Aggregate supply and demand modeling using GIS methods for the front range urban corridor, Colorado

Ahmet Karakas\textsuperscript{a,}\textsuperscript{*}, Keith Turner\textsuperscript{b}

\textsuperscript{a}Kocaeli \textit{"U}niversitesi, Mühendislik Fakültesi, Jeoloji Müh. Böl., İzmit, Kocaeli, Turkey
\textsuperscript{b}Colorado School of Mines, Department of Geology & Geological Engineering, Golden, CO, USA

Received 22 May 2003; received in revised form 1 March 2004; accepted 11 March 2004

Abstract

The combined use of allocation modeling and geographical information system (GIS) technologies for providing quantitative assessments of aggregate supply and demand is evaluated using representative data for the Front Range Urban Corridor (FRUC) in Colorado. The FRUC extends from the Colorado-Wyoming border to south of Colorado Springs, and includes Denver and the major urban growth regions of Colorado. In this area, aggregate demand is high and is increasing in response to population growth. Neighborhood opposition to the establishment of new pits and quarries and the depletion of many deposits are limiting aggregate supplies. Many sources are already covered by urban development or eliminated from production by zoning. Transport of aggregate by rail from distant resources may be required in the future.

Two allocation-modeling procedures are tested in this study. Network analysis procedures provided within the ARC/INFO software are unsatisfactory. Further aggregate allocation modeling used a model specifically designed for this task; a modified version of an existing Colorado School of Mines allocation model allows for more realistic market analyses. This study evaluated four scenarios. The entire region was evaluated with a scenario reflecting the current market and by a second scenario in which some existing suppliers were closed down and new potential suppliers were activated. The conditions within the Denver metropolitan area were studied before and after the introduction of three possible rail-to-truck aggregate distribution centers.

GIS techniques are helpful in developing the required database to describe the Front Range Urban Corridor aggregate market conditions. GIS methods allow the digital representation of the regional road network, and the development of a distance matrix relating all suppliers and purchasers.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Sand and gravel; Crushed stone; Quarry; Pit; Allocation

1. Introduction

Aggregate (crushed stone, sand and gravel) is one of the fundamental resources for urban development. It is used in nearly all-residential, commercial, and industrial building construction and in most public works projects. This study uses geographic information systems (GIS) methods to evaluate supply and demand models for aggregates along the Front Range Urban Corridor (FRUC), Colorado. The FRUC extends from Fort Collins to Colorado Springs, and includes parts of 16 Colorado counties.

The demand for aggregate is governed by rates of urban growth and development or re-development of needed infrastructure elements. The FRUC has an increasing need for quality aggregate materials to maintain its existing infrastructure as well as to support new development. Many high-quality aggregate...
resources are already depleted by exploitation, covered by urban spread, or eliminated from production by zoning. As a result, the demand for aggregate is increasing in the Front Range area.

Future aggregate demands may have to be satisfied by transport of aggregate from distant supply areas by rail. This would require one or more central trans-shipment sites in the Denver metropolitan area, so that the aggregate could then be transported by truck to areas of demand. Rail haulage of aggregate to the Denver market occurred in 1990–1993 during the construction of Denver International Airport. This project required large quantities of high-quality aggregate that the local production facilities were unable to produce. This experience is the basis for analyzing future scenarios involving rail-haulage of aggregate.

2. Description of the study area

This study evaluates aggregate supply and demand scenarios within a study area that extends from the Wyoming border to just south of Colorado Springs (Fig. 1). In the mid-1970s, the USGS mapped the majority of this area and named it the FRUC. It encompasses the majority of the urban growth along the Colorado Front Range. Denver is the geographic, economic, and cultural center of this region.

The study area covers an area of approximately 36,350 km² of the Colorado Front Range and extends about 131 km from east to west and 278 km north to south. It reaches onto the plains to include such communities as Greeley and Aurora, and extends approximately 29 km into the Front Range Mountains west of Denver. Eleven major counties included in the study area are shown in Fig. 1.

FRUC lies primarily within the South Platte drainage basin, but southern portions include part Arkansas River basin. The Front Range, which is the easternmost mountain range in Colorado, extends from the Arkansas River northward into Wyoming, where it is known as the Laramie Range. Most of the Front Range averages over 2100 m in elevation, with numerous rugged peaks over 3600 m high. The eastern margin of these mountains frequently includes a series of hogback ridges and valleys formed by erosion of tilted sedimentary formations displaying differing resistance to erosion.

3. Geologic setting

The core of the Front Range consists of Precambrian metasedimentary and meta-igneous crystalline rocks including gneiss, schist, and quartzite (Tweto, 1979). These rocks are intruded by a series of Precambrian massive to locally foliated granite plutons and smaller Tertiary intrusive bodies of varying composition ( Loving and Goddard, 1950). Tectonic events caused overlying Paleozoic and Mesozoic sandstones, shales, and limestones to be deformed forming a series of hogbacks within a north–south trending foothills belt. These formations dip steeply eastward and represent the western flank of large asymmetrical synclinal Denver Basin.

The Denver Basin contains a sequence of progressively younger sediments dominated by claystones, sandstones, coal, limestone, and shale sequences. The bedrock within the interstream area between the South Platte and Arkansas Rivers consists of a thick sequence of early Tertiary sediments ranging from claystone to coarse-grained arkose and conglomerate, along with some volcanic rocks.

Surficial processes related to stream erosion and deposition, glaciation, slope movement, and wind action produced a wide variety of deposits including moraines, outwash terraces, talus, and colluvium in the mountains and flood plains; terraces, pediment gravels, colluvium, dune sand, and loess in the plains region during the Quaternary (Schwochow et al., 1974a, b). The Quaternary geologic history of the FRUC is dominated by erosion. Alluvial processes within the valleys causing the formation of extensive alluvial valley fills dominated in the late Quaternary (Hunt, 1954).

4. Geologic aspects of aggregate resources

Geologic processes generate sources of aggregate, such as sand and gravel deposits and rocks for crushed stone. The sources of aggregate in the Front Range area can be separated into two major classes: alluvial sand and gravel deposits, and hard rock quarries. The FRUC depends on aggregate sources from both alluvial sand and gravel deposits and hard rock quarries. Fig. 2 shows sand and gravel pits and quarries, as well as active and potential source areas defined from the digital geologic map of Colorado (Green, 1992).

The majority of the sand and gravel is produced from alluvial deposits located along the channels, flood plains and stream terraces of the South Platte River and its tributaries. Quarries located in the Front Range produce crushed-rock aggregates from gneisses, schists, granitic rocks, basaltic flows and intrusives, quartzite, limestones, dolomites, and rhyolite.

4.1. Quarries

The principal Front Range rock types that are suitable sources of crushed-rock aggregate for use in construction are granite, gneiss, basaltic rock, quartzite, limestone, dolomite, and rhyolite. Sandstone, shale, and schist are quarried for various uses but are generally...
unsuitable for crushed stone aggregate due to the adverse soundness and texture of these rocks.

There are several major quarries producing aggregate in the Denver area (Fig. 2). Two quarries, one in Morrison and one in Golden, are located in an area of Precambrian gneisses and schists. One quarry located north of Golden, producing aggregate from an andesite dike, is another important crushed aggregate producer in the Denver area. Additional aggregate-producing quarries north of Denver are located near Lyons, processing fine-grained intrusive rock, and the other one located north of Lyons, processing granitic rock. There are two aggregate-producing quarries in the Colorado Springs area. One of them is quarried in Precambrian granite; while the other one is operated in Mesozoic and Paleozoic limestones and dolomites along the western front of the Rampart Range.

4.2. Sand and gravel deposits

Sand and gravel deposits are products of erosion of bedrock and surficial materials and the subsequent
transport, abrasion, and deposition of the particles. Sand and gravel are widely distributed throughout
the eastern plains of FRUC as stream-channel, flood plain and terrace deposits. Sand and gravel deposits of
the South Platte River and its tributaries are an important source of good-quality aggregate in the
northern FRUC, including Denver. Sand and gravel deposits of the Arkansas River and its tributaries
provide aggregate sources for the southern portions of the Front Range study area. Aggregate resource areas
are defined as areas where extractable sand and gravel deposits are available. FRUC sand and gravel resource
areas often include more than one of the Quaternary surficial units.

Many of the higher valleys and peaks in the northern portion of the Front Range were extensively modified by
intense alpine glaciation during the Quaternary (Thornbury, 1965). However, glacial meltwaters produced
extensive alluvial deposits along the major tributaries to the South Platte River, and along the South Platte
and Arkansas Rivers. The sand and gravel deposits within the South Platte River valley and its tributaries,
valleys, flood plains and terraces represent a significant natural resource in the Front Range area.
5. Economic aspects of aggregate

The widespread uses of aggregate resources emphasize the importance of its general availability and its economic significance. The economic value of a given deposit is a function of its proximity to the market area as well as its quality and size (Barksdale, 1991). The transportation cost from a supply area to demand area is an important part of the total cost. Truck haulage of 50 km approximately doubles the delivery price. Thus, the extracted natural aggregate is ideally used within 50 km of origin especially when trucks haul the aggregate. Aggregates are bulky and have a high place value that haulage rapidly inflates their cost. Increase in haulage distance raises the cost of aggregates to consumers.

The impacts of aggregate hauling by trucks such as traffic congestion, air pollution, road damage and transportation hazards force the aggregate haulage within short distances. In a real market condition, demand areas tend to receive thier aggregate from the near supply areas due to lower delivery cost, lesser environmental impacts of aggregate haulage, delivery time and safety purposes. Therefore, a distance decay function is utilized to distribute aggregate supply to demand zones so the demand zones receive aggregate from the nearer suppliers.

Previous projects, studies and market figures assited defining the aggregate production and transportation costs used in allocation models. Another factor defining production cost is aggregate operation type. Aggregate final price includes production and transportation costs. Individual sand gravel pits and active resource areas cost aggregate for an averarge $7.00 ton$^{-1}$ and quarries produce aggregate with an averarge $7.50 ton$^{-1}$. A fixed $0.30 per 1.6 km (1 mile) is estimated for the transportation cost.

During construction of Denver International Airport, aggregate was supplied by rail from west of Cheyenne, Wyoming. The rail transport of this aggregate cost $3.95 ton$^{-1}$ (Kulvanit, 1991). Three distribution centers were modeled as new “quarries” with high production costs. Their production costs were estimated as $11.50 ton$^{-1}$ by adding the usual average quarry production cost ($7.50 ton$^{-1}$) to the rail transportation cost ($4.00 ton$^{-1}$). The delivery price of these rail-hauled aggregates were then computed in the CSM allocation model by adding the usual truck haulage costs of $0.30 per 1.6 km.

6. Methodology

The main purpose of this study is to utilize GIS techniques to distribute aggregate supplies from supply areas to demand areas by allocation models through a highway transportation network and evaluate the results. This study evaluates existing and alternative aggregate supply and demand scenarios for the Colorado FRUC. Fig. 3 defines the procedures used in the study. Two commercial GIS, ARC/INFO and ArcView were used to create and manage databases to: (a) define the locations and characteristics of specified existing and potential aggregate suppliers; (b) characterize the spatial distribution of aggregate demand; and (c) define the required transportation network linking suppliers and users of the aggregate.

The first phase of the study involved data acquisition. The data sets were gathered from several different data sources including the USGS, Colorado Geological Survey (CGS), US Bureau Census and ESRI (GIS software and data vendor). The data sets acquired from these sources are digital files, publicly available spatial data, published maps and tabulated data in reports and files.

These data sets were first processed with ARC/INFO and ArcView GIS. A supply database, a demand database and a highway transportation network were developed after processing the data sets for the allocation models. Then, two different supply and demand allocation models were performed with the developed databases and the highway transportation network. Information defining the suppliers, demand zones, and the highway network within the FRUC was supplied to these allocation models by using the GIS databases within the ARC/INFO software. The ARC/INFO Network Analysis procedures directly accessed this information. Extraction and reformating the appropriate information stored within the ARC/INFO GIS database created the input data files required by the CSM allocation model. These allocation models produced lengthy tabulated outputs. Lastly, the results for the allocation models were evaluated. Conclusions and recommendations are made based on the results and the experience gained in the study.

Alternative modeling strategies evaluated the approaches for allocating aggregate volumes from multiple sources to satisfy demands from multiple zones. The allocation procedure reflects transportation economics. The databases defining source areas and demand zones are readily modified creating a variety of aggregate production scenarios. Four different scenarios evaluated the current and the future aggregate market conditions in the study area. The GIS programs provide graphical displays of the allocations resulting from the modeling of these scenarios.

7. Supply demand allocation modeling

This study utilizes standard supply demand modeling procedures applied by geographers and economists for
many years to their studies and predictions of market forces. Data collected in earlier studies are used by this study to characterize the aggregate supply and demand conditions along the FRUC (Karakas, 1998). The procedures used in this study also reflect the experiences of others who have conducted aggregate market analyses in other locations.

7.1. ARC/INFO network analysis procedures

ARC/INFO network analysis is the first allocation modeling technique. Network analysis procedures perform allocation modeling, accessibility of a single location given the attractiveness of the other locations and the levels of interaction between pairs of locations accounting for location properties. The accessibility and interaction are performed by gravity modeling concepts.

Several ARC/INFO network analysis commands depend on an implementation of a shortest-path algorithm. There are several algorithms that can efficiently find least-cost paths through a network. The best-known and simplest path-finding algorithm is the one generally credited to Dijkstra (1959). ARC/INFO network analysis procedures use Dijkstra’s algorithm
Dijkstra’s algorithm solves the problem of finding the shortest path from an origin to a destination. The algorithm finds the routes by accounting cost precedence. This algorithm examines all possible paths between an origin and destination and chooses the one path with the least cost. ARC/INFO supports a specific network data model that allows map coverages defining networks, such as roads or railroads, to be used with the Dijkstra algorithm.

7.2. The CSM allocation model

The CSM allocation model was previously developed to support aggregate allocation evaluations by students in engineering geology design classes at CSM. This model was modified to use the GIS database created for the FRUC study area. It provided the bulk of the allocation modeling capabilities used in this study.

The CSM allocation model is designed to allow the allocation of aggregate produced by multiple suppliers to multiple users. It explicitly models a competitive market, where purchasers of aggregate typically allocate their acquisitions among competing suppliers. The distance matrix was developed from the ARC/INFO network model. Travel distances in kilometers are the measure of travel impedance. The CSM allocation model distributes aggregate volumes between suppliers and demand zones based on distance. However, two user-defined parameters control the allocation. The program allows the user to define a “local market distance (d_{min})” and a “maximum haul distance (d_{max})”.

The concept of the local market distance is that aggregate delivery costs are fixed within the short distances. Demand zones receive their entire aggregate demand from suppliers located within the local market distance. If more than one supplier is found within the local market distance, the volumes are divided equally among the suppliers.

The maximum haul distance is used to define the maximum economical distance over which aggregate can be transported from a supplier. It serves to restrict the allocation of aggregates from a supplier to distant purchasers. For many analyses, the maximum haul distance is defined as 50 km, because at this distance the delivery price of aggregate has roughly doubled from the pit- or quarry-head price. For distances greater than the local market distance (1.6 km) and less than the maximum haul distance (50 km), the CSM model allocates aggregate demand to suppliers based on an inverse distance squared decay function, described by Eq. (1): so that the demand zones receive their aggregate from the closer suppliers, as

\[ V_a = \frac{V_u(1/d^2)}{\sum (1/d^2)}, \]

where \( V_a \) = allocated demand volume (tons); \( V_u \) = total aggregate demand (tons); \( d \) = distance between demand and supply (km).

8. Development of required databases

The identification, acquisition, and conversion of suitable data defining the supply and demand conditions for aggregate within the FRUC, and proper processing and analysis procedures for these data, are critical to successful allocation modeling of current and future aggregate markets. Practical computational constraints such as personnel, time, computer resources, and cost made it impossible for this regional numerical model to resolve detailed local market features. The size of the Front Range Corridor, the complex geological conditions, and the limited availability of detailed information for many portions of the region are important considerations in deciding on the information categories and degree of detail. Therefore, the study proceed with the development of a regional digital databases that describe regional geologic and economic conditions represented at scales of 1:100,000 or 1:500,000.

The allocation models require a supply database representing the aggregate suppliers along with their locations, capacities and reserves. The supply database includes five distinctive suppliers. These are individual sand and gravel pits, quarries, potential and active resource areas and railroad to truck distribution centers (Fig. 2). Sixty-four aggregate suppliers are defined in the supply database. The aggregate demand database is the second required database used in allocation models. Aggregate demand is calculated based on population of each zip code area within the counties and an activity level reflecting the anticipated level of construction activity (Fig. 4). 171-demand areas are defined in the demand database.

Nasser (1987) reported that a regression analysis of historical data indicated the annual consumption rate for aggregate in the Denver metropolitan area ranged between 8.5 and 10 tons per capita from 1960 to 1985. Since current and projected population figures for counties are readily available, the relationship between population and aggregate use is a suitable method for estimating current and future aggregate demand. This study uses estimates of annual aggregate demand volumes at 8.5 and 10 tons/capita consumption rates. Estimated 1996 population values are used for each zip code.

Supply demand allocation modeling requires a network to link suppliers with demands. In this study, truck haulage transports aggregate from suppliers to users, so the principal highway network must be defined for use by the models. Highway and railroad networks were developed as the third database from USGS DLG files.
Digital information concerning transportation facilities is readily available from the US Geological Survey (USGS, 1989).

9. Developed analysis scenarios

Four different scenarios were developed. Scenarios 1 and 2 evaluated conditions within the entire FRUC:

- Scenario 1 evaluates current conditions with the aggregate being supplied by currently active sources, and is thus referred to as the “Regional Base Case”.
- Scenario 2 evaluates one possible future situation when some currently active producers cease operations and some potential sources become active. This scenario is referred to as the “Regional Future Case”.

Scenarios 3 and 4 evaluated conditions within the Denver Metropolitan Area:

- Scenario 3 evaluates market shares of 19 currently active producers located within the Denver Metropolitan Area, and thus is referred to as the “Denver Metro Base Case”.
- Scenario 4 evaluates the impact on the Denver market of introducing rail-hauled aggregate supplies
by adding three possible rail-to-truck distribution sites, and thus is referred to as the “Railroad Augmentation Case”.

10. Evaluation of allocation modeling results

Allocation modeling was first undertaken using the capabilities provided by the ARC/INFO network analysis procedures. This modeling technique analyzed only the “Regional Base Case” scenario. Having unsatisfactory results with network analysis led to use of CSM allocation model. The CSM allocation model subsequently performed the four scenarios. Following sections explains the results obtained from the both models.

10.1. Results obtained using arc/info network analysis procedures

The ARC/INFO network analysis procedures assessed only the Regional Base Case scenario in which 50 suppliers were selected to provide aggregate to all 171-demand zones. The 50 suppliers include all presently active sand and gravel sources and quarries to represent the current aggregate condition in the FRUC. The 11 potential sand and gravel sources and three railroad distribution sites were “ignored” by setting their annual production capacities to zero to eliminate from the computation. Demand volumes for each demand zone were assigned according to the 8.5tons/capita/year allocation assumptions. Table 1 contains summarized information obtained from the results. When applied to the FRUC aggregate supply demand data, this model produced the following results:

(a) Each demand zone receives aggregate from a single supplier;
(b) the aggregate volume provided from the designated supplier to a demand zone equals 100% of its estimated demand;
(c) suppliers generally have production volumes below their designated capacity, because the addition of the next potential demand zone would cause the demand on the supplier to exceed its production capacity;
(d) some suppliers have very low allocated production volumes because most of the nearby demand zones have previously been assigned to other suppliers;
(e) a few suppliers have zero assigned demands because all the potential demand zones have been assigned to other suppliers; and
(f) a few demand zones are found to be further than the maximum haulage (search) distance from all suppliers, and thus cannot have their demands satisfied.

10.2. Results obtained from the CSM allocation model

Further aggregate supply demand allocations were undertaken using the CSM allocation model. The following sections describe the evaluations of the results obtained by the CSM allocation model for each of four scenarios. The CSM allocation model produces lengthy tabular results documenting individual conditions for each supplier and demand zone involved in the analysis, as well as overall summary statistics.

10.2.1. Scenario 1—Regional Base Case

The Regional Base Case scenario includes all 50 currently active suppliers and all 171-demand zones. Table 2 summarizes the results obtained. Four demand zones were located further than 50 km from any supplier and the model could allocate no aggregate supplies to them. The model required four iterations to achieve the best possible balance between supply and demand throughout the region. The model was able to allocate 99.75% of the total demand, with an average delivery price of $11.15/ton. The total unsatisfied demand, termed as “shortfall”, was only 62,860 tons, or about 0.25% of the total demand.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of regional base case scenario in ARC/INFO network analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of suppliers</td>
<td>50</td>
</tr>
<tr>
<td>Number of demand zones</td>
<td>171</td>
</tr>
<tr>
<td>Number of suppliers without allocation</td>
<td>3</td>
</tr>
<tr>
<td>Number of demand zones without suppliers</td>
<td>6</td>
</tr>
<tr>
<td>Maximum haul distance (km)</td>
<td>50.0</td>
</tr>
<tr>
<td>Total requested demand (tons × 1000)</td>
<td>25556.360</td>
</tr>
<tr>
<td>Total allocated demand (tons × 1000)</td>
<td>24700.410</td>
</tr>
<tr>
<td>Total shortfall (tons × 1000)</td>
<td>855.950</td>
</tr>
<tr>
<td>Percent demand allocated (%)</td>
<td>97</td>
</tr>
<tr>
<td>Average delivery price ($/ton)</td>
<td>9.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Summary of regional base case scenario in CSM allocation model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of suppliers</td>
<td>50</td>
</tr>
<tr>
<td>Number of demand zones</td>
<td>171</td>
</tr>
<tr>
<td>Number of zones without suppliers</td>
<td>4</td>
</tr>
<tr>
<td>Local neighborhood distance (km)</td>
<td>1.6</td>
</tr>
<tr>
<td>Maximum haul distance (km)</td>
<td>50.0</td>
</tr>
<tr>
<td>Supply/demand balance tolerance (tons × 1000)</td>
<td>0.5</td>
</tr>
<tr>
<td>Total requested demand (tons × 1000)</td>
<td>25556.360</td>
</tr>
<tr>
<td>Total allocated demand (tons × 1000)</td>
<td>25493.500</td>
</tr>
<tr>
<td>Total shortfall (tons × 1000)</td>
<td>62.860</td>
</tr>
<tr>
<td>Percent demand allocated (%)</td>
<td>99.75</td>
</tr>
<tr>
<td>Average delivery price ($/ton)</td>
<td>11.15</td>
</tr>
</tbody>
</table>
10.2.2. Scenario 2—Regional Future Case

For the Regional Future Case scenario, five currently active source areas were assumed to be no longer in production and four potential source areas were assumed to have begun producing aggregate. All 171-demand zones were retained in scenario 2.

Table 3 summarizes the results obtained. Two demand zones were located further than 50 km from any supplier and so no aggregate the model could allocate supplies to them. This scenario required four iterations to accomplish the best possible balance between supply and demand throughout the region. The model was able to allocate 84% of the total demand, with an average delivery price of $10.99/ton. The total shortfall was approximately 4 million tons, about 15% of the total demand. A total of 54 demand zones with shortfalls were experienced in scenario 2. Nine of these demand zones received no allocated supply of aggregate and the remaining demand zones received part of their requested volumes.

These unsatisfied demands for aggregate are a measure of sensitivity of the market to the assumed haul distance constraints. Three demand zones are located in the northern corners of the study area, but the majority of the shortfalls occur south and west of Denver. The removal of three currently active major suppliers from the Denver metropolitan area apparently caused these large volumes of shortfalls.

10.2.3. Scenario 3—Denver Metro Base Case

For the Denver Metro Base Case scenario, 19 active suppliers located between Boulder and Castle Rock, but excluding suppliers located east of Aurora, were selected as Denver Metro Area suppliers. The Denver Metro Area market for aggregate extends beyond the limits of the rectangular study area used to define the suppliers shown in Fig. 4. The Denver Metro Area aggregate marketplace was defined by referring to the results of scenario 1. A total of 88 demand zones were found to have received at least 1% of the aggregate produced by one or more of these 19 suppliers. These 88 demand zones were considered to make up the Denver Metro Area aggregate market.

Table 4 summarizes the results obtained. No demand zones were located further than 50 km from any supplier either initially or after iteration 1. The model required four iterations to achieve the best possible balance between supply and demand throughout the Denver Metro Area. The model was able to allocate 95% of the total demand, with an average delivery price of $11.29/ton. The total shortfall was 867,500 tons, about 5% of the total demand.

10.2.4. Scenario 4—Railroad Augmentation Case

The Railroad Augmentation Case scenario included three additional suppliers, representing possible railroad-to-truck distribution centers, to the 19 suppliers used in Denver Metro Area Base Case scenario. This scenario evaluates the economic impact of railroad haulage of aggregate from distant sources on the Denver aggregate supply and demand conditions.

The Railroad Augmentation Case scenario involved 22 suppliers and 88 demand zones. These suppliers included 19 suppliers used in scenario 3 plus the three railroad-to-truck distribution centers. The demand zones remained the same as in Scenario 3. Table 5 summarizes the results obtained. The model required three iterations to achieve the best possible balance between supply and demand. The model was able to allocate 98.3% of the total demand, with an average delivery price of $11.90/ton. The total shortfall was 314,160 tons, about 3.5% of the total demand. Supplying aggregate by rail to the area decreased the shortfall but increased the delivery price.

11. Comparison of the allocation models

Two allocation models evaluated the aggregate supply and demand. The first model, network analysis, provided unsatisfactory results. The ARC/INFO net-
work analysis performs the shortest-path algorithm to assign demand zone volumes to their nearest supplier until either the supplier’s production capacity is reached, or the defined maximum search distance (50 km) is exceeded. The overall evaluation of this allocation attempt suggested that it did not fully reflect real-world market conditions for aggregate supply and demand. Their main limitations were:

- The “all-or-nothing” approach to satisfying aggregate volumes requested by individual demand zones prevented any detailed analysis of actual supplies to demand zones;
- the requirement that a demand zone must receive all its supplies from a single supplier;
- the tabulated results produced by the model required considerable manipulation before any meaningful evaluation could be undertaken;
- the suppliers did not fully interact or compete with each other in supplying aggregate to multiple demand zones; and
- the procedure did not provide detailed information concerning the interactions between suppliers and demand zones, even for the limited degree of interactions allowed.

Subsequent analyses by the modified CSM allocation model provided more useful results. In particular, the model was capable of allocating aggregate from multiple suppliers to multiple demand zones; thus it represented a real competitive market. However, the current version of the CSM allocation model is limited by not having full integration with the GIS capabilities of ARC/INFO and ArcView.

Both of the models analyzed the first scenario, the Regional Base Case scenario. Thus, it was possible to directly compare the results achieved by the CSM allocation model to the results of the ARC/INFO procedures. The results obtained from two models are slightly different. Overall information of base case scenario for the ARC/INFO network allocation model is in Table 1 and for the CSM allocation model is in Table 2. In the CSM allocation model, more than 50% of the suppliers (26 suppliers) distributed their supplies at 95–100% capacity range, while only about 20% of the suppliers (10 suppliers) allocated their supplies at 95–100% capacity range in the ARC/INFO model. The total aggregate shortfall resulted in the ARC/INFO model was larger than the CSM allocation model. Demand zones received a lower percentage of their total demand 97% by ARC/INFO model, while this increased to 99.75% in the CSM model.

12. Conclusions

This study evaluated the combined use of allocation modeling and GIS technologies for providing quantitative assessments of aggregate supply and demand. It demonstrates that GIS methods support allocation modeling techniques and make them easier to use and more responsive to the needs of users. The use of GIS makes it much easier to rapidly define alternative scenarios. GIS techniques assist the process by making the development of the required supply and demand databases more efficient and flexible, by using network modeling techniques to characterize the transportation of aggregate from suppliers to purchasers, and by providing maps of both the input data and the analysis results.

The study used data describing the aggregate supply and demand conditions within the Front Range Urban Corridor of Colorado. The Front Range Urban Corridor was chosen because the conditions of aggregate supply and demand were familiar and the data were more readily obtained. Thus, the results obtained by the modeling were easier to assess. However, the methods outlined in this study can be applied to the modeling of aggregate supply and demand for any location, provided appropriate data describing the aggregate market can be provided to the models.

The ability to rapidly develop and quantitatively analyze alternative aggregate supply and demand scenarios provides an important evaluation tool to the aggregate industry, to governmental regulatory agencies, and to the public hearings process. By tracking the responses of specific suppliers or demand zones through a series of alternative scenarios; the socio-economic impacts of the opening or closure of one or more suppliers, or changes in patterns of demand within the region, can readily be analyzed quantitatively.

Two allocation analysis modeling procedures were evaluated; the network analysis procedures provided within the ARC/INFO software, and a modified version of the CSM allocation model. Initial studies were undertaken using the ARC/INFO capabilities. These
were found to be less than satisfactory. Subsequent analyses by the modified CSM allocation model provided more useful results. In particular, the model was capable of allocating aggregate from multiple suppliers to multiple demand zones; thus it represented a real competitive market.

References