Journal of Transport Geography 18 (2010) 322–330

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Megaquarry versus decentralized mineral production: network analysis of cement production in the Great Lakes region, USA

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ARTICLE INFO

Keywords:
Megaquarry
Cement
Multimodal freight transportation
Network analysis
Energy
Cost optimization

ABSTRACT

The geography of mineral resources and human settlement influences the production–consumption cycle of cement and other mined construction materials, and affects the energy, cost and environmental burden associated with these materials. Although mines that supply most construction products have traditionally been located near major points of consumption, population pressures have raised the possibility that these small, widely scattered operations might be replaced by large, megaquarry operations. This study uses network analysis to compare transportation-related energy and cost for cement production from highly centralized facilities, or megaquarries, to that from smaller production facilities dispersed throughout the Great Lakes region of the United States. Results show that a transition to megaquarries can increase transport-related energy and associated environmental impacts by almost 50%. This suggests that decisions involving the location of mining operations for construction products are best made on a regional rather than local basis.

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1. Introduction

Construction materials constitute the largest flow of non-fuel, non-food raw materials in the US (United States Geological Survey, 1998). Many of these materials such as cement, gravel, and sand originate at quarries, are processed near or at the quarry site, and then are transported to their point of consumption. Current trends in construction mineral resource extraction show increasing centralization at large production sites, known as megaquarries, and consequent longer transport distances. This trend stands in contrast to traditional industrial location theory, which from its earliest established the importance of transportation-related costs on the location of industrial sites (Weber, 1909). This trend is particularly surprising because construction materials are heavy and have a relatively low value on a per-mass basis.

This research uses network analysis methods to quantify the increased transportation-related energy consumption and costs to the cement industry for adopting megaquarry production strategies. The freight transportation energy and cost of megaquarry cement production is compared to that of the existing configuration of plants in the Great Lakes region of the US. Results show that from the perspective of transportation energy and costs alone, the existing configuration and production capacities of cement plants in the region is suboptimal. Moreover, despite the existing suboptimal configuration, a trend towards megaquarry production, even when developed at an optimized site, will lead to greater transportation-related energy consumption and cost.

Although this study focuses on one region, its results support broader critiques of industrial location theory that emphasize the influence of environmental factors (McCann and Sheppard, 2003). Factors of potential importance to the location of cement plant include the spatial distribution of high quality mineral resources, complexity of environmental permitting, and community opposition to new sites or site expansion. These factors can create high barriers to siting at new locations or even significant expansions at preferred existing sites that might account for the current suboptimal configuration of plants that has remained largely unchanged for decades.

2. Background

2.1. Megaquarries

The primary raw material used in cement manufacture is limestone, which is extracted from a quarry typically located at the same site as the cement production plant. The site and size of a quarry, whether for cement manufacturing or aggregate production, will depend on physical constraints such as the dimensions of the mineral resource, availability of suitable transportation,

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doi:10.1016/j.jtrangeo.2009.06.007

and permitting and operational regulations. The size of a quarry is also affected by trade-offs between economies of scale achievable within a facility as production levels increase, and the cost of transporting materials farther to reach a broader customer base.

The aggregates industry already exhibits a trend towards megaquarry production, and experts and producers alike see increasingly consolidated operations as the likely future of production (Bliss et al., 2002). Megaquarries have been defined as sites producing at least five million metric tons per annum (Mtpa) with sufficient reserves to permit 50–100 years of production (Bliss, 2003). Megaquarries are attractive to aggregate and crushed stone producers, in part, because they can realize economies of scale in their quarry activities, and may find other economies of scale in processing and delivery operations. Cement producers would see the same benefits in megaquarry production sites as aggregates producers. Because cement plants and quarries are often co-located, cement producers may realize additional economies of scale in their manufacturing operations. The Great Lakes region, here defined as the US states of Michigan, Ohio, Indiana, Illinois, and Wisconsin, is an excellent candidate for megaquarry development due to relatively abundant limestone resources and access to an extensive water-based transport network.

As of 2004 three sand-and-gravel (aggregate) quarries in the United States met the production requirement of 5 Mtpa necessary to be considered megaquarries (Bolen, 2004). And, in 2005, 17 crushed-stone quarries met the production level for megaquarry status (Bolen, 2004; Willet, 2005). Estimates of reserves are not available for any of these operations, however, so only some may technically qualify as megaquarries.

While finding a site with enough reserves to support at least 5 Mtpa of production for upwards of 50 years might be difficult, obtaining approval to site a facility from surrounding communities is also a significant barrier to megaquarry development. For instance, the Glensanda, Scotland megaquarry was permitted in the late 1980s, but has since faced opposition to expansion (BBC News, 2005). In Harris, Scotland, another effort to set up a megaquarry that would extract 9 Mtpa with reserves for 60 years of operation also failed. Despite years of negotiation and investment, the operation was cancelled in the face of local opposition (BBC News, 2004). While we cannot quantify this aspect of megaquarry development, it is noted here as an additional important variable that influences the siting of industrial facilities.

2.2. Economies of scale in cement production

Norman (1979) estimated the economies of scale in US cement plants, and also reported on other studies performed in the European cement industry. Fig. 1 shows Norman's modeling results, as well as values from a 1971 European analysis (Pratten, 1971). Norman's estimate suggests that the largest economies of scale are realized up to about 1 Mtpa, with smaller increases up to about 2 Mtpa and essentially no reductions in average cost at higher production levels. Both cases evaluated production only, and did not account for effects related to transportation and distribution of cement to market. Although these studies are relatively old and the economies of scale achievable in modern cement plants have probably increased, they provide a basis for evaluation of existing plant capacity as a lower bound for potential economies of scale. With respect to the Great Lakes region, this comparison suggests that, with the exception of Lafarge's Alpena plant in Michigian, all plants could benefit from increasing production levels.

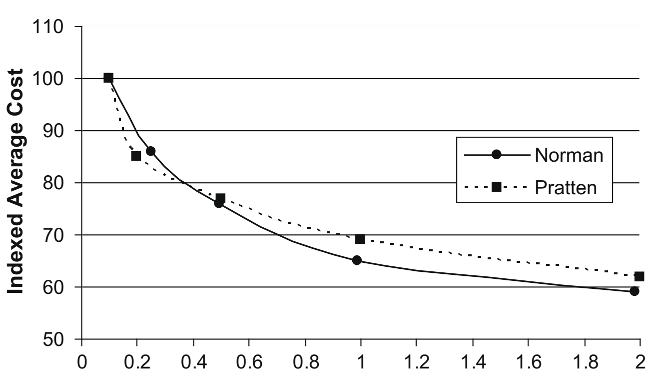

Fig. 1. Economies of scale in cement production. (*Sources:* Norman (1979) and Pratten (1971) in Norman (1979).)

McBride (1981) estimated the minimum efficient size (MES) for cement plants to realize all potential economies of scale, transportation and distribution aside, based on data reported between the years 1949 and 1971. The MES increased steadily over that time period due to improvements in technology. Since 1971 improvements have continued in kilns, process control technologies, and other manufacturing components, indicating that economies of scale might be achievable at even higher production capacities.

McBride (1981) states that the MES will always be larger than the optimal size when the cost of distribution is taken into account, because unless a very large market is proximal, the MES usually exceeds the local demand for cement. Thus, efficient and cost effective transportation is a key factor in determining the practical MES for a plant. The data shown in Fig. 2 may support this theory. The Alpena plant, which is located on the Great Lakes and can take advantage of efficient water transport, is the only plant operating at a rate of more than 2 Mtpa.

2.3. Transportation in the cement industry

Domestic freight transportation alone accounts for approximately 7.6% of all US energy consumption (Energy Information Administration, 2006; Federal Highway Administration, 2005). Fossil fuels provide most of the energy used for transportation of freight. Thus, freight transport is a concern for greenhouse gas emissions, other air pollution, and non-renewable resource depletion. If greater consolidation leads to greater distances for cement shipments, environmental burdens associated with freight transportation are likely to increase.

The cement industry uses three transportation modes to move its product to market; truck, rail, and barge or boat. In many cases an intermediate point, or terminal, is used to stockpile and store cement closer to consumers. Terminals also provide facilities for transferring cement from one transport mode to another, such as barge to rail and rail to truck. In the Great Lakes region large terminals are also attractive because of seasonal constraints on both consumption and shipping. Most cement is used during the warmer spring, summer and fall months, and shipping lanes are closed by ice during the winter. Cement is non-perishable and requires little energy and cost to store, so seasonality in consumption and shipping can be accommodated simply by large terminal facilities with extra storage.

The Great Lakes states support thirteen active cement plants (Fig. 2) with a total production capacity of approximately 12.5 Mtpa, approximately 14% of total US production. However, the region is a net importer of cement, some of which arrives in the form of clinker, the precursor to cement (van Oss, 2006). The largest plants in the Great Lakes region are located on the shores of the Great Lakes and have access to efficient water-based transport. The Alpena (Michigan) plant is by far the largest plant in the region, followed by the Charlevoix (Michigan) plant, and both use barges as their primary transport mode to cement terminals.

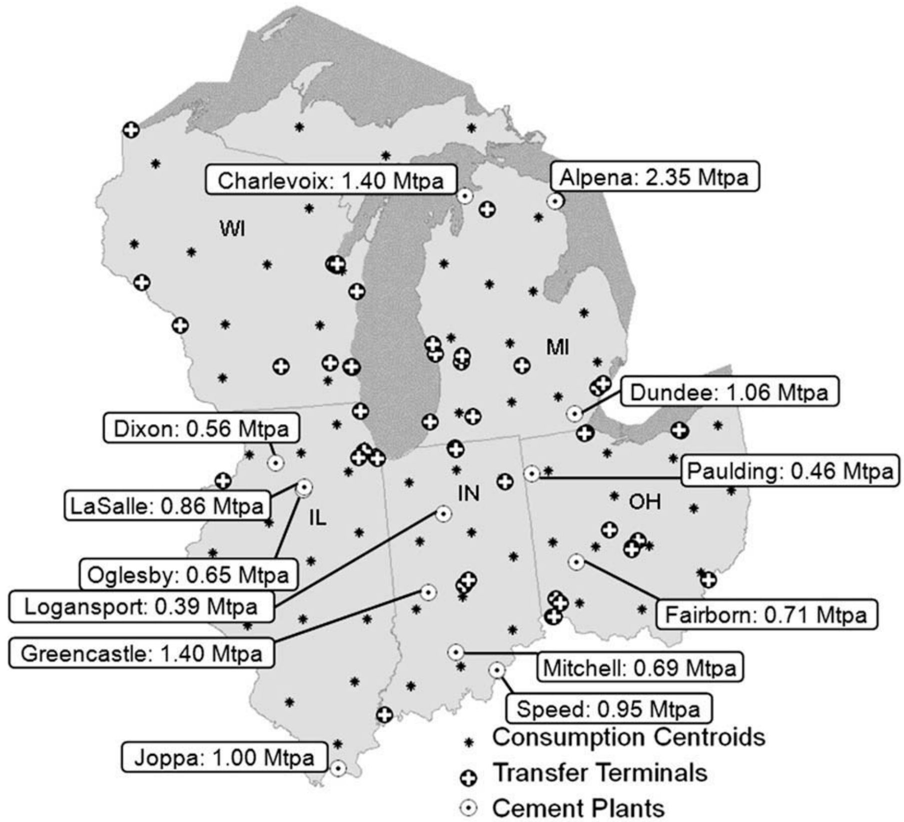

Fig. 2. Map of network nodes, including consumption centroids, transfer terminals, and cement plants and their production capacity. This map area includes the US states of MI, WI, IL, IN, and OH.

Many factors control how and why barge, rail, and truck transport modes are utilized. Barge routes are limited by the location of navigable waters and port facilities. Rail is limited both by the location and connectivity of active tracks and the ownership of those tracks. Trucks are not as limited because most highways in the US are open to truck traffic and many local roads and routes are open to commercial traffic for short-haul deliveries. The cost of these different modes of transport is a function of fuel consumption, facility and labor costs, and the cost of infrastructure maintenance, all of which vary greatly.

These transport modes vary in their costs and impacts, with barge transport more efficient than rail, and rail more efficient than truck. The US Department of Transportation (USDOT) estimates that one metric ton of material can be transported about 87 km (54 miles) by truck, 295 km (183 miles) by rail, and 750 km (466 miles) by barge on 3.8 L (one gallon) of fuel (Maritime Administration, 1994). On this basis, rail is about 3.4 times more efficient that truck, whereas barge is 2.5 times more efficient than rail, and 8.7 times more efficient than truck.

3. Network analysis methods

3.1. Previous work in the field

The 1960s heralded the first significant steps towards modern logistics for consumer goods and products. Companies began to design strategies and integrate their divisions responsible for handling storage, management, and transport of products. Companies increased their savings compared to their prior approach of disjointed and uncoordinated storage and shipment of their products (McKinnon, 2001).

Since the development of logistics as a field and the development of the modern computer, countless optimization models, from genetic algorithms, to agent-based models, to neural network models, have been developed to optimize logistics problems. As early as the mid-1970s, investigators began researching the impact of size and location of plants on the cost of producing and distributing products (Karnarni, 1983).

Some recent work has focused on the mechanics of modeling freight movement through networks, especially intermodal freight (Southworth and Peterson, 2000). And, more recently, the geography of freight logistics has become a focus of study (Hesse and Rodrigue, 2004). Our study contributes to this area of investigation, combining network analysis methods with questions of the geography of freight movements by testing the energy use and economic costs associated with changes in the spatial distribution of production.

Our work differs from previous studies in two ways; it is specific to a single commodity, cement, whereas previous work focused on more general questions of geography and freight logistics, and it tests the effects of a trend towards larger and more centralized production sites in the industry. This research also tests the effects of freight transportation optimized for cost versus energy consumption. The most cost-effective transport strategy is often equated with minimum energy consumption, and this study can help evaluate this assertion. Comparisons of this type are essential to intelligent regional scale, land-use decisions.

3.2. The freight transportation network

The cement transportation network is multi-modal because it involves paths that utilize more than one transport mode. Each transport mode participating in the network requires a spatial

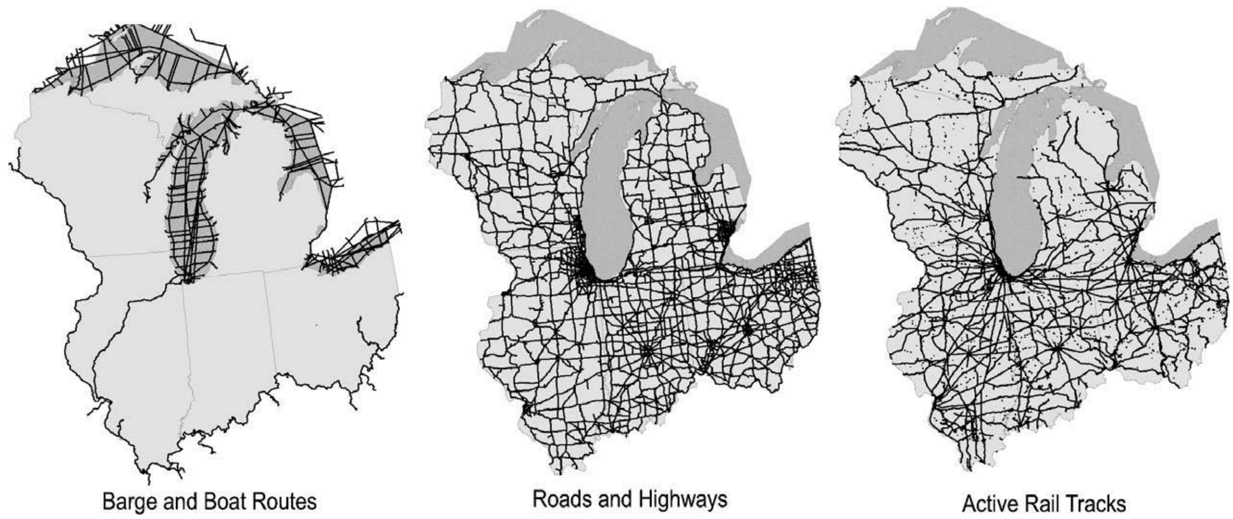

Fig. 3. Maps of freight transportation modes, including barge/boat routes, roads and highways, and active rail tracks.

dataset that is a virtual map of all possible paths for each mode. Fig. 3 shows the modal networks for barge, rail, and truck transport modes (Vanderbilt Engineering Center for Transportation Operations and Research, 1999; Federal Highway Administration, 2003; Federal Railroad Administration, 2003).

In addition to the network lines representing transportation modes, three types of network nodes are needed: plants that produce cement; terminals that store and transfer cement, and points of consumption (Fig. 2). Cement plant locations are based on datasets from the USGS (United States Geological Survey, 2003).

Consumption of cement is modeled by consumption-weighted geographic centroids for polygons consisting of one to seven counties depending on size and population density. Centroids are weighted using the combined population of all the counties that they include and the per-capita average cement consumption for the host state.

Cement terminal locations and the transport modes they are equipped to serve are derived from addresses of terminals for cement companies as listed in an annual industry publication (Cement Americas, 2005). These nodal datasets are shown in Fig. 2.

All paths evaluated in the study begin at a cement plant and end at a consumption centroid. Access and egress links from all points, such as cement plants, cement terminals, and consumption centroids must be added to the network in order to create connectivity between the layers. Transfers between modes are restricted to cement terminal nodes. Fig. 4 shows a schematic representation of how the different network datasets can interact and a possible path for cement delivery.

Network analysis identifies the most efficient path from one point to another by performing least-cost path calculations. These calculations depend on the impedance factor assigned to each part of the path. Impedance is a measure of the resistance encountered when traversing a node or line segment. If the parameter of interest is time, for example, then the average time over a distance (e.g., h/km) for each segment of the path will be the impedance value. Under these conditions fast roads have less impedance and will be selected over slow ones, all else equal. However, because the objective is to identify the overall route with the least impedance, in this example of time as the parameter of interest, selection of a path is a function of both road speed and total distance traveled. Economic cost, energy consumption, pollution emissions, or time are all parameters that can be modeled by appropriate impedance factors.

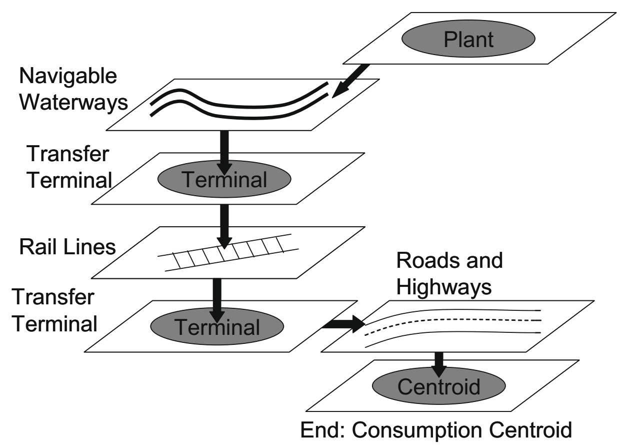

Fig. 4. Example of network dataset connectivity used in this study.

3.3. Transportation costs: monetary and energy costs of freight transport

Transportation costs were estimated from two main sources. The first are from the Bureau of Transportation Statistics (BTS), which produces average revenue data for all freight transportation by truck, class I rail, and barge (Bureau of Transportation Statistics, 2004). Average revenue values for 2003 were brought forward to 2005 dollars using the Consumer Price Index (CPI) for transportation. The results in per ton-km are costs of 20.54¢ for truck, 1.73¢ for class I rail, and 0.55¢ for barge. As these are revenue figures, they can only be considered the upper boundary of transport cost for each mode assuming each industry is operating at-cost or at a profit. Additionally, because profitability between modes may vary, the relative costs between modes can only be considered a rough estimate.

The second source of data is a cost study performed for the Washington State Department of Transportation (WDOT) to examine options for the transport of wheat (Jessup and Casavant, 1998). Brought forward to 2005 dollars, the WDOT study reported costs of about 0.65¢ per ton-km for barge transport, 2.06¢ for rail, and 4–7.5¢ for truck. These estimates are close to the BTS estimates for barge and rail, but significantly lower for truck. This might be explained by the percent of long-haul versus short-haul legs assumed for truck transport in the two studies; the difference between revenue, reported by the BTS, and cost, reported by the WDOT; or the portion of trucking costs attributable to fuel prices, which increased between 1998 when the WDOT study was performed, and 2003 when the BTS numbers were reported (Energy Information Administration, 2009).

The BTS and WDOT numbers both demonstrate a ratio of barge to rail costs of 1:3. But the ratio of rail to truck costs ranges between 1:2 and 1:12. These ratios are what determine the least-cost paths selected in the network analysis, because the relative cost of the different modes are what give rise to the preference of one mode over another.

While the cost of energy may be a significant part of the cost associated with freight transport, monetary cost estimates may not be representative of the energy efficiency of modes. A number of analyses characterizing the energy efficiency of transport modes have been conducted, though most are decades old. The most comprehensive is a Congressional Budget Office (CBO) report from 1982 that characterizes both the operational energy, including refinery losses for the fuels consumed, and the energy for upkeep and maintenance of the infrastructure (Mudge, 1982).

Eastman (1981) estimated fuel for various freight transportation modes, but in the estimates for waterway transportation Great Lakes shipping was specifically excluded, which is critical to this study. An older report developed by the Rand Corporation in 1971 also estimated fuel efficiency of rail, truck and barge transport. The CBO, Eastman, and Rand Corporation estimates for energy consumption in freight transport are compared in Table 1. The actual energy consumption estimates are shown, along with ratios normalized to rail and truck.

Costs for cement delivery are likely dominated by the cost and energy of transport, and in this analysis only transport and handling costs at terminals are considered. However, this same approach could not be applied to perishable goods, and goods with high storage costs, because operation and maintenance of storage facilities could be an important contributor to the energy consumption and cost.

3.4. Network impedance scenarios

In Section 3.3 freight network costs and energy consumption are identified on a per ton-km basis. These are types of network impedances, and they can be expressed as relative impedances, such as the relative energy consumption ratio identified in Table 2. Network impedance refers to the resistance or impedance encountered when a line segment or node is traversed. Six alternative ratios for relative modal impedance were developed and used in this analysis (Table 2). These are divided into two groups. One group, labeled Barge 1–3, holds truck to rail transport efficiency constant while varying barge efficiency. The second group, labeled Truck 1–3, holds the barge to rail relative impedances constant while varying truck impedance.

In addition to impedances associated with transport network lines, terminal nodes also have impedances associated with transferring material from one mode to another. Since relative impedances are used on network lines, distance-equivalent impedances for modal transfers are necessary. Two methods for modeling transfer impedances, referred to as variable and fixed, are used.

Variable impedances avoid rail and barge transport segments that are too short to make sense in real-world conditions. Modal transfers are limited to terminal sites, but multiple terminals may exist near one another, especially in large urban areas. Switching between modes at nearby terminals must be avoided; thus rail haul distances are constrained to be at least 80 km in the variable impedances. Because short distances on barges, especially given the terminal systems used for cement, are not common, barge haul distances are constrained to be at least 160 km trips. In all cases the minimum distance is cut in half for rail and barge modes where the material is loaded at the cement plant directly to rail or barge, because loading material to a transport mode occurs at every facility and is considered a fixed cost for all modes.

Table 3 shows the values for transfer impedance used in the analysis. The six impedance scenarios (Barge 1–3 and Truck 1–3) are entered into the equations for each type of terminal transfer. Variable transfer impedances are labeled with their corresponding network line impedance. Because network impedances are all ratios with rail travel normalized to a value of one, these transfer impedances are calculated in units of equivalent kilometers of rail travel.

Alternative fixed terminal impedances are also used, and are based on the cost estimates provided by an industry source of $0.05 per ton for barge transfers and $0.02 per ton for rail and truck. These estimates are converted to rail distance-equivalents for use in the network analysis. This conversion divides the transfer cost by the cents per ton-km by rail estimate from the BTS of about 1.73¢. The result is an equivalent rail distance of 116 km for a rail-to-truck transfer and 290 km for a barge-to-rail or barge-to-truck transfer.

The network analysis tests a total of 12 impedance scenarios by modeling the six different network impedance alternatives with

Table 1
Energy consumption (MJ/ton-km) and relative modal efficiencies for freight transport by road, rail and barge.

Estimate source	Transport mode		
	Truck	Rail	Barge/boat
CBO[a] Estimated energy consumption	2.023	0.817	0.390
Energy consumption relative to waterway	5.2	2.1	1.0
Energy consumption relative to rail	2.5	1.0	0.5
CBO[b] Estimated energy consumption	1.517	0.477	0.303
Energy consumption relative to waterway	5.0	1.6	1.0
Energy consumption relative to rail	3.2	1.0	0.6
Rand estimated energy consumption	1.734	0.542	0.361
Energy consumption relative to waterway	4.8	1.5	1.0
Energy consumption relative to rail	3.2	1.0	0.7
Eastman estimated energy consumption	1.693	0.496	0.195
Energy consumption relative to waterway	8.7	2.5	1.0
Energy consumption relative to rail	3.4	1.0	0.4

[a] CBO estimate including upkeep and maintenance of infrastructure.
[b] CBO estimate for operational energy, including refinery losses in fuel production.

Table 2
Relative impedances on transportation network lines.

	Impedance					
	Barge 1	Barge 2	Barge 3	Truck 1	Truck 2	Truck 3
Roadway	3.18	3.18	3.18	11.87	6.42	3.53
Railway	1	1	1	1	1	1
Waterway	0.64	0.33	0.17	0.32	0.32	0.32

Table 3
Variable transfer impedance in equivalent rail distance (rail-km).

Terminal type	Network impedance scenario					
	Barge 1	Barge 2	Barge 3	Truck 1	Truck 2	Truck 3
Truck–rail	87.2	87.2	87.27	434.91	216.75	101.27
Barge–truck	289.68	116.36	140.61	489.02	270.25	155.38
Barge–rail	289.68	116.36	53.33	54.1	54.1	54.1

Table 4
Summary of network impedance scenarios.

Scenario	Network impedance type	Transfer impedance type
B1V	Barge 1	Variable
B2V	Barge 2	Variable
B3V	Barge 3	Variable
T1V	Truck 1	Variable
T2V	Truck 2	Variable
T3V	Truck 3	Variable
B1F	Barge 1	Fixed
B2F	Barge 2	Fixed
B3F	Barge 3	Fixed
T1F	Truck 1	Fixed
T2F	Truck 2	Fixed
T3F	Truck 3	Fixed

variable terminal transfer impedance, and then fixed transfer impedances. Table 4 summarizes the twelve different impedance scenarios. For the sake of simplicity, labels are provided that refer to the network impedance type and transfer impedance type (Barge 1 = B1, Truck 1 = T1, variable transfer = V, fixed transfer = F, and so forth).

3.5. Network analysis

In this modeling approach the optimization is constrained to existing cement plant sites, rather than, for example, all potential suitable sites for a megaquarry. Optimal delivery paths from every cement plant to every centroid are determined for each impedance scenario. These paths and the total impedance associated with each one are calculated using the Network Analyst Extension for ArcGIS 9.2 software (Environmental Systems Research Institute, 2006). The optimal delivery paths provide the basis for identifying the best single megaquarry to supply the entire Great Lakes region, the optimal capacity for the existing configuration of cement plants, and then the optimal sites and capacities for a multiple-megaquarry outcome.

4. Results and analysis

4.1. Megaquarry optimization results

Table 5 shows the optimal megaquarry site results for the entire Great Lakes region, as well as two smaller sub-regions. Key outcomes from the results for the Great Lakes region analysis include:

- Only two of the 13 plants qualify as optimal megaquarry sites even though 12 distinct impedance scenarios were tested.
- These two optimal megaquarry sites, Alpena and Logansport, are the largest and smallest plants in the region, respectively.
- Transfer impedance was very influential in determining the optimal megaquarry site. For impedance scenarios T1V–T3V Alpena is the optimal megaquarry, and for T1F–T3F the Logansport facility is the optimal site. The only difference between these two sets of scenarios is transfer impedance; they have identical modal impedances.

Table 5
Megaquarry optimization results.

Impedance scenario	Entire region	Ohio removed	Southern region removed
B1V	Logansport	Logansport	Logansport
B2V	Logansport	Logansport	Alpena
B3V	Alpena	Alpena	Alpena
T1V	Alpena	Alpena	Alpena
T2V	Alpena	Alpena	Alpena
T3V	Logansport	Logansport	Alpena
B1F	Logansport	Logansport	Logansport
B2F	Logansport	Logansport	Logansport
B3F	Logansport	Logansport	Logansport
T1F	Logansport	Logansport	Logansport
T2F	Logansport	Logansport	Logansport
T3F	Logansport	Logansport	Logansport

The Alpena site only qualifies as the optimal megaquarry when the impedance scenarios use the variable transfer impedance rather than the fixed transfer impedance. The fixed barge transfer costs are more than two and a half times greater than rail and truck transfer costs, and much larger than the variable barge transfer costs. The Alpena plant is reliant on barge transport and always requires at least one barge transfer. Thus, when fixed transfer costs are used, which impose a particularly high penalty for barge transfers, the Alpena plant faces a handicap compared to the Logansport plant which distributes via truck or rail. This shows that estimates of terminal transfer costs may have significant impact on the selection of an optimal megaquarry site.

One reason for Logansport's frequent selection as the superior megaquarry site for the region is its central location between the Detroit and Chicago metropolitan areas, which are major consumers of cement. While the Paulding and Dundee plants are near the Logansport plant, Logansport has two advantages over its neighbors. First, the Chicago area is the single largest consumer of cement in the region, so Logansport's location slightly west of the other plants is more efficient for delivery to Chicago. Second, it has direct access to rail transport, which its neighbors do not. Logansport also experiences an advantage due to the boundaries of the region selected for the analysis. Alpena, for example, is at the northeastern margin of the region selected, so the total distance of travel for cement to reach almost all the consumption sites is higher than for Logansport which is located near the center of the region.

To address the sensitivity of megaquarry site selection to regional boundaries of this type, parts of the selected region were removed and the megaquarry analysis repeated. First to be removed were the consumption centroids in Ohio, the easternmost part of the region. This produced no change in megaquarry selection results (Table 5). Second to be removed were the southern consumption centroids in the region. As shown in Table 5, removal of the southernmost consumption centroids causes Alpena to become the optimal megaquarry for five impedance scenarios and shows that the region selected for analysis does affect megaquarry selection results.

4.2. Optimized decentralized cement production

Network analysis results determine the best plant to supply each consumption site. These results can then be used to determine the optimal production capacity for each plant from a transportation-energy or -cost perspective. Comparison of optimal plant capacities to existing plant capacities can then be made to determine whether the current configuration of cement production for the region is approximately optimal based on the methods used in this analysis.

The plant capacity optimization ensures that total plant capacity for the region will exactly equal the total cement demand for the region, 15,728,000 tpa. The objective function for this optimization is minimization of the cost or energy required to meet cement demand at each node. Production levels at each plant are constrained only to be greater than zero. Imports and exports are not considered in this analysis, although the region is a net-importer of cement.

The analysis shows that the Alpena, Dundee, LaSalle, and Paulding plants often have optimized plant capacities that exceed their actual plant capacities. The Logansport and Fairborn plant are always modeled to exceed their actual capacities, and the Logansport and Alpena plants consistently provide a considerable percentage of the total supply for the region across all the cost scenarios. The Speed plant proves to be suboptimal to deliver cement to every consumption point in the Great Lakes region, which results in a capacity of zero for the plant. As with the megaquarry analysis, the Logansport plant performs very well and looks like it should

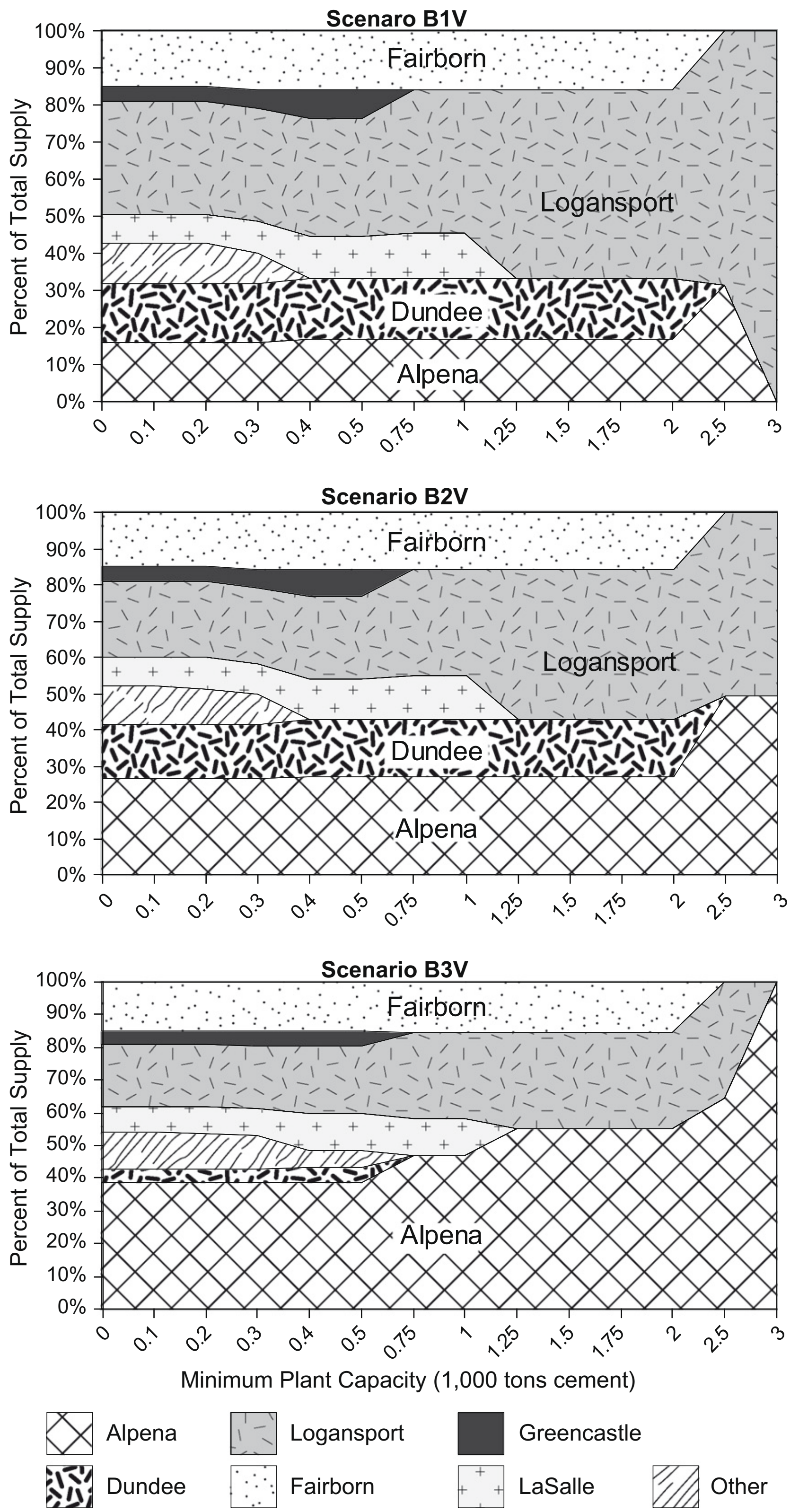

Fig. 5. Cement plant capacity with increasing minimum capacity constraint.

be the largest plant in the region, when in fact it is the smallest. In contrast, the Charlevoix plant is modeled to produce only 0.9% of the cement supply in the region, when its actual real-world capacity is the second largest in the region at 11.2% of total regional production.

A comparison of the total impedance for supplying the region from the optimal megaquarry leads to impedance levels (which can be translated into cost or energy increases) that range from 19% to 49% higher than the optimized decentralized production system depending on the impedance scenario tested.

4.3. Multiple megaquarries

The megaquarry and decentralized production optimizations do not consider the feasibility of a plant's size. The decentralized optimization results in some plants that produce very low volumes of cement that might not be viable in the real world, and the megaquarry optimization model requires a single facility to produce more than 15 Mtpa of cement, a production level that far exceeds the largest cement plant in the world.

For these reasons, a second approach to megaquarry evaluation was carried out. In this evaluation not a single, but a few megaquarries in the region are able to supply cement. This second approach constrains the decentralized production optimization with a theoretical minimum capacity for a viable plant. The outcome of this modeling shows how multiple megaquarries might arise and coexist in a region.

Identifying the appropriate minimum plant capacity is complex and uncertain, as discussed in Section 2.2. Instead of defining a single level for minimum operating capacity, a range of minimum capacities between 100,000 and 3,000,000 tpa are used to evaluate the effect of increasing the minimum efficient plant size. When plants fall below the minimum capacity constraint, they are closed down, and the defunct plant's customers are allocated to the competitor who can supply the customer most efficiently.

Results for a selected number of impedance scenarios are shown in Fig. 5, where plant capacities are represented by the percent of total regional consumption they supply. In some cases a single plant rises as a megaquarry. Thus, by the time a minimum capacity of 3 Mtpa is reached only a single producer remains in the analysis producing enough cement to meet the total cement demand of the region. For the majority of scenarios, however, two plants supply the entire region, both with capacities of approximately 7.5 Mtpa, significantly higher than the minimum capacity constraint.

Even at a minimum capacity of 1 Mtpa, the number of plants serving the region falls to between three and five. Thus, because the region has a consumption of 15 Mtpa, at least one plant, or more, is operating far above 1 Mtpa. These results show how the development of one or more megaquarries might occur even when the minimum viable plant capacity is much lower than the megaquarry threshold. It also shows that multiple megaquarries might be a more realistic alternative than a single regional megaquarry because two out of every three scenarios results in the development of two regional megaquarries rather than one as the minimum plant capacity increases.

4.4. Translating impedance to economic costs and energy consumption

In order to relate modeling results of network impedance to estimates of cost and energy associated with freight distribution by mode, cost and energy estimates from data sources are matched to the scenarios they are most similar to and compared. The cost estimates from the BTS and the WDOT are most similar to scenarios T1F and B3F, respectively. The fixed transfer cost is selected for the monetary estimates since they are derived from monetary cost

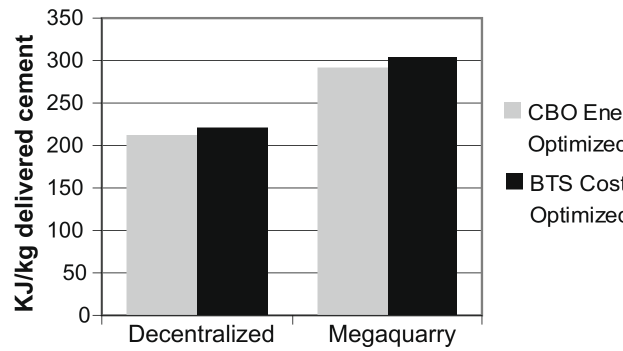

Fig. 6. Comparison of average transport energy to supply a kilogram of cement, based on CBO modal energy use estimates.

estimates provided by an industry source. For energy consumption, the CBO estimates that do not include infrastructure maintenance, and the Eastman study estimates are most similar to scenarios B1V and T3V, respectively.

The four scenarios that closely match the BTS costs, WDOT costs, CBO energy consumption estimates, and Eastman energy consumption estimates all result in the same megaquarry site selection, the Logansport facility. While all four scenarios selected the same site, the network optimization results were different in each case. If the CBO energy consumption estimates are substituted into the network results for the B1V and T1F and scenarios, which are most similar to the CBO energy and BTS cost estimates, a comparison of total energy consumption for the different network optimizations can be made (Fig. 6).

Fig. 6 shows that decentralized production is far more efficient at supplying the region than is a megaquarry. In both cases when optimized based on BTS cost estimates, the result is an increase in energy required to supply cement. On a per-kg-of-cement basis, the increase is about 4% for both the decentralized and megaquarry optimizations.

Results from this modeling have application in answering real-world questions about sustainability. The different relative modal impedances and transfer impedances cover a spectrum of scenarios, some of which simulate monetary costs and some energy consumption. Varying the modal impedance and terminal transfer impedances leads to differences in optimal delivery path selection. This means that when the monetary cost of transport modes are not congruent with the energy consumption or environmental damage associated with transport modes, the distribution network is likely operating sub-optimally from an environmental sustainability perspective.

5. Conclusions

Comparison of results from an optimal megaquarry supplying the Great Lakes region with cement and supplying the region by optimized distribution from the existing cement plant layout shows that a megaquarry is considerably less efficient from a freight transportation perspective. Delivery of cement from a megaquarry rather than the existing configuration increases impedance between 19% and 49%, which reflects the range of monetary costs and energy consumption intensities of transport. This increase does not reflect the efficiency that might be achievable from economies of scale within the plant and quarry operations however.

While this research has shown that smaller facilities supplying a smaller, more local, customer base are preferable from energy and cost perspectives, communities often want quarries and plants far from their own back yard and might opt for the less efficient megaquarry scenario. Thus, decisions about land use and facility siting require a more holistic perspective that accounts for where the product is consumed and the transportation-related burdens of its delivery, which significantly increase with centralization.

Further research should integrate current data on economies of scale achievable in modern cement plants and quarries to understand the energy, environmental, and cost implications of megaquarry development over the full life cycle of cement production. This research, coupled with our findings on transport-related burdens, can help industry, land managers, communities, and policy-makers make the most energy-efficient decisions about land use.

Acknowledgements

This research was funded through a National Science Foundation Materials Use: Science, Engineering, and Society (MUSES) Biocomplexity Program Grant (Nos. CMS-0223971 and CMS-0329416). MUSES supports projects that study the reduction of adverse human impact on the total interactive system of resource use, the design and synthesis of new materials with environmentally benign impacts on biocomplex systems, as well as the maximization of efficient use of materials throughout their life cycles. The authors would also like to thank Sarah Crane for her valuable contributions to this research effort, and Hendrick van Oss and James Bliss of the US Geological Survey for sharing their expertise with the authors.

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