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

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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 Chhajed, 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.

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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. Nourbaksh 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 whiles 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) whiles 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;

Notation	
Priority1	Priority level for market traders
Priority2	Priority level for exporters at the airport
Priority3	Priority level for exporters at the harbor
Priority4	Priority level for farmers
P1	Positive deviational variable for market traders
P2	Positive deviational variable for exporters at the airport
P3	Positive deviational variable for exporters at the harbor
P4	Positive deviational variable for farmers
N1	Negative deviational variable for market traders
N2	Negative deviational variable for exporters at the airport
N3	Negative deviational variable for exporters at the harbor
N4	Negative deviational variable for farmers
T1	Minimum total transportation cost for market traders
T2	Minimum total transportation cost for exporters at the airport
T3	Minimum total transportation cost for exporters at the harbor
T4	Minimum total transportation cost for farmers
$D_{(WH,MKT)}$	Distance between warehouse and market
$D_{(WH,AP)}$	Distance between specific warehouse and airports
$D_{(WH,HB)}$	Distance between warehouse and harbours
$D_{(WH,FI)}$	Transportation distance from farm to warehouse
$Y1_{(WH,MKT)}$	Binary variable
$Y2_{(WH,AP)}$	Binary variable
$Y3_{(WH,AP)}$	Binary variable
$Y4_{(WH,FI)}$	Binary variable
A_D	Production capacity of a specific district
C_{AP}	Commerical capacity of specific airports
C_{HB}	Commerical capacity of a specific harbor
C_{MKT}	Commercial capacity of a particular market
$X1_D$	Binary variable
$X2_D$	Binary variable
$X3_D$	Binary variable
$X4_{FI}$	Binary variable
$Site_D$	Binary variable
P	Number of warehouses to site

Minimize

$$\left(\text{Priority1}\times\left(\frac{\text{P1}}{\text{T1}}\right)\right)+\left(\text{Priority2}\times\left(\frac{\text{P2}}{\text{T2}}\right)\right)+\left(\text{Priority3}\times\left(\frac{\text{P3}}{\text{T3}}\right)\right)+\left(\text{Priority4}\times\left(\frac{\text{P4}}{\text{T4}}\right)\right) \tag{1}$$

Subject to

$$T1=\left(\sum_{WH,MKT} D_{WH,MKT}\times Y1_{WH,MKT}\times\frac{1}{A_D\times C_{MKT}}\times Cost_{WH,MKT}\right)+N1-P1 \tag{2}$$

$$\sum_{WH} Y1_{WH,MKT}\geqslant 1 \tag{3}$$

$$\sum_{MKT} \mathrm{Y1}_{WH,MKT}\geqslant \mathrm{X1_D} \tag{4}$$

$$Site_D = X1_D \tag{5}$$

$$Site_D \geqslant Y1_{WH,MKT} \tag{6}$$

$$\mathrm{T2}=\left(\sum_{WH,\mathrm{AP}} \mathrm{D}_{WH,\mathrm{AP}}\times \mathrm{Y2}_{WH,\mathrm{AP}}\times\frac{1}{\mathrm{A_D}\times \mathrm{C_{AP}}}\times \mathrm{Cost}_{WH,\mathrm{AP}}\right)+\mathrm{N2}-\mathrm{P2} \tag{7}$$

$$\sum_{WH} Y2_{WH,\mathrm{AP}}\geqslant 1 \tag{8}$$

$$\sum_{AP} Y2_{WH,\mathrm{AP}}\geqslant X2_D \tag{9}$$

$$Site_D = X2_D \tag{10}$$

$$Site_D \geqslant Y2_{WH,\mathrm{AP}} \tag{11}$$

$$\mathrm{T3}=\left(\sum_{WH,\mathrm{HB}} \mathrm{D}_{WH,\mathrm{HB}}\times \mathrm{Y3}_{WH,\mathrm{HB}}\times\frac{1}{\mathrm{A_D}\times \mathrm{C_{HB}}}\times \mathrm{Cost}_{WH,\mathrm{HB}}\right)+\mathrm{N3}-\mathrm{P3} \tag{12}$$

$$\sum_{WH} Y3_{WH,\mathrm{HB}}\geqslant 1 \tag{13}$$

$$\sum_{HB} Y3_{WH,\mathrm{HB}}\geqslant X3_D \tag{14}$$

$$Site_D = X3_D \tag{15}$$

$$Site_D \geqslant Y3_{WH,\mathrm{HB}} \tag{16}$$

$$\mathrm{T4}=\left(\sum_{\mathrm{WH,FI}} \mathrm{D_{WH,FI}}\times \mathrm{Y4_{WH,FI}}\times \mathrm{C_{FI}}\times \mathrm{Cost_{WH,FI}}\right)+\mathrm{N4}-\mathrm{P4} \tag{17}$$

$$\sum_{WH} Y4_{\mathrm{WH,FI}}\geqslant 1 \tag{18}$$

$$\sum_{FI} Y4_{\mathrm{WH,FI}}\geqslant X4_{FI} \tag{19}$$

$$Site_D = X4_D \tag{20}$$

$$Site_D \geqslant Y4_{\mathrm{WH,FI}} \tag{21}$$

$$\sum Site_D = P \tag{22}$$

The objective function (Eq. (1)) minimizes the normalized transportation coefficient of all the stakeholders. In this particular instance there are four stakeholders represented in this model namely market traders (stakeholder 1), exporters at airport (stakeholder 2), exporters at harbor (stakeholder 3) and farmers (stakeholder 4). The Priority1, Priority2, Priority3 and Priority 4 variables represent the preferential normalized weights that the decision maker can attach to the minimization of the deviation from a target for a particular stakeholder. Hence assuming a decision maker wants to prioritize farmers over all the other stakeholders in siting the facilities the Priority4 variable will have a higher value than Priority1, Priority2, and Priority 3. The transportation coefficients (T1, T2, T3 and T4) computed using the stakeholder specific pseudo p-median models serve as normalization constants for the respective positive deviational variables (P1, P2, P3 and P4). The objective function therefore minimizes the sum of the weighted and normalized deviational variables for all stakeholders.

Constraints (2)–(6) represent the pseudo p-median component for market traders in the goal programming model. This essentially ensures that in siting the storage facilities to suit all stakeholders, the final choice of locations minimizes the transportation coefficient of the market traders (Eq. (2)) and all market traders are assigned to storage facilities and vice versa (Eqs. (3)–(6)). Constraints (7)–(11) represent the pseudo p-median for exporters at the airports. Similar pseudo p-median models are also present for exporters at the harbor (Eqs. (12)–(16)) and farmers (Eqs. (17)–(21)). Constraint (22) is used to specify the "p" number of storage facilities to site to suit all stakeholders.

2.2. Application to the maize supply chain in Ghana

Maize forms a vital component of the staple diets of Ghanaians as it

Table 1
Initial transportation cost for farmers in existing, optimal and goal programming networks.

Scenario	Existing Network (USD)	Optimal Network (USD)	Percentage Improvement	Goal Programming Optimal Network (USD)	Percentage Improvement
1	5.27E+07	3.53E+07	33%	4.06E+07	23%
2	3.18E+10	1.82E+10	43%	2.70E+10	15%
3	1.39E+10	1.20E+10	13%	1.11E+10	20%
4	7.95E+09	4.51E+09	43%	7.14E+09	10%
5	6.38E+09	3.82E+09	40%	5.27E+09	17%
6	6.16E+09	3.94E+09	36%	5.48E+09	11%
7	7.06E+09	4.89E+09	31%	5.53E+09	22%
8	9.39E+09	7.23E+09	23%	8.54E+09	9%
9	6.93E+09	4.63E+09	33%	5.61E+09	19%
10	7.48E+09	6.50E+09	13%	5.82E+09	22%
11	5.48E+09	2.03E+09	63%	4.93E+09	10%
Average	9.32E+09	6.16E+09	34%	7.86E+09	16%

accounts for about 55% of Ghana's total grains production (Akramov and Malek, 2012). In designing an efficient network of grain storage facilities to aid the respective stakeholders in the supply chain, the following data was obtained. The district grain production data for all districts in Ghana spanning the period 1997–2011 was obtained from the Ministry of Food and Agriculture. The interconnecting distances between respective stakeholders were also obtained using the Google Distance Matrix Api® service. The human population of the respective districts was also obtained from the Ghana Statistical Service. The various components of the DSS were built using Matlab® R2016b, GAMS® Distribution 24.8.3, and Esri ArcGIS®.

3. Results and discussion

In ascertaining the efficacy of the DSS, simulations were run to compare the total transportation cost within phantom networks designed with the DSS and that of the government of Ghana's network of 48 grain storage facilities. The two categories of phantom networks compared to the government's existing network were a stakeholder specific optimal network and a goal programming network optimized for multiple stakeholders. The robustness of these networks was also determined by simulating their initial and final (after 55 years of use) total transportation cost.

The simulations showed that the initial total transportation cost incurred by farmers in the existing network of storage facilities was 34% higher than what they would have incurred if grain storage facilities were optimally sited to suit solely farmers. Furthermore, in circumstances were the storage facilities were optimally sited to suit multiple stakeholders (i.e. goal programming optimal network), the farmers incurred a total transportation cost which was 16% cheaper than what they will incur in the existing network of grain storage facilities (Table 1). The difference in percentage improvement of the total transportation cost for farmers in the optimal network and those in the goal programming network is due to the fact that as the number of stakeholders increase, the cumulative percentage improvement originally due a single stakeholder (in this case the farmers) is optimally distributed amongst multiple stakeholders (farmers, market traders and exporters/importers at the airports and harbours). The optimal distribution amongst several stakeholders therefore results in the reduction in the percentage improvement to a single stakeholder. The analysis also showed that after 55 years of varying district grain surpluses patterns, the stakeholder specific optimal network was 26% cheaper in transportation cost as compared to the existing network. The goal programming network was also 12% cheaper than the existing network over the 55 years period (Table 2). The reduction in percentage improvement after the 55 year period can be attributed to the fact that prevailing conditions which resulted in the earlier 26% improvement might have varied or changed significantly over the period. This change in the original conditions therefore results in a reduction in the percentage improvement. The change in the prevalent condition may be due to climate change, rural urban migration, reduction in acreage of arable lands, etc.

Further simulations also showed that market traders would have incurred a 55% cheaper total transportation cost than they do with the existing network of storage facilities if the existing network were optimally designed solely to suit them. Even if it were designed to optimally suit all stakeholders, the market traders would have incurred a 23% cheaper total transportation cost than they do with the existing network of facilities. The simulations showed that after 55 years, the market traders in an optimal network will incur a 21% cheaper total transportation cost than they would in the existing network. An analysis of their performance in the goal programming network also shows that their total transportation cost will still be 23% cheaper than what they will incur in the existing network (Table 3). This poor performance of the existing network in comparison with the optimal and goal programming networks was consistent for the other stakeholders in the

Table 2
Transportation cost for farmers in existing, optimal and goal programming networks from 5 to 55 years.

YEAR	Existing Network (USD)	Optimal Network (USD)	Percentage Improvement	Goal Programming Optimal Network (USD)	Percentage Improvement
5	5.27E+07	3.53E+07	33%	4.06E+07	23%
10	3.18E+10	2.04E+10	36%	2.96E+10	7%
15	1.39E+10	1.04E+10	25%	1.25E+10	10%
20	7.95E+09	7.14E+09	10%	5.31E+09	33%
25	6.38E+09	6.25E+09	2%	5.78E+09	9%
30	6.16E+09	3.94E+09	36%	5.82E+09	5%
35	7.06E+09	6.84E+09	3%	6.29E+09	11%
40	9.39E+09	6.04E+09	36%	8.20E+09	13%
45	6.93E+09	2.78E+09	60%	6.59E+09	5%
50	7.48E+09	4.76E+09	36%	7.18E+09	4%
55	5.48E+09	5.14E+09	6%	4.85E+09	12%
Average	9.32E+09	6.70E+09	26%	8.37E+09	12%

Table 3
Initial percentage improvement in total transportation cost for stakeholders in the respective networks.

Stakeholder	Percentage improvement of Optimal network over Existing network of warehouses (%)	Percentage improvement of Goal programming network over existing network (%)
Market traders	55	23
Exporters/Importers at Airports	33	20
Exporters/Importers at Harbours	58	21

Table 4
Percentage improvement in total transportation cost of stakeholders after 55 years.

Stakeholder	Percentage improvement of Optimal network over Existing network of warehouses (%)	Percentage improvement of Goal programming network over existing network (%)
Market traders	67	21
Exporters/Importers at Airports	20	20
Exporters/Importers at Harbours	19	12

supply chain (Tables 3 and 4).

The apparent inefficiency (in terms of total transportation cost) of the existing network of grain storage facilities suggested by the simulations has several deleterious implications for society. Firstly, an inefficient network represents a monumental loss of capital for the governments and donor agencies that built them. Such a network also does nothing to curb the alarmingly high levels of postharvest losses found in the developing world. The high postharvest losses therefore perpetuate the poverty of the nationals of these countries as they can lose as much as 50% of their agricultural produce (McNeil, 2013). There are also food security implications as a significant quantum of the produce is lost postharvest. The environmental impact of the high food miles ensuing from such avoidable inefficiencies should encourage governments to use decision support systems to optimize the design of such vital networks (Kissinger, 2012; Pretty et al., 2005).

4. Conclusion

The simulation essentially showed that the existing network of grain storage facilities is not efficient for all the stakeholders in the supply chain. This partly explains why the facilities are not patronized by all the stakeholders thereby being left to deteriorate. This also reveals the inherent inefficiencies that come with the intuitive method of designing networks of grain storage facilities. The share quantum of possible solutions to select from makes it difficult to undertake such siting decision by human intuition. Decision makers in developing countries should therefore be encouraged to employ the use of decision support systems in their decision making. This decision support system also removes the obstacles that precluded the use of other DSS in developing countries. This proposed DSS uses data (grain production data, human population census and road distances) that are available in most developing countries. It also offers a relatively flatter learning curve as officials with low technical background can be proficient users after a short period of training. It is recommended that similar DSS be developed for other supply chain in developing countries to aid the provision of efficient agricultural systems.

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