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The storage location problem in a coal supply chain: background and methodological approach

Introduction

In order to achieve two main objectives: (1) reduce risk and (2) increase the expected rate of return on invested capital, coal mining and coal trading companies have looked for new ways to improve their supply chain networks. Developments in the supply chain design and analysis have helped coal mining and coal trading companies expand their businesses, but at the same time, have forced them to consolidate their assets and downsize any underused storage facilities. In the coal industry, the problem of consolidation and downsizing becomes much more complicated due to the variety of different coal grades involved, locational zones and different number of market players.

For the last decade, the storage allocation and assignment problem has received a great deal of attention within the Logistics and Operation Research (OR) area. Yet, little attention has been given to the modeling of coal supply chains and the issue of strategic supply chain planning of coal-producing and coal-trading companies. In recent years, few papers addressing the logistics of coal trade and coal supply chain have appeared in literature (see Bogacz 2015; Cheng et al. 2016; Kamiński and Saługa 2014; Magda et al. 2014). Furthermore, globalization and the growing competition between producing and trading companies have

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forced the coal industry to dramatically change and re-engineer their corporate structures, as well as to find new ways to optimize their distribution networks, size, number and location of storage facilities, transportation routes and shipment quantity.

A wide number of mathematical techniques and different approaches have been used in the optimization of integrated production-distribution networks and facility location problems. An extensive number of linear programming, mixed integer programming models and Lagrangian relaxation models can be found in literature. Melo et al. (2009) present an in depth facility location and supply chain management review, whereas more recent surveys by Fahimnia et al. (2013) and Liotta et al. (2015) present a number of state-of-the-art production-transportation and production-distribution (PD) optimization models. Despite the vast literature and numerous mathematical models on PD and facility location analysis, there is a need for decision-support tools that address the problem of storage and distribution network reconfiguration of coal-producing companies and coal-trading companies.

Coal storage facilities are crucial components in the coal supply chain. Generally, in a supply chain, warehouses are the primary facilities to store goods; however, in the coal supply chain, warehouses rarely store coal. Hence, it is fairly usual to find in all stages of the coal supply chain, coal storage facilities such as silos, stockpiles and storage domes, which provide high space utilization and minimize the handling and movement of raw materials and resources (Gu et al. 2007; Myerson 2015).

Significant advancements in storage allocation planning have made the application of warehouse consolidation and optimization methodologies to coal storage facilities possible. Hence, it is worth reviewing some of the fundamental principles in warehousing systems.

Three general types of warehouses that have been distinguished in literature (Berg and Zijm 1999):

- Distribution warehouses – facilities in which goods from manufacturers are collected and are prepared for distribution to customers. Also, depending on the type of industry, some goods can be assembled in these facilities. Manufacturing companies mainly use distribution warehouses to deliver goods to retail stores.
- Production warehouses – facilities which are mainly used for the storage of raw materials and intermediate products. In a production facility, intermediate storage is needed when production processes are not fully synchronized.
- Contract warehouses – warehouses in which a third-party logistics company handles the warehousing space, operations, equipment and staff.

Furthermore, Gu et al. (2010) described three primary roles that warehouses play in a supply chain network:

- A storage role, aimed to work as a buffer between supply and demand, keeping product quantities available for fossil fuels' consumers,
- A consolidation role, pulling together small orders (batching) and consolidating them into a larger shipment, lowering the total transportation costs (this would also include coal blending for instance),

- A customization role or value-added-processing role in which branding, labeling, packaging or final assembly takes place – this role would be of key interest for retail trading companies.

It has been observed that, particularly in coal-producing companies and coal-trading companies, storage facilities play multiple roles, such as postponement and customization roles. For instance, a postponement role in which different grades of coal are kept in the most generic form until they move into processing, blending, and transportation.

Similar to the generic warehouse consolidation problem (WCP), in specific cases of coal-producing and coal-trading companies, storage facilities that are redundant or underutilized can be eliminated without causing a negative impact on customer and service levels. One of the challenges in this real-world problem is to determine when and which facilities should be phased-out and which of them and their capacities can be consolidated (Min and Melachrinoudis 2001). Further, in this type of models it is of paramount importance to keep a balance between customer service and logistic costs, without overlooking labor availability, regional tax incentives, and local regulations. The WCP and the effect of capacity relocation is shown schematically in Fig. 1.

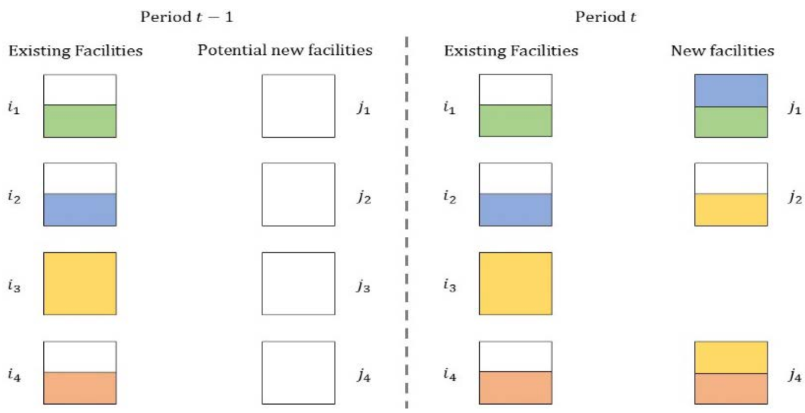

Fig. 1. Warehouse consolidation problem and the effect of capacity relocation
Source: Adapted from Melo et al. 2005

Rys. 1. Problem optymalizacji lokalizacji składów węgla oraz skutki relokacji zdolności magazynowych

The research of Min and Melachrinoudis (2001), which laid the theoretical foundations of the warehouse network-restructuring problem, proposes a single objective mixed-integer programming model. It determines the optimal number of units in a restructured warehouse network. Moreover, it is a decision-aid tool that includes capacity limits and service requirements and can be traced back to the concepts of a p-median model. It is worth mentioning that a p-median problem is primarily concerned with minimizing the average distance between supply/demand facilities and selecting the optimal site among the alternatives of established locations, whereas Min and Melachrinoudis (2001) describe that a WCP is mainly concerned with

- which warehouses to retain,
- which new warehouses to establish, and
- which new warehouses to phase-out among existing locations.

In an improved version of this model (Melachrinoudis and Min 2007) warehousing costs were broken down and variable warehousing costs (e.g. unit warehousing costs, unit transportation cost, costs savings from the closure of a warehouse, cost of moving and relocating unit capacity) were incorporated. In several subsequent papers, Melachrinoudis and Min further develop a series of mathematical models that solve various real-world warehouse redesign problems. Melachrinoudis et al. (2005) formulate and validate a physical programing (PP) model that minimizes annual costs and maximizes customer coverage within a specific delivery time. The multi-criteria mixed-integer programming model allows the decision maker to express the degree of desirability of service performance (customer coverage) through the implementation of range-boundaries.

Anaraki et al. (2011) study the problem of a two-echelon warehouse network with multiple customer zones, manufacturing plants and warehouses. The model, which is formulated as a mixed-integer programming model, considers delivery lead times, customer due dates, and capacity constraints. As a result, the model is decomposed into a master and a sub-problem through a Bender decomposition approach. Melo et al. (2005) addressed a multi-commodity problem in which the capacity from a facility can be partially transferred to a different facility. A novel aspect of the Mixed Integer Linear Programming (MILP) model is the incorporation of a dynamic planning horizon and fluctuating demands. Furthermore, the model tackles the essential issue of investment cost for facility relocation, and relocation costs due to capacity shifts. A more recent work by Kiya and Davoudpour (2012) carries out a two-stage stochastic programming approach to re-designing a warehouse network. Uncertainty is introduced as variability in the operational data and product demand at a customer location.

This paper proposes a MILP model mainly intended for storage and distribution network reconfiguration of a coal-producing or trading company. The model, which can be implemented in a high-level mathematical modelling system such as GAMS or AIMMS, captures essential methodological features of a warehouse restructuring and/or consolidation problem. It is designed to minimize total costs while meeting capacity limits and locational zone restrictions. With this scope in mind, Section 2 describes the problem setting and Section 3 presents the model formulation. The paper ends with a set of conclusions and recommendation for future research.

1. Problem setting and description

This section presents a case study of a coal-producing company that seeks to optimize its coal-storage operations and decrease its number of storage facilities.

After a careful evaluation of the operating profile and strategic plans of the company, senior executives have decided to embark on a major company overhaul. The company, hereafter referred to as *Col-Corp*, in order to preserve its anonymity and confidentiality, is primarily located in Poland. In order to downsize and optimize its storage and distribution system, the top management of *Col-Corp* is interested in finding an appropriate storage and distribution network configuration that will derive in logistics and transportation costs reductions, taking into account all the units. Moreover, the company would like to phase-out and consolidate redundant and/or underutilized storage facilities.

Col-Corp owns and operates approximately 20 storage facilities in a specific region, having each facility store different quantities and grades of coal. Furthermore, *Col-Corp* owns all facilities, property and material handling equipment. As a requirement in this storage and distribution network reconfiguration, the main region is subdivided into sub-regions and each sub-region is treated as an independent area. The storage facilities supply various grades of coal to a specific number of demand regions that are located in these sub-regions. *Col-Corp's* main mode of transportation is truckload freight. Moreover, the goal of the company is to save in inventory, transportation and storage costs due to economies of scale.

Senior executives of the abovementioned company are aware that implementing a warehouse-centralization strategy to their coal storage facilities offers a number of advantages as well as a number of disadvantages (these have been discussed in detail by Melachrinoudis and Min 2007; Min and Melachrinoudis 2001). To mention some of the most relevant advantages: storage-centralization can increase inventory velocity, improve capacity utilization and promote a higher throughput, bring substantial savings in inventory and transportation costs due to bulk storage and large-volume shipping from/to centralized locations and reduce administrative costs. On the other hand, important drawbacks include an increase in lead times, possibly deterioration of customer services, and longer distances between warehouses.

Over the years, the number of coal storage facilities of *Col-Corp* increased but an optimization procedure has never been applied to carry out the assignment of demand regions to specific storage facilities. Thus, top management is interested in applying a decision-support tool and replace their intuitive and heuristic manual methods. A major requirement from *Col-Corp* in the formulation of the model is the way in which sub-regions are treated. The coal storage facilities located in a sub-region "A" are only allowed to supply coal to demand regions located in the same sub-region. If a coal storage facility is located in sub-region "A" and a demand region is located in sub-region "B", and the distance between "A" and "B" is relatively small, the shipment of coal between these two facilities is not allowed.

To facilitate *Col-Corp's* model formulation, some key assumptions are necessary. The assumptions are summarized below:

- Strategic planning horizon.
- No change in coal demand during the model's planning horizon.
- Shipment between facilities located in different sub-regions is not allowed.
- A demand region must be served by only one storage facility.
- All commodities are aggregated into one single product that is expressed in Polish Zlotys (PLN).
- When a given storage facility is definitively closed, a different storage facility can fully accommodate the capacity of the facility that is being closed without incurring additional costs.

2. Model Formulation

This section presents the mathematical description of the proposed coal-storage facility restructuring and consolidation model. The model addresses the issues presented in the aforementioned case study and it is formulated as follows:

- Indices and sets
  - i = index for existing storage facilities and candidates for consolidation; $i \in I$,
  - j = index for demand region; $j \in J$,
  - f = index for coal grades; $f \in F$.
- Model parameters
  - $q_{i,f}$ = Net capacity of coal f in storage facility i,
  - $f_{i,f}$ = Fixed cost of maintaining the storage facility i assigned to coal f,
  - $v_{i,f}$ = Variable cost of operating the storage facility i related to coal f, excluding transportation costs,
  - $d_{j,f}$ = Demand for coal grades f of demand region j,
  - $s_{i,j}$ = Distance in km from demand region j to storage facility i,
  - $c_{i,j,f}$ = Capacity margin of coal grades f for demand region j to storage facility i,
  - τ_f = Variable transportation cost per km,
  - M = Auxiliary value – a large number.
- Decision variables
  - $x_{i,j,f}$ = Amount of coal f shipped from storage facility i to demand region j,
  - $y_{i,j,f} = \begin{cases} 1, & \text{if storage facility } i \text{ supplies coal } f \text{ to demand region } j \\ 0, & \text{otherwise,} \end{cases}$
  - $z_i = \begin{cases} 1, & \text{if the facility } i \text{ remains open} \\ 0, & \text{otherwise.} \end{cases}$
- Mathematical formulation

Minimize:

$$\sum_{i,f} f_{i,f} z_{i,f} + \sum_{i,j,f} v_{i,f} y_{i,j,f} + \sum_{j} \tau_f s_{i,j} x_{i,j,f} \tag{1}$$

Subject to:

$$\sum_{j} (1 + c_{i,j,f}) x_{i,j,f} \leq q_{i,f} z_{i,f} \quad \forall i \in I,\ \forall f \in F \tag{2}$$

$$\sum_{i} x_{i,j,f} \geq d_{j,f} \quad \forall j \in J,\ \forall f \in F \tag{3}$$

$$x_{i,j,f} \leq y_{i,j,f} M \quad \forall i \in I,\ \forall j \in J,\ \forall f \in F \tag{4}$$

$$\sum_{i} y_{i,j,f} = 1 \quad \forall j \in J,\ \forall f \in F \tag{5}$$

$$y_{i,j,f} \leq z_i \quad \forall i \in I,\ \forall j \in J,\ \forall f \in F \tag{6}$$

$$x_{i,j,f} \geq 0 \quad \forall i \in I,\ \forall j \in J,\ \forall f \in F \tag{7}$$

$$y_{i,j,f} = (0,1) \quad \forall i \in I,\ \forall j \in J,\ \forall f \in F \tag{8}$$

$$z_i = (0,1) \quad \forall i \in I,\ \forall f \in F \tag{9}$$

The objective function, equation (1), minimizes the total coal-supply chain costs. It is composed of coal storing fixed costs (related to storage of particular coal grades) and variable costs, plus transportation costs which depend on the distance from a demand region to a storage facility. Constraint (2) states that the total amount of given coal (also in various grades and quality) shipped from a storage facility to a demand region does not exceed the net capacity of the supplying facility, plus certain capacity margin for each storing facility. Constraint (3) ensures that demand for coal in a demand region is satisfied by the total volume of this energy carrier shipped from a given storage facility. Constraint (4) states that a coal storage facility can serve a demand region only if it remains open. Constraint (5) limits the quantity flow from a coal storage facility to only one demand region. Constraint (6) ensures that a coal storage facility can only remain open if it supplies a demand region. Constraint (7) assures the non-negativity of the decision variables. Constraints (8) and (9) restrict the variables to binary values.

The proposed model, which can be implemented in a modeling system such as GAMS or AIMMS, can be applied for solving real-world coal storage facility and optimization problems.

3. Concluding remarks

Rapid changes in the coal market as well as fierce global competition have forced coal-producing and coal-trading companies to reformulate their business and corporate strategies. In order to adjust to new market conditions, some companies implement innovative practices when facing new challenges. For instance, to improve their flexibility, management efficiency and competiveness, coal-producing and coal-trading companies have looked for solutions in various scientific disciplines including operation research, transportation research, production and operations management, among others.

This paper presents the background and methodological approach of a storage location problem in a coal supply chain. Moreover, it provides a literature review on warehouse consolidation models and subsequently proposes a mixed-integer linear programming model for coal storage and distribution network optimization. The model proposed in this paper is fully capable of providing the optimal set of coal-storage locations while allowing decision makers to validate various network configuration options. Hence, for further research, it would be desirable to implement the proposed model to different mineral sectors and mineral mining companies and other supply chain areas.

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LOKALIZACJA SKŁADÓW WĘGLA W ŁAŃCUCHU DOSTAW DO ODBIORCY – TŁO I PODEJŚCIE METODYCZNE

S ł o w a k l u c z o w e

kopalnie węgla, handel węglem, optymalizacja dostaw, MILP, lokalizacja magazynów

S t r e s z c z e n i e

Wśród szeregu przedsięwzięć realizowanych przez przedsiębiorstwa produkujące i handlujące węglem kamiennym w kierunku osiągnięcia dwóch podstawowych celów swojej działalności, jakimi są (1) zmniejszenie ryzyka oraz (2) zwiększenie oczekiwanej stopy zwrotu z zaangażowanego kapitału, istotną rolę pełni konsekwentne usprawnianie sieci dostaw tego nośnika energii pierwotnej. Projektowanie przedmiotowego systemu oraz analiza łańcucha dostaw węgla stwarza warunki dla dalszej ekspansji spółek; zmusza jednocześnie ich zarządy do przeprowadzania konsolidacji posiadanych aktywów oraz redukowania niewykorzystanych zasobów magazynowych. W branży węglowej problem ten komplikuje się głównie ze względu na zmienność parametrów jakościowych występującego w obrocie węgla (w konsekwencji dużej liczby klas/sortymentów), różnorodną lokalizację oraz dużą liczbę uczestników rynku.

Problem efektywnej alokacji powierzchni magazynowych stanowi coraz częściej poruszane zagadnienie w literaturze przedmiotu. Niestety, jak dotychczas niewystarczające zainteresowanie towarzyszyło zarówno modelowaniu łańcucha dostaw węgla jak i problemowi planowania strategicznego

w spółkach węglowych i przedsiębiorstwach handlujących węglem. Poprzez analogię do ogólnego problemu konsolidacji powierzchni magazynowych można pokazać, że w przypadku przedmiotowych przedsiębiorstw niepotrzebne lub niewykorzystane kubatury składowisk mogą zostać wyeliminowane bez spowodowania negatywnych skutków dla odbiorców. W odniesieniu do powyższego, w artykule przedstawiono zwięzłą analizę tła problemu oraz zaproponowano rozwiązanie zagadnienia rekonfiguracji sieci dystrybucyjnej rozważanych przedsiębiorstw wydobywających i handlujących węglem kamiennym z wykorzystaniem podejścia programowania matematycznego liniowego całkowitoliczbowego (MILP). Podobny model (który może być zaimplementowany w systemie modelowania, takim jak GAMS lub AIMMS), uwzględnia wszystkie istotne elementy metodyczne problemu konsolidacji powierzchni magazynowych i może być skutecznie wykorzystany do celów praktycznych.

THE STORAGE LOCATION PROBLEM IN A COAL SUPPLY CHAIN: BACKGROUND AND METHODOLOGICAL APPROACH

Keywords

coal mining companies, coal trading, supply optimization, MILP, warehouse location

Abstract

In order to achieve two main objectives: (1) reduce risk and (2) increase the expected rate of return on invested capital, coal mining and coal trading companies have looked for new ways to improve their supply chain networks. Developments in the supply chain design and analysis have helped coal mining and coal trading companies expand their businesses, but at the same time, have forced them to consolidate their assets and downsize any underused storage facilities. In the coal mining industry, the problem of consolidation and downsizing becomes much more complicated due to the variety in quality parameters (hence many coal grades) involved, locational zones and different number of market players. Furthermore, for the last decade, the storage allocation and assignment problem has received a great deal of attention within the Logistics and Operation Research (OR) area. Yet, little attention has been given to the modeling of coal supply chains and the issue of strategic supply chain planning of coal-producing and coal-trading companies. Similar to the generic warehouse consolidation problem (WCP), in specific cases of coal-producing and coal-trading companies, storage facilities that are redundant or underutilized can be eliminated without causing a negative impact on customer and service levels. In this context, this paper discusses the background of the problem and proposes a mixed-integer linear programming (MILP) model mainly intended for storage and distribution network reconfiguration of a coal-producing or trading company. The model, which can be implemented in a high-level mathematical modelling system such as GAMS or AIMMS, captures the essential methodological features of a warehouse restructuring and/or consolidation problem and can be applied in practice.