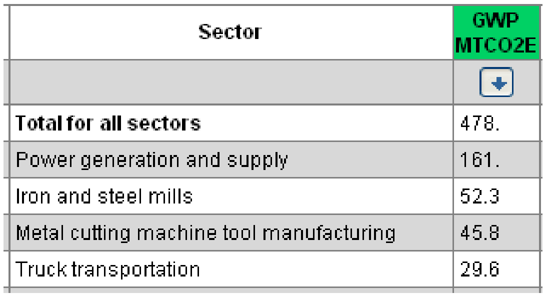
Environmental analyses are inherently difficult due to data limitations. Data is often outdated or costly to obtain. Data can also have the problem of being specific to the region in which the analyses were conducted. While the numbers presented in this paper are imperfect, they are reasonable estimates that allow for supply chain tradeoff arguments to be presented.

Economic input-output life-cycle assessment (EIOLCA) from Carnegie Mellon University [2007] is used in the case study of this paper to determine lifecycle emissions. EIOLCA is an environmental database for the U.S., which includes the entire supply chain for industry activity. Unlike process based life-cycle assessments, the advantage of the input-output methodology is its ability to avoid drawing boundaries on the assessment. The EIOLCA database uses industry-level economic input-output data tables provided by the U.S. Department of Commerce and U.S. environmental data to determine environmental impact per dollar of economic activity.

To illustrate how EIOLCA is used in the case study of this paper, consider the "metal cutting machine tool manufacturing" sector. The EIOLCA GWP results for spending $1M in this sector are presented in Figure 2. It is seen that the "power generation and supply" sector emits 161 metric tons of CO_{2eq} for every $1M spent on machine tool manufacturing. The power generation value, however, is based on the average electricity mix of the United States. This value can be adjusted to reflect region electricity mix differences, as is done in the case study of this paper to understand supply chain decision impacts.

Data collected by previous researchers on the CO_2 emissions and energy demands of freight transport are compiled. In some cases this data incorporates the entire lifecycle and in others it is only the use-phase. All attempts are made to be clear about these differences when results are presented. For the reasons stated earlier on the importance of considering regional water use independently, water use of transportation is not included here because it is a life-cycle rather than regional metric.

A metric of transportation environmental impact can be either based on the cargo's weight or volume; in this analysis the weight based approach is chosen. While the volume transported may determine how many vehicles are required for transportation, weight will directly impact fuel efficiency [Facanha, 2006]. Weight based approaches are more appropriate as they assume packing efficiency is maximized and provide a baseline of impact.



Sector	GWP MTCO2E
	⬇
Total for all sectors	478.
Power generation and supply	161.
Iron and steel mills	52.3
Metal cutting machine tool manufacturing	45.8
Truck transportation	29.6

FIGURE 2. SCREENSHOT OF EIOLCA RESULTS FOR $1M SPENT IN THE "METAL CUTTING MACHINE TOOL MANUFACTURING" SECTOR.

Transportation Energy

The transportation energy of inland water freight, trucking, and rail are based on the analysis by Spielmann *et al*. [2005]. This assessment looked at 5 truck varieties ranging in net energy use from 1.5kJ/kg-km for the 40t truck to 3.8kJ/kg-km for the 16t truck, 2 train types ranging from 0.22 to 0.23kJ/kg-km, and 1 inland waterway transport option demanding 0.38 kJ/kg-km. Spielmann's values are averaged to compare relative transportation mode impact.

Recent life-cycle assessments on air freight are not available; therefore the transportation energy of air freight is approximated using 2004 data from the U.S. Bureau of Transportation Studies [DOE, 2004]. Air Freight demanded 713 trillion btu over 32.446 million ton-miles of transportation; therefore, the direct energy use of air freight was 15.9 kJ/kg-km. This method is compared with Spielmann's results in Table 1, illustrating that the results for Spielmann and U.S. BTS are reasonably close.

TABLE 1. COMPARISON OF ENERGY RESULTS FOR TWO METHODS

	Spielmann	U.S. BTS
	Energy [kJ/kg-km]	Energy [kJ/kg-km]
Rail	0.23	0.23
Water Freight	0.37	0.37
Trucking	2.44	2.29
Air Freight		15.9

Transportation Global Warming Potential

The complete life-cycle GWP of these transportation modes is not available. However, CO_2 data from Facanha *et al*. [2006] is used as an estimate of GWP emissions for rail, trucking, and air freight. 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 life-cycle CO_2 emissions.

Water freight data is determined from Corbett *et al*. [2003], who assessed use-phase emissions. Corbett finds the use-phase CO_2 emissions of international waterway transport to be 0.18 g/kJ where the energy intensity of inland waterway transport is, on average, 0.37kJ/kg-km [DOE, 2004]. Therefore, use-phase emissions of waterway transport are 67 mg-CO_2/kg-km. Note that values are combined here based on international and inland water freight measures to obtain an average water freight value.

DISCUSSION AND RESULTS

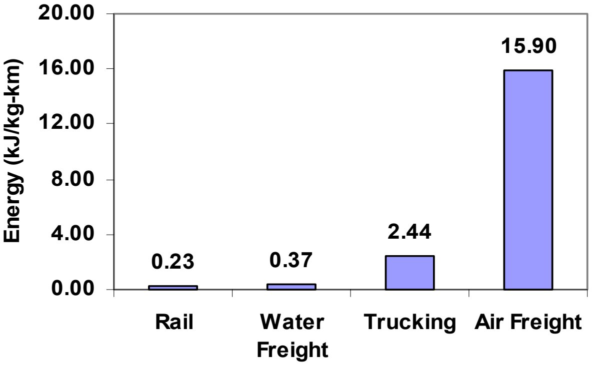
Transportation

Transportation is a significant part of the manufacturing supply chain, and is clearly necessary to transport goods throughout the global economy. Data on the environmental impact of potential transportation modes is used for decision making tradeoffs between environmental impact, cost, and flexibility.

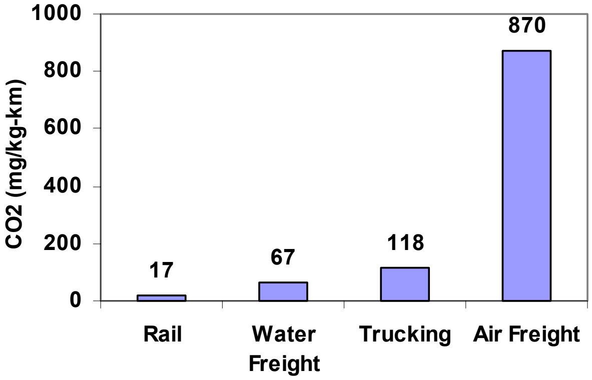
Four transportation modes were investigated: air freight, rail, trucking, and inland waterway transport. Air freight is found to have the highest greenhouse gas emissions and energy consumption per kg transported a km (Figure 2).

It is important to note that the data presented here is based on data for inland and international water freight. There may be efficiencies realized by larger ships traveling over longer distances for international water freight that are not reflected here. While different values for shipping over longer and shorter hauls would be useful, it is not included here due to data limitations.

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.



(A)



(B)

FIGURE 2. COMPARISON OF TRANSPORTATION MODE IMPACTS (A) ENERGY (B) CO2 EMISSIONS.

Manufacturing Location

Manufacturing location will not only impact the distances traveled and feasible transportation modes, but also the environmental impact of the factory. Manufacturing a product the same way in two locations may have vastly different implications for the manufacturing environmental impact of that product because of regional differences in electricity generation, water scarcity, resource availability, and infrastructure.

GWP Of Electricity Generation. Although the electricity required to manufacture a product is not likely to vary significantly between locations (except due to climate variations), the global warming potential of electricity generation will differ.

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/kWh for coal to 0.60 kg/kWh for natural gas [DOE, 2000]. These variations effect the environmental impact of a kWh used in each location.

To further illustrate this variability Figure 3 shows the GWP for electricity generation in countries with available data. Data is available only for Europe and the US [Ecoinvent, 2007]; however the GWP variations are apparent. France has the lowest greenhouse gas emissions per kWh because 78% of their electricity generation is nuclear and 12% is from renewables such as wind, solar, and hydro electricity [European Commission, 2007]; Germany, on the other hand, derives 27% of its electricity from nuclear and 10% from renewables with the remainder coming from the burning of fossil fuels [European Commission, 2007].

Similarly, regional differences within a country can produce variations in the greenhouse gas emissions per kWh of electricity demand. This is seen in Figure 4, for a sample of states within the United States. Again, depending on the energy mix within each state, the emissions vary substantially.

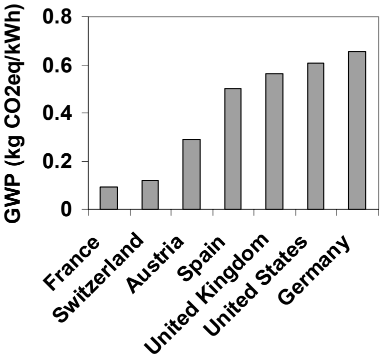


FIGURE 3. GREENHOUSE GAS EMISSIONS PER KWH OF ELECTRICITY CONSUMED [ECOINVENT, 2007].

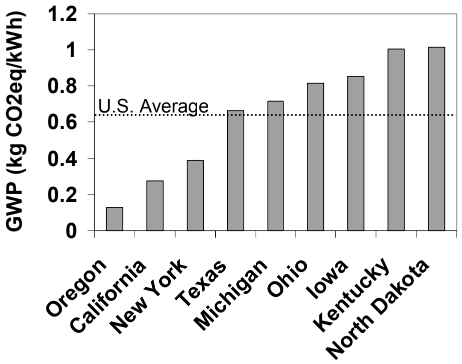


FIGURE 4. GREENHOUSE GAS EMISSIONS IN U.S. STATES [EIA, 2002].

Water Scarcity. 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 [Dublin Principles, 1992]. The available renewable freshwater resource in each community varies drastically. Figure 5 illustrates this point by showing the daily renewable freshwater per capita for a variety of countries. The renewable amount only includes what could be consumed indefinitely without depleting underground aquifers, lakes, and rivers. Therefore, water use must be considered in tandem with water scarcity.

China, as an example, is currently facing a threat of water shortage. The water table is dropping at a rate of over a meter a year, indicating a loss of non-renewable water resources [Yardley, 2007]. For industries planning to continue or install in China, the possibility of drought is well worth considering. Additionally, the available water throughout the world is expected to shift as climate change progresses, making available renewable water resources an important metric to be aware of when planning and installing manufacturing facilities.

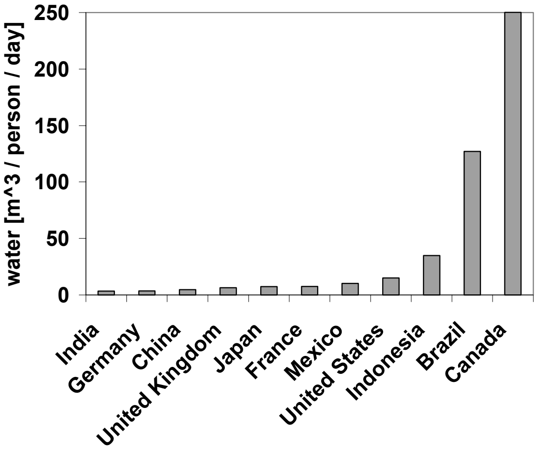


FIGURE 5. RENEWABLE FRESHWATER RESOURCES PER PERSON PER DAY [FAO OF THE UN, 2002].

TOOL DEVELOPMENT

To enable visualization and decision making about supply-chain and manufacturing costs, both environmental and economic, researchers at the University of California at Berkeley are developing a supply-chain based life-cycle assessment tool (Figure 6). The tool's current functionality includes the ability to dynamically select between alternate transportation modes and manufacturing locations to understand life-cycle sensitivity. The tool's development has been supported by SolFocus Inc., a solar energy company; the tool also incorporates SolFocus' cost models to determine tradeoffs between economic and environmental goals.

For a tool such as this to be successful, and allow for supply chain decision making, the researcher must have knowledge of potential resource locations, supplier locations, and manufacturing sites. Knowledge of a manufacturing stage's resource requirements allows for tradeoffs to be determined between the suitability of different locations.

CASE STUDY

As a theoretical exercise to understand some of the tradeoffs mentioned in this paper, consider the GWP of manufacturing a generic American automobile, as discussed by Zhang *et al.* [2005]; this vehicle is worth \$23480 and weighs 1532 kg.

An estimate of the U.S. supply chain for automobile manufacturing can be determined from EIOLCA, where it is seen that manufacturing Zhang's generic American automobile has a GWP of 14700 kg CO_{2eq}, of which 4404 kg are caused by the "power generation and supply" sector. The EIOLCA "power generation and supply" sector is based on the average U.S energy mix, which can be translated to the Michigan energy mix for a car specifically assembled in Detroit, Michigan; the result is 15520 kgCO_{2eq}/kWh.

The vehicle can either be transported from Michigan to the consumer, as shown in Figure 7, or, if possible, manufactured locally using the local energy mix. In this example, it is assumed that all pre-assembly supply chain impacts are the same. Figure 8 compares the potential GWP savings between manufacturing the vehicle local to the consumer versus manufacturing the

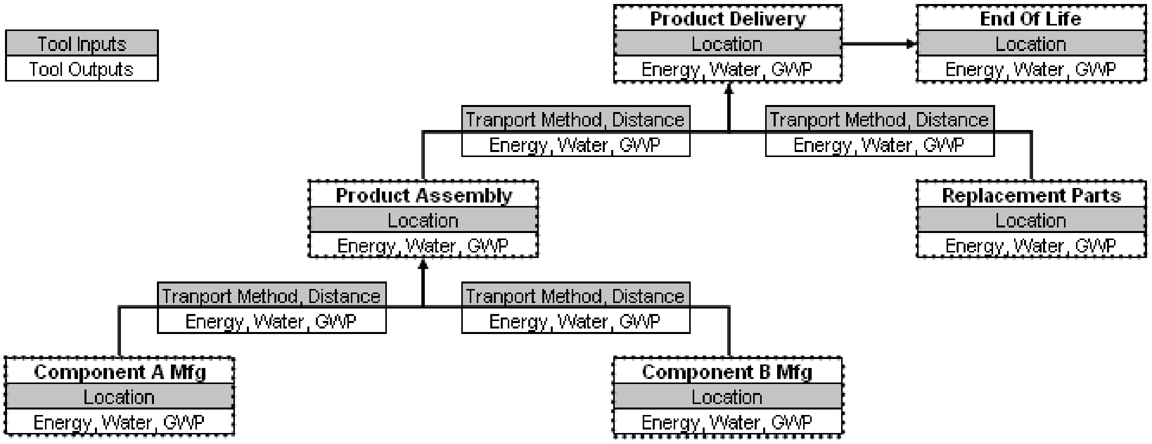


FIGURE 6. SUPPLY CHAIN ENVIRONMENTAL ASSESSMENT TOOL ARCHITECTURE

vehicle in Michigan and trucking it to the consumer. The tradeoffs are between the energy mix GWP and the transportation GWP. California and Texas have an energy mix with a GWP/kWh that is less than Michigan, therefore these states save GWP by manufacturing locally. Ohio and Kentucky both have an energy mix with a GWP/kWh that is worse than Michigan, which is not offset by saving on 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. Given limited data, this analysis provides a way to approximate environmental tradeoffs in differing regions of the country.

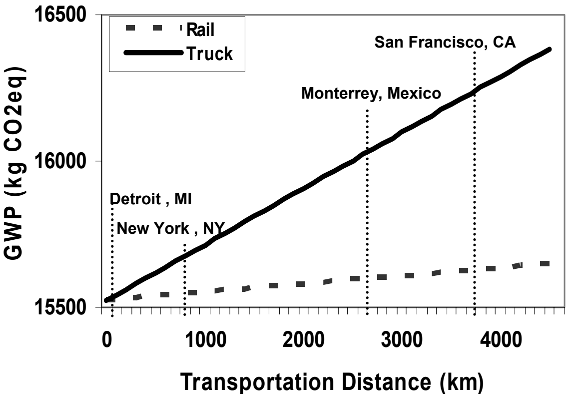


FIGURE 7. INCREMENTAL GWP OF TRANSPORT (BASE OF 15520 kg CO_{2eq} FOR ASSEMBLY IN DETROIT, MI).

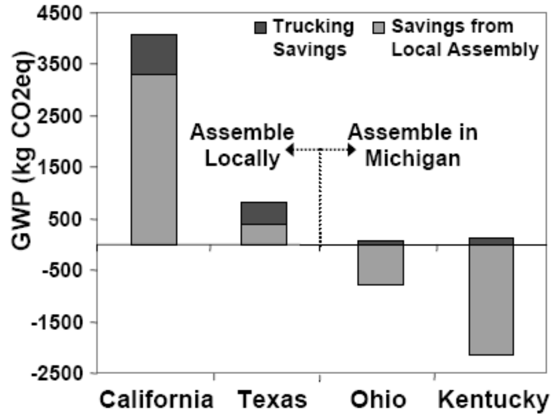


FIGURE 8. SAVINGS REALIZED BY ASSEMBLING A VEHICLE LOCAL TO THE CONSUMER.

CONCLUSIONS

The importance of incorporating supply chain considerations into manufacturing environmental assessments has been discussed. Based on the considerations and tradeoffs highlighted in this paper, a set of guidelines to insure a successful supply chain analysis are:

1) Knowledge of potential supplier and manufacturing locations, and the resource (materials, water, energy) availability and infrastructure at each potential location must be understood. This analysis should extend to the entire supply chain. Location choice is shown to affect the emissions associated with electricity consumption and water availability.
2) In addition to knowing the resources available at potential sites, 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 greenhouse gas emissions and energy consumption per kg transported a km.

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