THE COMPOSITE SUPPLY CHAIN EFFICIENCY MODEL

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ABSTRACT

In an effort to compete globally, South African supply chains must achieve and maintain a competitive advantage. One way of achieving this is by ensuring that South African supply chains are as efficient as possible. Consequently, steps must be taken to evaluate the efficiency levels of South African supply chains. This paper discusses the composite supply chain efficiency model using variables specifically identified as problem areas experienced by South African supply chains. The composite supply chain efficiency model evaluates the overall efficiency of a supply chain based on three criteria, namely, reliability efficiency, cost efficiency and speed efficiency. It identifies bottlenecks along the supply chain and in so doing identifies key focus areas for firms if they want to improve their overall efficiency and become more competitive.

Keywords: supply chains, efficiency, modelling, DEA

1. INTRODUCTION

South Africa is striving to become a major force in the global market; however, it is presently facing many obstacles. Poverty, a high level of unemployment, a lack of skills and an inefficient utilisation of infrastructure are all aspects that are hindering the country's growth. In addition, logistics was identified by the South African government in the Accelerated and Shared-Growth Initiative of South Africa (ASGISA) as being a potential hurdle that may limit future growth in the country (Ittmann 2007).

The growth and development of South Africa's economy and the resulting wellbeing of its people are closely linked to trade; with more than 95% of South Africa's trade volume taking place via sea transport (Chasomeris 2005). In order to be able to compete with global supply chains, existing maritime supply chains to and from South Africa must function efficiently and new efficient supply chains must be developed. Many export industries are dependent on imported inputs and the importance of efficient import supply chains cannot be over emphasised.

The efficiencies of the supply chains on which the trade of many of South Africa's competitors in world markets depend, have received concerted attention by industry and the governments in those countries. However, South Africa's government has only recently realized the importance of such a focus (Neill 2003).

The model presented in this paper proposes a set of guidelines that can assist South African industries in becoming internationally competitive by providing them with a tool for evaluating their levels of efficiency both as an individual firm and as a component in an overall supply chain. The model also helps them to identify the processes that need improvement to increase their overall supply chain efficiency.

2. EXISTING PRACTICES IN SOUTH AFRICA

Measuring supply chain efficiency in South Africa is hindered by a number of obstacles. Firstly, a large percentage of companies do not understand the importance of determining the levels of efficiency in their supply chains and therefore do not record any data that can be used in a model for measuring supply chain efficiency. Secondly, several supply chains in South Africa consist of both public and private sector participants. Therefore certain links and nodes are provided by the private sector, while the others are provided by the public sector. This complicates the process of measuring supply chain efficiency as the main goal of the private sector is to maximise profit, while the public sector generally takes social considerations into account, and it becomes more difficult to achieve efficiency as the overall goal. Thirdly, the models that are currently available to companies, for example, the SCOR model, are expensive and require extensive training to be able to use effectively and therefore exclude small firms with a limited budget. Finally, there is unwillingness in South Africa to share information between different companies along a supply chain, which makes accurate supply chain efficiency measurement more complex.

Further, South African supply chains cannot be viewed in isolation. For South African firms to be able to compete globally, they have to meet international standards. This can only be achieved if South African firms are aware of how they perform in comparison to international benchmarks.

3. MODEL

The model is broken into and is presented in four steps:

The first step involves the determining of factors that influence the overall level of efficiency in a South African supply chain. A detailed background study was conducted to investigate and build upon strengths, as well as to investigate any weaknesses identified by previous research on the topic. An analysis of existing practices in South African supply chains was undertaken and guidelines devised according to both local and international best practice. Qualitative research was conducted to understand and determine bottlenecks that are currently plaguing South African supply chains.

Factors that influence supply chain efficiency in South Africa, as identified through the study, are:

- The ratio of idle time to productive time
- Throughput, lead time and utilisation of the supply chain capacity
- Infrastructure availability and utilisation
- Low transport productivity
- Method of freight handling
- Interface arrangements
- Labour competency
- Communication throughout the supply chain
- Incidence of damage to goods and pilferage
- Imbalances in cargo flows
- Documentation required
- Customer co-operation

These factors can typically be categorised as either Supply Chain Efficiency Measures or Logistics Performance Measures. Parameters were chosen according to those factors that were considered as important in determining efficiency across a supply chain. The parameters are broken down into three broad categories, namely, speed, reliability and cost. This also includes determining whether these factors can be considered inputs or outputs (i.e. consumables or deliverables) of the supply chain. The list of factors from which the applicable factors that affect a specific supply chain can be selected or derived are given above. The factors selected by a specific supply chain for inclusion in the model can differ from supply chain to supply chain.

The second step involved taking a model orientated view of the supply chain by subdividing it into links and nodes. Information was collected about different performance measures that could be used to calculate the performance of each of the five links and nodes in terms of the three main parameters, and finally, measures were identified that could be used to calculate the influence that the factors identified above have on the overall efficiency of a supply chain. Generic links and nodes identified for this model are: Sources or Suppliers, Points of Production, Transportation links, Points of Storage and Transhipment and Markets or Customers.

The third step in the model involves the use of formulae to convert the factors that influence supply chain efficiency into measurements of efficiency within each link or node in the supply chain in terms of reliability efficiency, speed efficiency, and cost efficiency. These calculations will give a good indication of how the individual firms along the supply chain are performing.

The information gathered in step three is then carried forward to the final step where it is used to compare the reliability efficiency, speed efficiency and cost efficiency across the individual links or nodes in the supply chain with similar links or nodes of other supply chains using Data Envelopment Analysis (DEA) to determine the 'frontier' or most efficient supply chain (the frontier can consist of a combination of various different supply chains). Finally, each individual supply chain can be compared with the frontier in order to determine how efficient it is and where the bottlenecks occur. Figure1 shows a graphic representation of how the composite supply chain efficiency model was developed.

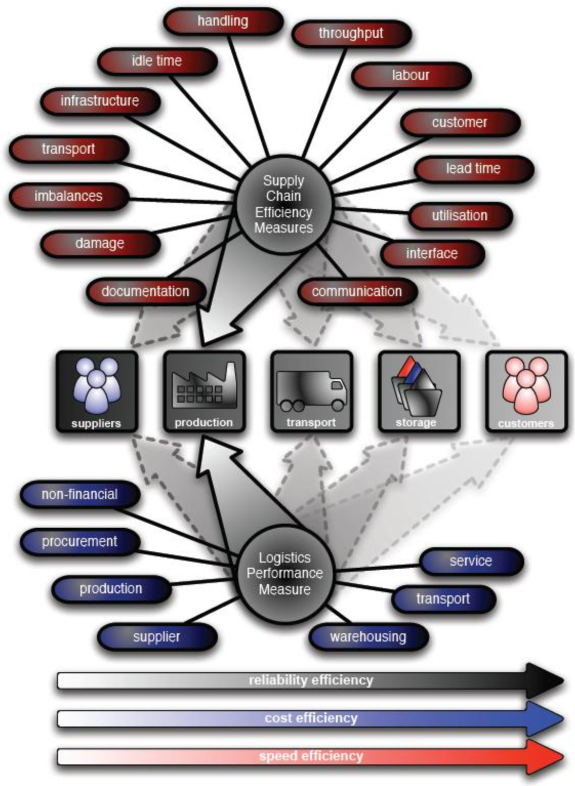

Figure 1: Graphic representation of the composite supply chain efficiency model

The generic nature of the model allows it to be used on a variety of different supply chains. If a firm finds that it wants to make changes to the input factors selected, by either including additional factors or removing some of the factors included. Depending on the focus of the supply chain under investigation, different variables can be used to calculate its efficiency. For example, for a supply chain carrying perishables products, speed is very important and therefore variables will be included to calculate the efficiency of the supply chain in terms of speed. However, for a supply chain carrying low valued bulk products speed is not important and can therefore be left out of the calculation.

It is also important to note that even though it may not be possible to compare supply chains that are exactly the same, as no two supply chains are exactly the same; benefits are still achieved by comparing supply chains with similar characteristics. For supply chains to be considered to have similar characteristics, it is important that they have three factors in common. Firstly, it is important that the supply chains have the same drivers, i.e. they must focus on the same focal points (in terms of this paper, they must arrange reliability efficiency, cost efficiency and speed efficiency in the same order of importance). Secondly, it is important that they have the same geographical context, i.e. they must all be either local supply chains or all international supply chains. Finally, the supply chains must handle goods with similar commodity characteristics, i.e. they all handle perishable products or they all handle dry bulk goods.

4. MODEL CONSTRUCTION

The mathematical technique chosen for the fourth step of the model is Data Envelopment Analysis. DEA is a mathematical programming technique that calculates the relative efficiencies of multiple DMUs based on multiple inputs and outputs (Wong and Wong 2007). DEA has been proven in various forms of academic literature as a suitable mathematical method for measuring efficiency (Seiford 1994; Bell and Morey 1995; Talluri and Sarkis 2001; Wong and Wong 2007; Wong and Wong 2008). DEA measures the relative efficiency of each DMU in comparison with all other DMUs and therefore has the ability to determine the effect that the DMU has on the overall efficiency of the supply chain under investigation. An efficiency score of a DMU is generally defined as the weighted sum of outputs divided by the weighted sum of inputs, while weights need to be assigned. The DEA model computes weights that give the highest possible relative efficiency score to a DMU while keeping the efficiency scores of all DMUs less or equal to 1 under the same set of weights (Wong and Wong 2007).

Since DEA is a form of linear programming, it follows that one of the simplest ways of solving the problem is by writing it in its canonical form.

$$Maximise\ \ z = \sum_{r=1}^{s} u_r y_{rj_0}$$

Subject to: (1)

$$\sum_{i=1}^{m} v_i x_{ij_0} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0, \quad j = 1,2,...,n$$

$$u_r \ge \varepsilon, \ \ r = 1,2,...,s \quad v_i \ge \varepsilon, \ i = 1,2,...,m$$

In linear programming (LP) it is possible for DEA to formulate a partner linear program or LP using the same data, and the solution to either the original LP (the primal) or the partner (the dual) provides the same information about the problem being modelled. The dual model is constructed by assigning a variable (dual variable) to each constraint in the primal model and constructing a new model based on these variables (Emrouznejad 2001).

The main reason for using a dual to solve a DEA model is that the primal model has n + s + m + 1 constraints whilst the dual model has s + m constraints. As n, the number of units, is usually considerably larger than s + m, the number of inputs and outputs, it can be seen that the primal model will have many more constraints than the dual model (Emrouznejad 2001). For linear programs in general, the more constraints there are, the more difficult it is to solve the problem. The dual for equation (1) can be given as follows:

$$\theta^* = Minimise\ \theta$$

Subject to: (2)

$$\sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{ij_o} \qquad i = 1,2,...,m;$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{rj_o} \qquad r = 1,2,...,s;$$

$$\lambda_j \ge 0 \qquad j = 1,2,...,n.$$

By virtue of the dual theorem of linear programming $z^* = \theta^*$. Therefore either equation (1) or equation (2) can be used to calculate the solution. The optimal solution, θ^*, yields an efficiency score for a particular DMU. The process can be repeated for each DMU_{jo}. DMUs for which $\theta^* < 1$ are inefficient, while DMUs for which $\theta^* = 1$ are boundary points.

Some boundary points may be “weakly efficient” because they include non-zero slacks. This may result in lower confidence levels in the solutions found as alternate optima may have non-zero slacks in some solutions, but not in others. Input slacks indicate the surplus number of inputs that are being utilised by DMU_{jo} and the output slacks represent the shortfalls in the outputs of DMU_{jo}. Therefore the slacks can be used by managers to identify bottlenecks in supply chains. This problem can be avoided by rewriting equation (2) to include the slacks which are taken to their maximal values. This equation can be written as follows:

$$Maximise = \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+$$

Subject to: (3)

$$\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta^* x_{ij_o} \qquad i = 1,2,...,m;$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{rj_o} \qquad r = 1,2,...,s;$$

$$\lambda_j, s_i^-, s_r^+ \geq 0 \quad \nabla i, j, r$$

where the choices of s_i^- and s_r^+ do not affect the optimal θ^* which is determined from equation (2).

According to the definition for DEA efficiency by Cooper, Seiford and Zhu (2004) the performance of DMU_{jo} is only fully (100%) efficient if and only if both (i) $\theta^*=1$ and (ii) all slacks $s_i^- = s_r^+ = 0$. The definition for weakly DEA efficient states that the performance of DMU_{jo} is weakly efficient if and only if both (i) $\theta^*=1$ and (ii) $s_i^- \neq 0$ and/or $s_r^+ \neq 0$ for some i and r in some alternate optima (Cooper, Seiford and Zhu 2004).

The variable θ gives the technical efficiency, which is what the model is trying to calculate and s_i^- and s_r^+ are the input and output slacks respectively. When DMU_{jo} is proven as either strongly or weakly DEA efficient then no further calculations are required. However, when DMU_{jo} is inefficient, appropriate adjustments (equations 4 and 5) can be applied to the inputs and outputs in order to make DMU_{jo} more efficient.

$$x'_{ij_o} = \theta^* x_{ij_o} - s_i^{-*}, \qquad i = 1,2,...,m \qquad (4)$$

$$y'_{rj_o} = y_{rj_o} + s_r^{+*}, \quad r = 1,2,...,s \qquad (5)$$

The dual model of the above formulation, which is also known as the envelopment model, has the ability to identify possible solutions to improve the efficiency of a DMU and in so doing highlights ways in which managers can make improvements to the supply chain. An additional convexity constraint $\sum_{j=1}^{n} \lambda_j = 1$, can be added to equation (3) to yield a measure of the pure technical efficiency if the constant return-to-scale (Banker et al. 1984) assumption does not apply. The above model (equation (3)) is used to calculate the technical efficiency of a supply chain and can therefore be referred to as the technical efficiency model.

The next step in developing a model to measure supply chain efficiency across an entire supply chain is to minimize costs along the supply chain without reducing the level of outputs achieved. This can be calculated by the cost efficiency model shown below:

$$Minimise \sum_{i=1}^{m} c_{ij_o} x_i$$

Subject to: (6)

$$x_i \geq \sum_{j=1}^{n} x_{ij} \lambda_j \qquad i = 1,2,...,m$$

$$y_{rj_o} \leq \sum_{j=1}^{n} y_{rj} \lambda_j \qquad r = 1,2,...,s$$

where c_{ijo} is the unit cost of the input i of DMU_{jo} which may vary from one DMU to another. The total cost efficiency (CE) of the DMU_{jo} would be calculated as:

$$CE = \frac{c'_{ij_o} x'_{ij_o}}{c'_{ij_o} x_{ij_o}} \qquad (7)$$

Equation 7 above can be described as the ratio of minimum cost to the observed cost. It is then possible to calculate the allocative efficiency (AE) by dividing the cost efficiency by the technical efficiency (TE) as shown in equation 8 below.

$$AE = \frac{CE}{TE} \qquad (8)$$

The AE measure includes slacks which reflect an inappropriate input mix (Ferrier and Lovell 1990). This information together with the opportunity cost calculated provides important information regarding the technical and cost efficiency along a supply chain. This information can be helpful to managers as it provides them with reliable criteria on which to base their decisions for allocating resources and it helps to identify ways of ensuring that the supply chain adjusts to the changing needs of the customers.

5. MODEL VERIFICATION AND VALIDATION

The first three steps of this model are verified and validated by the fact that they can be replaced by the well-respected Balanced Scorecard method. The Balanced Scorecard method is implemented by many firms around the world. Data measured by either the first three steps of this model or the Balanced Scorecard method will give similar results.

DEA is suitable to be used as a tool for measuring supply chain efficiency because it can handle multiple inputs and outputs and it does not require unrealistic assumptions on the variables which are inherent in typical supply chain optimisation models (Wong and Wong 2007). Various sources of literature substantiate the use of DEA in measuring efficiency (Seiford 1994; Bell and Morey 1995; Talluri and Sarkis 2001).

According to the literature and experts in the field, DEA is mainly used for two different evaluation purposes. First, it can be used to compare the performance of one firm or one department with another, given the major assumptions that all firms or departments have similar strategic goals and directions (Wong and Wong 2008). Second, DEA can be used to compare the efficiency of a department or firm with historical data in order to see how it has performed over time.

DEA has the ability to compare variables with various different units and provide meaningful results. When DEA is used to compare different supply chains, i.e. competing supply chains with similar characteristics, the results obtained represent the leading supply chain as well as how the other supply chains compare (the leading supply chain is not necessarily an actual working supply chain. It can be made up of a combination of links or nodes from different supply chains). When DEA is used to compare one supply chain over time, i.e. with historical data, it indicates how the supply chain has improved or deteriorated over time.

6. ADVANTAGES OF THE MODEL

The advantages of the model include the fact that it is a generic model for measuring supply chain efficiency. It defines a framework that helps with the identification of the major links or nodes of a typical South African supply chain. The supply chain efficiency results generated by the model can be used to identify weaknesses/bottlenecks in South African supply chains. The results can also be used for the analysis of the causes of the weaknesses/bottlenecks.

An additional advantage of the method applied to this model is that it has the ability to compare individual nodes both separately and as part of an entire supply chain, i.e. a firm that wants to know how it compares to similar firms will be able to use the model as well as a firm that is looking to determine which is the most efficient supply chain.

7. EXAMPLE

The composite supply chain efficiency model was applied to the iron ore supply chain from Sishen to Saldanha to validate the robustness of the model.

The example used is an input-oriented model with variable returns to scale. It is developed as an input-oriented model, because the efficiency of the supply chain must be measured to determine whether it is achieving the current level of outputs given the minimum level of inputs. If it is possible to decrease the inputs while retaining the required level of outputs then it is operating inefficiently. Mines operate according to demand. Therefore, as the demand from customers increases, mines strive to increase their extraction. However, when demand remains unchanged, mines improve their efficiency levels by reducing the resources required to meet the output. Variable returns to scale is the best option to use, because various links and nodes in the supply chain may exhibit increasing, constant and decreasing returns to scale.

A variable in the model is classified as an input if it is a ratio used to measure resources placed into the link or node or used in its operation to achieve an output or a result. A variable in the model is classified as an output if it is a ratio used to measure the work done by the link or node. The variables used in the model were divided into categories according to the appropriate link or node. They were then further divided into subcategories to measure the efficiency of the link or node in terms of reliability efficiency, cost efficiency and speed efficiency. All variables that were classified as being either utilised in the working of the supply chain or as having an impact on the working of the supply chain were classified as inputs, while all variables that were classified as a consequence of the supply chain were classified as outputs.

7.1. Supply Chain Efficiency Measurement Software

A software tool was developed by Gerber (2009) to reduce the effort required to handle the creation and solving of the LP problem and the organising of the DEA results that are required to implement DEA. The sum of the number of variables and the number of constraints are typically the sum of the number of DMUs and the number of measurements per DMU. For this model it is more than 120, which is extremely cumbersome and error prone if done by hand.

The software makes use of standard file formats so that programs like Microsoft Excel can be used to input the data for the model analysis. Results of the analysis are also written to a standard file format so that further analysis of the results can be done in a program like Excel. The tool can also be used to determine the maximum value for the lower bound of the variable weights, giving the highest possible distinction between efficient and inefficient DMUs.

7.2. Analysis of Results

The study showed that the average efficiency of the rail leg was 97.34%, while the average efficiency of the mine and the port were 97% and 95.44% respectively. All three links or nodes performed well, which corresponds to the fact that the iron ore supply chain is one of the most efficient, if not the most efficient, supply chain in South Africa.

According to the study, the three areas on which the mine needs to focus in order to improve efficiency are system uptime (in terms of reliability efficiency), utilisation (in terms of reliability efficiency) and communication (in terms of cost efficiency). The three areas of importance for the rail operator are communication (in terms of cost efficiency), throughput efficiency (in terms of reliability efficiency) and cost per ton of iron ore transported (in terms of cost efficiency). The port needs to focus on infrastructure (in terms of cost efficiency), communication (in terms of reliability efficiency) and labour (in terms of cost efficiency). The results obtained from the composite supply chain efficiency model were compared to results obtained by an independent company who used the

Balanced Scorecard method to measure the efficiency of the Sishen-Saldanha supply chain. Similar results were obtained by both studies.

An additional factor to highlight is the fact that the supply chain was only compared with itself through the use of historical data. It would be interesting to be able to compare the Sishen-Saldanha supply chain with the Pilbara iron ore supply chain in Australia.

8. VALIDITY AND RELIABILITY

The reliability of the composite supply chain efficiency model was tested by test-retest reliability and alternative-form reliability. The test-retest realiability estimates were obtained by using the composite supply chain efficiency model to analyse the same set of data more than once and to analyse another set of generated data. Similar results were obtained from each evaluation, thus proving test-retest reliability. Alternative-form reliability was tested by comparing the results obtained by the composite supply chain efficiency model when run through the program written by Gerber (2009) with results obtained when it was run through the well-known computer program DEA-P (2003) as well as a program written for Excel by Naude (2009). Similar results were obtained in all three cases, thus proving alternative-form reliability.

The validity of the composite supply chain efficiency model was tested by content validity and concurrent validity. The content validity of the composite supply chain efficiency model was proven, because the variables included in the model were chosen based on a literature review as well as interviews that were conducted with business executives who work with supply chains on a daily basis and who are aware of the main problems that are being faced by South African supply chains. Concurrent validity of the composite supply chain efficiency model was proven when feedback was given to the firms that were involved in the case study and they agreed with the results that were obtained.

9. CONCLUSIONS

The composite supply chain efficiency model is a simple to use, systematic and inexpensive and can therefore be utilized by small firms with a limited budget. Its generic nature means that it can be used to measure supply chain efficiency across various different types of supply chains. It can either be used to compare different supply chains or it can be used to compare the same supply chain over time to determine whether any improvements have been made. It can be applied to South African supply chains handling a wide variety of products that are either local or export oriented, to determine whether they are operating efficiently or not. The results obtained from the composite supply chain efficiency model are easy to understand and can therefore help firms and entire supply chains identify areas to focus on to improve their overall levels of efficiency and in so doing make them more competitive.

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