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Decision support system for designing sustainable multi-stakeholder networks of grain storage facilities in developing countries

E. Essien^{a,*}, K.A. Dzisi^b, Ahmad Addo^b^a University of Ghana, Legon, Ghana^b Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

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ABSTRACT

Governments in developing countries often face the daunting task of designing a network of grain storage facilities to simultaneously benefit the various stakeholders (farmers, market traders, exporters, etc.) in the grain supply chain irrespective of the conflicting objectives of these stakeholders. Existing decision support systems either require data that are unavailable in most developing countries or have objectives irrelevant in the context of developing countries. This paper therefore develops a decision support system that integrates transportation, pseudo p-median, forecasting and goal programming models to optimally design networks of grain storage facilities to reduce the transportation cost of respective stakeholders. The effectiveness of the proposed decision support system has been demonstrated by comparing phantom networks developed with the decision support system to the Government of Ghana's network of 48 grain storage facilities.

1. Introduction

The alarmingly high levels (30–50%) of postharvest losses in developing countries compel governments and donor agencies to provide grain storage facilities (McNeil, 2013). These facilities essentially have systems to aid in the efficient processing and storage of agricultural commodities to reduce commodity deterioration. There have however been concerns about the sustainability of these facilities in some developing countries for several reasons. For instance, the climate dependent nature of agriculture in these countries makes the facilities highly susceptible to climatic shocks. Thus a minor change in the climatic pattern could render the facilities dormant for an entire year. Furthermore, unlike the farmer in the developed country who sizes a storage facility based on the production capacity he/she can guarantee (because of mechanization), grain storage facilities in developing countries are mostly sized based on the aggregated capacity of the cluster of farmers it is supposed to service. There is therefore an inherent uncertainty in the production capacity of any cluster as most of the smallholder farmers do not have stable production levels. Thus, storage capacities of facilities determined using the aggregated capacity of the cluster may result in high levels of unused capacity. Coulter et al., for instance report of high levels of unused storage capacity in Ghana (Coulter et al., 2000). The resulting insufficient revenue generation makes the storage facilities economically unsustainable.

A possible solution to improving the sustainability of the storage

facilities is to site them strategically to allow for its concurrent use by other stakeholders. The unused capacity resulting from uncertainties in agricultural production can be ameliorated by incentivizing other stakeholders (market traders, exporters/importers, etc.) whose capacities are relatively easy to forecast to concurrently use the facilities. This will effectively eliminate any dormancy within the storage facilities as well as improve their sustainability. In a country like Ghana where there is reported unused capacity for grain storage but high demand for storage space for imported commodities such as sugar, rice, and fertilizer, one could site the storage facility to simultaneously suit farmers, market traders, importers and exporters (Coulter et al., 2000).

The quantum of possible solutions to the problem of siting facilities to suit all stakeholders precludes the use of human intuition for solving such problems. Several mathematical models have therefore been developed to solve such location problems in agriculture. These models as applied in agriculture are usually multi-faceted. They solve for the optimal locations to site the facilities, determine the catchment areas to be served by respective facilities and the corresponding routing decisions (Lucas and Chhaged, 2004). The plurality of features significantly increase the size of most real world location problems found in agriculture. They are therefore mostly solved with commercial solvers or specialized heuristic algorithms. Another important feature of the location models found in agriculture is their ability to deal with variability. The models account for variability in production which may occur as a result of climatic changes within and across years.

* Corresponding author.

E-mail address: ing.essien@gmail.com (E. Essien).

Researchers have used several mathematical techniques such as queuing theory, probability theory, system reliability theory, and game theory to capture this variability (An et al., 2015; Bardossy and Raghavan, 2016; Berman et al., 2007; Ghodratnama et al., 2015; Hahn et al., 2016; Snyder and Daskin, 2005). These models also allow for studying the effect of varying commodity production levels across a period of time. This is necessary as in practical terms, production or demand will vary and the facilities sited must be resilient to such changes.

Although facility location problems in developing countries have all the features (large scale and variability) stated above, the models reported in the literature cannot readily be applied because of some issues. The first problem with the existing models is that because they are designed for a developed country context, they require data that are mostly unavailable or unreliable in developing countries. Nourbakhsh et al., for instance developed a mathematical model for siting new grain pre-processing plants aimed at reducing postharvest losses. Their model however requires parameters such as the background traffic and actual traffic capacities of respective roads. Because their numerical example was for Illinois, the data was readily available online at the Illinois Department of Transportation website (Nourbakhsh et al., 2016). Such vital databases are rare in developing countries hence the use of such models are impractical without adaptation.

Furthermore, to the best of our knowledge, none of the existing models capture the various stakeholders which usually characterize supply chains in developing countries. Thus, the existing models normally site warehouses or facilities to suit just one stakeholder. Unlike what pertains in developing countries, individual stakeholders in developed countries usually have the financial resources to purposely design networks of storage facilities to suit just them. Most of the existing models therefore optimize the network of storage facilities for a single stakeholder. Also most multi-criteria facility location models in literature optimally site facilities to achieve the various objectives of a stakeholder (Chauhan and Singh, 2016; Datta, 2012; Dosal et al., 2013; Hahn et al., 2016; Nguyen and Notteboom, 2016; Wang, 2015). However, as explained earlier, the sustainability of the network of facilities in developing countries is highly dependent on siting to promote the concurrent use by multiple stakeholders. This work therefore develops a decision support system (DSS) that uses readily available data to site facilities to allow for the concurrent use by multiple stakeholders. This system will enable the design of efficient and sustainable networks of facilities that will significantly reduce post-harvest losses. The DSS could also be used to compute the efficiency of existing networks of storage facilities in order to determine the plausible options for optimization.

2. Methodology

2.1. Development of conceptual framework

The initial stage of this framework deals with the determination of the major stakeholders in the supply chain and their respective requirements. A typical grain supply chain will have its important stakeholders being farmers, market traders, exporters/importers and the government who has the resources to site storage facilities for these stakeholders. The major requirement addressed with this decision support system is transportation cost minimization. The DSS undertakes the transportation cost minimization in two stages. The first stage involves the use of pseudo p-median and transportation models to compute the theoretically attainable least total transportation cost for each stakeholder. This represents the theoretical least total transportation cost attainable if a network of grain storage facilities were optimized solely for that particular stakeholder. This cost is however, rarely attained in the developing countries' context as the network of GSF is rather intended for all stakeholders and not for a particular stakeholder. A goal programming component of the DSS is used to site facilities such

that deviations of each stakeholders transportation cost from the already determined theoretically attainable least total transportation cost is minimized. A stakeholder in the supply chain therefore evaluates the quality of a siting decision by computing the resultant deviation (positive or negative) from the theoretically attainable least total transportation cost. The sensitivity of the resulting siting decisions to changes in grain production is investigated using the forecasting model component of the DSS. Brief descriptions of the various components of the DSS are given below;

2.1.1. Principal components

The DSS is an integration of a Pseudo P-median, Transportation, Goal programming and forecasting models.

2.1.1.1. Pseudo P-median model. This is a mixed integer linear programming (MILP) model that outputs a "P" number of optimal locations to site a facility given a set of sources, destinations, production capacities of the sources, and the interconnecting distances between source and destination locations. Thus assuming a decision maker wants to choose 50 out of 200 farming communities to site grain storage facilities to reduce the total transportation cost of all the market traders as they access the storage facilities, the set of 200 farming communities becomes the source locations while the maize markets becomes the destination set. Using the grain production capacities of the farming communities and their respective travel distance to the maize markets, the model will determine the 50 optimal locations to site the facilities to reduce the total transportation cost of the market traders as they access the warehouses. The stakeholder specific nature of the formulation allows one to compute the best locations a stakeholder would have to choose to minimize transportation cost. A detailed formulation and use of the Pseudo P-median model can be found in Essien (2017).

2.1.1.2. Transportation model. This is a mixed integer programming model that computes the total transportation cost a particular stakeholder will incur in using a particular network of storage facilities. Thus the model minimizes the transportation cost (which is a product of the distance traveled to access a facility, the amount of product being moved to or from a facility and the vehicular cost per kilogram per kilometer) while ensuring that each constituent of a particular stakeholder group is assigned to a facility. The cost computed with this model represents the minimum transportation cost attainable with a particular configuration of stakeholders and storage facilities. A detailed description can be found in Essien (2017).

2.1.1.3. Forecasting model. The third component of the decision support system is a Seasonal Autoregressive Integrated Moving Averages (SARIMA) model which was used to provide 55 years forecast of grain surpluses of respective production centers. These forecasts were used as inputs in the pseudo p-median, transportation and goal programming models to determine the sensitivity of any location decision to changes in production volumes. A detailed description of this model is also found in Essien (2017).

2.1.1.4. Goal programming model. This is an MILP model that determines the optimal locations to site facilities so as to minimize deviations from the determined minimum attainable transportation cost (computed using the pseudo p-median and transportation models) for respective stakeholders. This goal programming model amalgamates the individual pseudo p-median models to represent a scenario where all stakeholders know their attainable minimum total transportation cost and are siting storage facilities to reduce deviations from that figure. This mimics what happens in reality as all the representatives of stakeholders will have an idea of candidate locations that will reduce their respective transportation cost. A mathematical formulation of this model is given below;

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