# The Measurement of Supply Chain Efficiency: Theoretical Considerations and Practical Criteria

by

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# DECLARATION

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: .......................................
L.L. Goedhals-Gerber

Date: ...........................................

# Dedication

*To the three men, who at various stages of my life acted selflessly for my benefit, and in so doing enabled me to achieve something that at one stage seemed impossible - my father, my brother and my husband, your love and kindness will never be forgotten - thank you.*

# ABSTRACT

## The Measurement of Supply Chain Efficiency: Theoretical Considerations and Practical Criteria

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 dissertation develops 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.

# UITTREKSEL

### The Measurement of Supply Chain Efficiency: Theoretical Considerations and Practical Criteria

In 'n poging om wêreldwyd te kompeteer, moet Suid-Afrikaanse voorsieningskettings 'n mededingende voordeel behaal en handhaaf. Een manier om dit te bereik is om te verseker dat Suid-Afrikaanse voorsieningskettings so doeltreffend as moontlik funksioneer. Gevolglik moet stappe gedoen word om die doeltreffendheidsvlakke van die Suid-Afrikaanse voorsieningskettings te evalueer. Hierdie proefskrif het die saamgestelde voorsieningsketting doeltreffendheidsmodel ontwikkel wat veranderlikes gebruik wat spesifiek geïdentifiseer is as probleemgebiede in Suid-Afrikaanse voorsieningskettings. Die saamgestelde voorsieningsketting doeltreffendheidsmodel evalueer die algehele doeltreffendheid van 'n voorsieningsketting gebaseer op drie kriteria, naamlik, betroubaarheidsdoeltreffendheid, koste-doeltreffendheid en spoed-doeltreffendheid. Dit identifiseer knelpunte in die voorsieningsketting en identifiseer belangrike fokusareas vir ondernemings wat aangespreek moet word as hul algehele doeltreffendheid wil verbeter en meer mededingend raak.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AE | Allocative Efficiency |
| ASGISA | Accelerated and Shared-Growth Initiative of South Africa |
| BCC | Banker, Charnes, Cooper |
| BP | Best Practice |
| BSC | Balanced Scorecard |
| CBR | Case Based Reasoning |
| CCR | Charnes, Cooper, Rhodes |
| CE | Cost Efficiency |
| CRS | Constant Returns to Scale |
| D&PL | Delta and Pine Land Company |
| DEA | Data Envelopment Analysis |
| DMU | Decision Making Unit |
| DRS | Decreasing Returns to Scale |
| EOQ | Economic Order Quantity |
| FCL | Full Container Loads |

| | |
|---|---|
| FMCG | Fast Moving Consumer Goods |
| GDP | Gross Domestic Product |
| GFB | General Freight Business |
| IVR | Interactive Voice Response |
| LCL | Less-than-full Container Loads |
| LP | Linear Programming |
| MACE-SCM | Multi-Agent Collaboration Engine for Supply Chain Management |
| MSA | Moving South Africa |
| NPA | National Ports Authority |
| PMG | Performance Measurement Group |
| RO-RO | Roll-On-Roll-Off |
| SACD | South African Container Depots |
| SAPO | South African Port Operations |
| SCM | Supply chain management |
| SCOR | Supply Chain Operations Reference |
| SKU | Stock Keeping Unit |
| SMME | Small, Medium and Micro Enterprises |
| TE | Technical Efficiency |
| TEU | Twenty-foot Equivalent Unit |
| TNPA | Transnet National Ports Authority |
| TPT | Transnet Port Terminals |
| VRS | Variable Returns to Scale |

# CHAPTER 1

# Introduction

## 1.1 Background

Since the nineteen eighties, economic cycles, technological developments and market forces have led both private institutions and public entities to examine and adapt their supply chain strategies. Trade liberalisation has raised the levels of competition, not only in the world markets for goods, but also in the markets for services. Some of these forces include the globalisation of businesses, an increase in product variety, increasing complexity of supply networks, and the shortening of product life-cycles. It has therefore had an impact on international transport services and global supply chains. To stay competitive, proactive companies have striven to achieve greater coordination and collaboration among supply chain partners in an approach called “supply chain integration”.

### 1.1.1 A Brief Description of a Supply Chain

A supply chain is a term that is given to the alignment of firms that bring products (i.e. finished goods and services) to markets (Grant et al., 2006). Supply chains are made up of suppliers, purchasing, materials management, production, inventory management, physical distribution, marketing and sales, customers and the final consumers and can be defined as “the total sequence of business processes, within a single or multiple enterprise environments that enable customer demand for a product or service to be satisfied” (Logistics Bureau, 2007).

Supply chains are fundamental to international trade in order to move raw materials, intermediate and finished products efficiently from origin to destination and so enable firms to compete successfully (Shister, 2005). Bottlenecks in supply chains prevent the seamless movement of products and reduce the comparative advantage of traders, while efficient throughput enhances that advantage.

In order to improve their market shares, firms need to create a competitive advantage, and when doing so through supply chain efficiency, the question arises whether all functions should be provided by a single organisation or whether each function should be provided by a specialist firm that focuses on maximising their own individual efficiency. One argument is that the separation of supply chain activities among different companies enables specialization and economies of scale (Trkman et al., 2005); while another argument is that when a supply chain consists of more than one organization the firms often tend to optimise their own performance, disregarding the effect on the entire supply chain. The problem involved becomes more complicated when the participants in the supply chain pursue individual profits or objectives that differ from the overall objective of the supply chain. For example, in South Africa, several supply chains include links and nodes provided by the private sector, while the others are provided by the public sector. 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. From a value chain perspective the effectiveness of a supply chain can be expressed in terms of “the degree to which the desired level of service is provided to meet stated goals and objectives” (Pienaar, 2009a), while efficiency is defined as “a measure of the way that the allocation of resources maximises outputs with the given inputs and technology” (Pienaar, 2009a). For the purpose of this research, the model developed will focus on maximising efficiency.

An examination of the arguments shows that the viewpoints merely reflect different priorities. The main issue is that link providers need to take the efficiency of the entire chain into account rather than that of individual elements. Supply chain managers that operate an integrated chain for a single purpose have an advantage over managers of chains that contain links operated for individual gain, but might lose that advantage if the efficiency of the individual links, whether for individual gain or not, contribute to a superior efficiency for the entire chain.

### 1.1.2 The Historical Development of Supply Chain Management

During the 1960s and 1970s, firms around the world adopted physical distribution or outbound logistics as the approach of choice in order to achieve or maintain a competitive advantage. Physical distribution focused on a set of interrelated activities that included transportation, distribution, warehousing, inventory levels, packaging and materials handling to ensure the efficient delivery of finished goods to customers (Langley et al., 2008).

Towards the end of the 1970s and during the 1980s, firms began to realise that further benefits could be achieved if they took both inbound (materials management) and outbound logistics into consideration. The combination of the two focus areas was labelled as business logistics. Business logistics provided firms with the opportunity of planning their operations from the procurement of the raw materials up until the delivery of the final goods to the consumer.

During the 1980s and 1990s, firms identified that they could achieve even greater advantages than previously enjoyed by expanding their logistics processes to include all the firms along the supply chain. This concept became known as supply chain management. Supply chain management is an approach to analysing and/or managing logistics networks (Langley et al., 2008). The ultimate objective is to improve a firm's competitive position in the global market place and to maintain that position in spite of intensive customer forces and rapidly changing customer needs. The firms who understand the true effect that logistics can have on supply chain management take advantage of all opportunities to implement the correct improvements in their structures and strategies.

Supply chain management is defined by The Global Supply Chain Forum (2009) as "the integration of key business processes from original supplier through to end user, to provide (physical[1]) products, services and information that add value for customers and other stakeholders".

### 1.1.3 South African Supply Chains

South Africa's freight transport operators are divided into various different role-players. Transnet Freight Rail is South Africa's only rail freight transport provider. It is a division of Transnet Ltd, for which the South African Government holds one hundred percent of the shares. Transnet Pipelines is also a division of Transnet Ltd. Transnet Pipelines is the custodian of the country's strategic pipeline assets and is responsible for transporting petroleum and gas products via pipeline across

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[1] added by author.

South Africa. Road transport is provided by numerous different operators since the deregulation of freight movements by road, whilst the ports are managed by Transnet National Ports Authority and are operated by a combination of Transnet Port Terminals and private terminal operators.

Transnet, as the holding company of rail, port and pipeline undertakings, is responsible for ensuring that those transport industries operate to world-class standards (Transnet website, 2009). However, because it is a State-owned company, Transnet finds itself wrestling with social and economic issues i.e. maximising efficiency through necessary job cuts in the face of union opposition.

Transnet Freight Rail has lost a large percentage of its market share in terms of break-bulk and containerised goods to road carriers since the deregulation of road transport. Due to a number of logistical inadequacies and political perspectives, Transnet Freight Rail has been forced to cut back on capital spending during recent years. As a result, the quality of the rail infrastructure, rolling stock and services on some rail lines does not meet the requirements for efficient supply chains. However, the operation of the rail services carrying large quantities of bulk commodities from mines to the ports are world renowned. Transnet is currently investigating ways to correct the shortcomings of rail transport in South Africa (Transnet, 2006).

After careful investigation into the possibility of selling off state-owned transport services, it was decided that it would be in South Africa's best interests to keep the core assets under the government's control and rather enter into public-private participation agreements for the supply of railway and port services (Erwin, 2005). Areas of importance that have been identified as vital to the efficient operating of a supply chain in South Africa are improvements to asset utilisation, network configurations, cost and revenue management, logistics management, communication systems and documentation flow (Anonymous, 2003). The objective is for improvements in these areas to assist in achieving the seamless movement of cargo along entire supply chains. According to Pojie & Davids (2002) the more proactive steps that are being considered are the integration of the management of the role-players along the supply chain, and the development of better information systems, with greater accessibility to information for all participants. Ramchand (2007) supports the argument and states that in order for South African supply chains to be competitive globally it is important that all links and nodes along a supply chain must share information with one another and the infrastructure and equipment used by the various links and nodes must be rendered more functional and be well maintained (Anonymous, 2003).

### 1.1.4 An International Perspective

One of the most important trends in global transportation is that many countries have been liberalising and deregulating various aspects of their transport systems (Department of Public Enterprises, 2000). This has particularly been the case with ports, which in many countries has resulted in port operations being separated from landlord functions (South Africa followed this trend in May 2001 by splitting Portnet into the National Ports Authority (NPA), now known as Transnet National Ports Authority (TNPA), and South African Port Operations (SAPO), now known as Transnet Port Terminals (TPT)). The global trend is furthermore to privatise and/or commercialise parastatal transport operations. Japan and New Zealand, for example, have both completely privatised their rail systems (Department of Public Enterprises, 2000). Such liberalisation has also started in rail transport in Europe and the United Kingdom, where a portion of the rail systems have been privatised. In other countries, for example, Argentina, there has been concessioning (Department of Transport, 1998).

The maritime industry differs considerably from the other modes of transport. Global shipping lines are privately owned and operated, and there has been increasing competition in maritime transport. In addition, liner shipping companies are horizontally and vertically integrating with other modal partners, which has resulted in the rise of intermodal shipping. The rise in intermodal shipping and the increased integration of the modes has resulted in larger ships that require deeper ports and fewer ports of call. That has led to economies of scale and a reduction in sea freight rates (Department of Public Enterprises, 2000).

Transport operators tend to consolidate globally through alliances, joint ventures or outright acquisition (Department of Public Enterprises, 2000). In addition to the increased integration between modes, there has been a shift towards integration within the value chain. This is partially to reduce costs and gain market share, but, more importantly, to meet the needs of global customers (Department of Public Enterprises, 2000).

Globally, manufacturers have improved their supply chains by moving towards just-in-time manufacturing processes and the reduction of inventory costs. Sophisticated information technology and logistics add value to the supply chains and enable global manufacturers to obtain their production from multiple sources around the world. International market leaders utilise high-precision, flexible, integrated transport services and logistics that deliver to multiple global locations.

### 1.1.5 Measuring Supply Chain Efficiency

Firms strive to be as competitive as possible, so that they can maximise the number of goods and services that they provide. In so doing, they try to operate as efficiently as possible. However, it is very difficult for a firm to determine whether or not they are operating efficiently without evaluating their performance. One way for firms to evaluate their efficiency levels is to measure them with the help of a quantitative model.

By measuring its actual efficiency levels, a firm has a better idea of how it is performing based on certain criteria. It highlights the areas of weakness in the firm and therefore makes it easier for the firm to make the changes necessary to improve their overall efficiency levels.

The same basic concept can be used for a supply chain. However, for a supply chain it is important that the role players take the efficiency of the entire supply chain into consideration when determining the efficiency levels. On a supply chain level it is also possible for firms to identify bottlenecks that can be worked on in order to improve the overall efficiency of the supply chain.

## 1.2 Motivation for the Study

South Africa is striving to become a major force in the global market; however, it is presently facing many obstacles. Poverty (Everatt, 2004), a high level of unemployment, a lack of skills (SouthAfrica.info, 2006) 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, 2007a).

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); it is important that South Africa's international supply chains are competitive. In order to be able to compete with global supply chains, existing maritime supply chains [2] to and from South Africa must function efficiently and new efficient supply chains must be developed. South Africa's economy benefits directly from foreign revenue that enters the country through goods and services that are sold to other countries and therefore it is clear that steps must be taken to

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[2] for the purpose of this dissertation a maritime supply chain represents a supply chain that includes a deep-sea leg.

improve the efficiency of export supply chains. Many export industries are dependent on imported inputs and the importance of efficient import supply chains cannot be over emphasised.

Although 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 government in those countries, South Africa's government has only recently realised the importance of such a focus (Neill, 2003).

The motivation behind this dissertation is to develop a theory for measuring supply chain efficiency in order to determine the optimal output of specific supply chains in South Africa and through that knowledge, assist South African producers and transport operators to improve the performance of supply chains and so grow the economy. By raising supply chain efficiency, public entities and private corporations will enable the landed costs of products imported to and exported from South Africa to be reduced.

This dissertation investigates both qualitative and quantitative ways to assist companies in achieving optimal supply chain efficiency. Business logistics chains or product supply chain management require coordination and functional integration of the elements or activities in the chain. That implies collaboration, i.e. all links and nodes along the supply chain need to be planned to function for the common purpose of achieving the efficiency of the entire chain.

## 1.3 Objectives of the Study

The main objective of this study is to propose a guideline 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.

## 1.4 Layout of Contents

Chapter 2 explains the methodology used in the dissertation. It describes how the research was conducted and how the conclusions and recommendations were drawn up.

Chapter 3 provides a literature review of relevant research. It defines the important terms that are used throughout the study and in so doing identifies the assumptions adopted.

Chapter 4 introduces basic measures that are used to measure performance at every stage along a supply chain. Advanced models that have been used to measure supply chain efficiency are identified and benchmarking is defined as well as the role it fulfils in determining the overall level of efficiency in a supply chain.

Chapter 5 deals with factors that influence efficiency levels in South African supply chains. It contains a brief discussion of each of the factors as well as a formula for measuring the effect of the factor on a supply chain.

Chapter 6 provides a model-orientated view of a generic South African supply chain by breaking a supply chain down into five main links or nodes. By doing this, it provides the building blocks with which the mathematical model is built.

Chapter 7 explains the construction of the mathematical model and analyses. It utilises the information that has been collected to develop a model that can measure the overall efficiency of a supply chain.

Chapter 8 provides a practical application to the generic model.

Chapter 9 contains the conclusions and recommendations on how to improve the efficiency along a supply chain.

In this dissertation, a method for measuring supply chain efficiency is developed taking into account *inter alia* the different factors (internal and external) that influence supply chain efficiency, the different methods of measuring supply chain efficiency, the methods applied historically, as well as the productivity and utilisation measures explained in Chapter 3.

# CHAPTER 2

# Methodology

## 2.1 Introduction

A methodical approach was undertaken for the study. The study was divided into different stages, the first of which involved a literature review on relevant topics to determine the amount of research already completed on the subject. This background study was used as a starting point for the research to build upon any strength that has already been identified in literature as well as to investigate any weaknesses in the existing research in more detail. Next questionnaires were conducted to understand and determine bottlenecks that are currently plaguing South African supply chains. Finally, a mathematical model was built to measure efficiency across entire supply chains. The model also has the ability to pinpoint where the problem areas along the supply chain are found.

## 2.2 Methodology

An analysis of existing practices in South African supply chains has been undertaken and guidelines devised according to both local and international best practice. All the information is used to formulate a mathematical model for measuring supply chain efficiency. South African companies will be able to use this model as an instrument for identifying whether or not their supply chains are operating efficiently and to pinpoint those processes that need improvement.

The study includes a literature review via the Internet, publications and questionnaires in order to:

- Determine the research undertaken
- Analyse the traditional and innovative models that are presently being used
- Determine what the present measurement tools are and any envisaged changes
- Obtain independent views on the usefulness of the present modelling systems
- Obtain independent views on the efficiency of South African supply chains
- Devise a generic model for measuring supply chain efficiencies

The study also analyses previous studies of major South African supply chains undertaken and adds to their results, to the extent that further analysis is feasible. It also:

- Identifies the major categories of links or nodes in supply chains
- Identifies weaknesses/bottlenecks in the supply chains
- Provides an analysis of the causes of the weaknesses

Although literature is a helpful source of information, it needs to be considered in conjunction with practical experience and application. Consequently, questionnaires were sent to experts in the field to determine various concerns that exist along South African supply chains and to develop a better understanding of the workings of South African supply chains. Participants were identified by dividing South Africa's supply chains into different categories according to product characteristics, i.e. bulk commodities, containerised goods, fast moving consumer goods, the textile industry, the motor vehicle industry and perishable products and firms from each category were contacted and asked questions about the factors that affect them (a copy of the questionnaire can be found in Appendix A. Factors that influence supply chain efficiency in South Africa, as identified through the questionnaires, 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

After the factors that affect the efficiency levels of South African supply chains were identified a second questionnaire was drawn up and firms were asked (either via telephone or e-mail) to provide data for the evaluation phase of the study. Firms were sent a questionnaire via e-mail. E-mail was chosen as the format for conducting the questionnaire, because it can reach a large sample of firms across the country all at the same time. In addition, it is an inexpensive way of conducting interviews, but still gets the results required. A copy of the questionnaire can be found in Appendix B. Participants were given a month to complete the questionnaire, after which a second e-mail was sent as a reminder. Participants who still did not complete the questionnaire after the second e-mail was sent (another month was given to complete the questionnaire) were either visited in person (if they were close enough for the author to meet with them) or contacted via telephone.

Although the firms had agreed to take part in the study, once they received the questionnaires and realised the kind of information that was required to complete them, problems ensued. Firstly, many of the firms that were approached were not willing to share the type of information that was requested by the author as they considered it confidential and were concerned that if they released the information it could be used to develop a competitive advantage over the firm. Secondly, many of the firms that were approached were not aware of the importance of evaluating the firm through mathematical formulae and therefore did not record the data necessary to answer the questions. Thirdly, the questionnaires required a substantial amount of information and were therefore relatively time consuming to complete. Participants found this problematic and some simply chose to ignore the request.

Due to the problems encountered whilst conducting data gathering, historical data was only collected from one supply chain, i.e. the Sishen-Saldanha iron ore supply chain. Six years of historical data was collected from the mine, eight years of historical data was collected from the rail transport operator and nine years of historical data was collected from the port. The amount of data collected was insufficient to obtain meaningful results, because for the method used in the mathematical model the number of input and output variables needs to be less than half of the number of decision making units (DMUs) (in this dissertation a DMU represents one year for either the mine, rail transport operator or port). In order to make the model as inclusive as possible, fourteen input variables and four output variables (eighteen variables in total) were used. This meant that in order for the model to provide significant results at least thirty six years of historical data was required from each link or node in the supply chain. Due to the fact that the example used in this dissertation is for explanatory purposes only, data was generated from the original, real data sets using two different recognised statistical methods.

For the first method that was tried, under the advice of Nel (2008) the data collected for each DMU was studied carefully and the probability distribution[1] of each individual input or output was found using the Palisade Decision Tools (2004) software package. For example, with the mine, the data collected per efficiency measurement over the six years, i.e. measurements for each of the six DMUs, was put into the Palisade Decision Tools (2004) software and a distribution was calculated. Figure 2.1 shows a graphical representation of the distribution of the throughput efficiency of the mine in terms of time.

After the distribution was found, the Palisade Decision Tools (2004) software package was used to generate data with the same distribution, so that it could be compared with the original set of data. The distributions differed for the various input or output variables. One example of the type of distrubution that was found was the BetaGeneral distribution.

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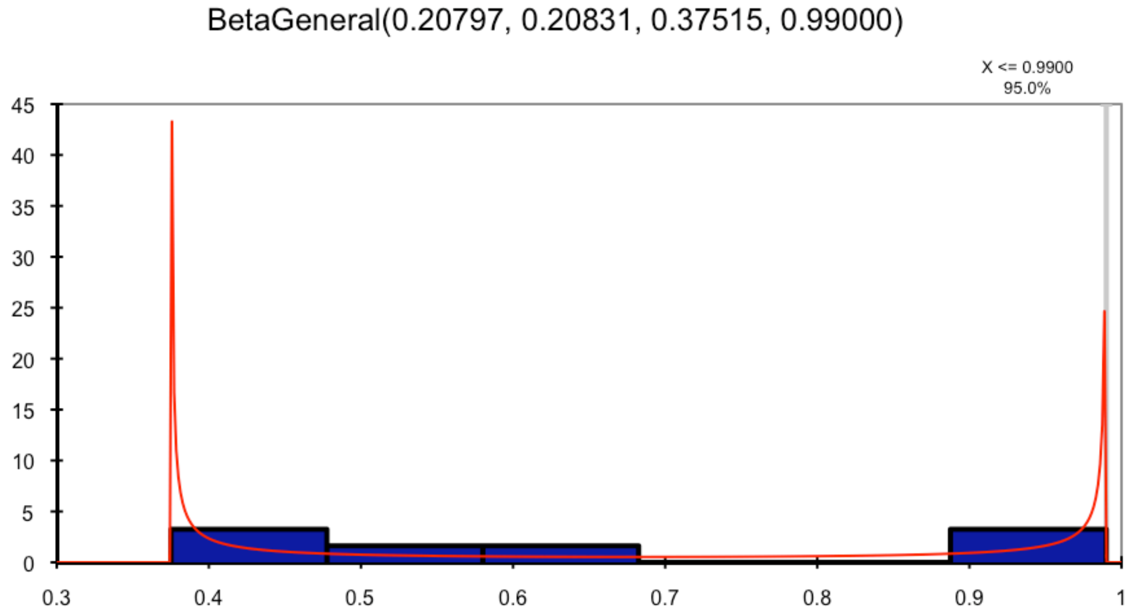
[1] In probability theory and statistics, a probability distribution identifies either the probability of each value of an unidentified random variable (when the variable is discrete), or the probability of the value falling within a particular interval (when the variable is continuous). The probability distribution describes the range of possible values that a random variable can attain and the probability that the value of the random variable is within any (measurable) subset of that range and (Everitt, 2006).

**Figure 2.1:** Distribution of the throughput efficiency of the mine in terms of time



The general formula for the probability density function of the beta distribution is

$$f(x) = \frac{(x-a)^{p-1}(b-x)^{q-1}}{B(p,q)(b-a)^{p+q-1}} \quad a \leq x \leq b; p, q > 0$$

where $p$ and $q$ are the shape parameters, $a$ and $b$ are the lower and upper bounds, respectively, of the distribution. $B(p,q)$ is the beta function. The beta function has the formula

$$B(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}dt,$$

The case where a = 0 and b = 1 is called the **standard beta distribution**. The equation for the standard beta distribution is

$$f(x) = \frac{x^{p-1}(1-x)^{q-1}}{B(p,q)} \quad 0 \leq x \leq 1; p, q > 0,$$

The general form of a distribution is usually defined in terms of location and scale parameters. However, the beta distribution is different in that the general distribution is defined in terms of the lower and upper bounds. The location and scale parameters can be defined in terms of the lower and upper limits as given below:

$$\begin{aligned} location &= a \\ scale &= b - a. \end{aligned}$$

Other distributions that were found included the Exponential, Logistic, Extreme Value and Triangle distributions.

In order to validate[2] the data that was generated, a second method was used to generate a completely seperate set of data. Consultation with Nel (2009) and Lamont (2009) identified the need to investigate the covariance[3] between the input and output variables. The method involved using the multivariate normal distribution to generate the random data. According to Lamont (2009), the model builder's decision regarding choice of attributes must be primarily based on the opinions of people operating in the relevant field. Whether or not correlation exists between inputs and outputs can be determined through knowledge obtained from practical experience. Statistical tests for correlation can be applied as a secondary decision tool. For instance, in case of doubt regarding the inclusion of an attribute, the Pearson-correlation test can be used to determine whether correlation exists between the attribute under evaluation and the rest of the identified data.

It is the opinion of the author that the inputs and outputs included in the model are correlated. Pearson-correlation tests conducted on the variables confirmed this assumption. According to Johnson & Wichern (2007), data that is proven to be both univariate normal and bivariate normal can be assumed to follow an approximate multivariate normal distribution. The data was therefore tested for univariate and bivariate normality using the Statistica (2008) statistical analysis program. Firstly, all the data was tested for univariate normality using Q-Q plots. The plots are a representation of the sample quantile versus the quantile one would expect to observe if the observations actually are normally distributed. When the points lie close to the straight line, it is possible to assume a normal distribution (Johnson & Wichern, 2007).

Secondly, the data was tested for bivariate normality. For data to meet the requirements of bivariate normality the contours of constant density would be ellipses, i.e. scatterplots drawn of the data should exhibit an overall pattern that is nearly elliptical (Johnson & Wichern, 2007). The statistical analysis of the data highlighted problems with a few variables that were originally included in the composite supply chain efficiency model for measuring the efficiency of the iron ore supply chain. These variables were imbalances in cargo flows in the rail leg, and the percentage of defective goods and the percentage of damages to goods for all three links or nodes. Careful consideration of the variables in question identified the reasons behind the problems. The Sishen-Saldanha railway line is a dedicated railway line that transports iron ore from Sishen to the Port of Saldanha. It is not required to carry any goods on its return leg and therefore imbalances in cargo can be left out of the evaluation of the rail leg. Due to the nature of iron ore, there is very little chance that the commodity can be damaged or defective,

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[2] Validity is defined as "the amount of systematic error in a measurement" Tull & Hawkins (1993)

[3] Covariance is defined as "a measure of the strength of the correlation between two or more sets of random variables"

so both measurements were left out of the evaluations of all three links or nodes. Once the three variables were removed from the evaluation, all the remaining variables met the requirements of both the univariate normal distribution as well as the bivariate normal distribution and could therefore be considered multivariate normal. Therefore for the purpose of the dissertation the multivariate normal distribution was used to generate the additional data required to test the model using the statistical program R 2.9.2 (2009). Although this is not the ideal situation, the purpose of the research is to develop a generic guideline for measuring supply chain efficiency and not to present a case study of an actual supply chain. Thus, because the data was generated using a recognised statistical method, it can be assumed that the data meets the necessary requirements for testing the authenticity of the model.

In the later stages of the model developed, Data Envelopment Analysis (DEA) is used. DEA measures the relative efficiency of each DMU in comparison with all other DMUs and therefore has the ability to determine the affect that the DMU has on the overall efficiency of the supply chain under investigation. DEA has been proven in various forms of academic literature as a suitable mathematical method for measuring efficiency. A more detailed description of DEA and how it works can be found in Chapter 4.

A software tool was developed by Gerber (2009) to reduce the effort required to handle the creation and solving of the linear programming problem and the organising of the DEA results that is 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.

Comparisons have been drawn and a model for measuring supply chain efficiency using DEA has been developed specifically for the circumstances prevailing in South Africa. DEA has been proven to be a reliable, flexible and efficient tool in measuring efficiency across a broad range of applications and is used in numerous publications (for a detailed literature review of DEA and its applications, interested readers can refer to Seiford (1994)).

The reliability of the composite supply chain efficiency model was tested by test-retest reliability and alternative-form reliability. Test-retest realiability is defined as "applying the same measure to the same objects a second time" (Tull & Hawkins, 1993). Alternative-form reliability is defined as "measuring the same objects by two instruments that are designed to be as nearly alike as possible" (Tull & Hawkins, 1993).

The validity of the composite supply chain efficiency model was tested by content validity and concurrent validity. Content validity is defined as "assessing the representativeness or the sampling adequacy of the items contained in the measuring instrument" (Tull & Hawkins, 1993). Concurrent validity is defined as "assesing the extent to which the obtained score may be used to estimate an individual's present standing with respect to some other variable" (Tull & Hawkins, 1993). The composite supply efficiency model was proven to meet all the requirements of test-rest reliability, alternative-form reliability, content validity and concurrent validity.

# CHAPTER 3

# Literature Review

## 3.1 Introduction

As a result of globalisation and the liberalisation of world trade, the sourcing of production factors and consumer products from destinations across the globe is increasing the reliance by manufacturers and traders on international chains of supply. The efficiency of those maritime supply chains has also become of critical importance for successful competition in the world markets that have emerged through the dismantling of trade protection (Fourie, 2006). Distribution competitiveness in physical trade with the rest of the world is now essential for economic growth.

This chapter gives a brief introduction on the evolution of supply chains and supply chain management. It provides definitions and describes the terms that are used throughout this dissertation. It also highlights the definition of each term used as a foundation for the calculations that follow.

## 3.2 A brief history

The terms “physical distribution”, “business logistics management” and “supply chain management” are often used interchangeably in academic and business literature although their meanings differ. In order to understand the true meaning of each term it is important to know where they originated and what they mean.

The physical distribution of goods started with the realisation by communities that they could improve their welfare by specialising in the products that they produced and trading produce not needed for their own consumption, in exchange for goods from elsewhere that would raise the quality of their existence. Although similar in concept, business logistics is not exactly the same. Business logistics systems allow world businesses to take advantage of the fact that countries and the people who occupy them are not equally productive and through efficient business logistics contributes to a higher economic standard of living across the globe.

Through the globalisation of world markets it has become vitally important to be able to move raw materials, semi-processed goods and manufactured goods seamlessly from origin to destination. Countries have realised that products supplied to their customers and consumers must be provided on an internationally competitive basis and therefore private companies and public entities are continually striving to find ways of outperforming their competitors in order to achieve or maintain a competitive advantage in the market.

As firms realise the importance of being able to prevent unnecessary costs in the movement of raw materials, semi-manufactured or manufactured goods as well as in the service industry, a new trend developed in the business world.

Private firms and public entities began to split the supply chain and its management into a separate, standalone function within their firms. Academics started to study the different facets of a supply chain in order to identify and develop ways of improving the supply chain and industries transformed the way they operated. As time went by, more and more knowledge was gained about supply chains and today, it is possible to find numerous different definitions for a supply chain in literature. The definitions range from short, simple definitions to longer, more complex definitions.

## 3.3 Definition of a Supply Chain

The development and functioning of supply chains have become topics for academic research with a consequent proliferation of definitions and acronyms. Definitions that have been examined for the purpose of this thesis are as follows:

According to Beamon (1998), a supply chain is *"an integrated manufacturing process wherein raw materials are converted into finished*[1] *products, then delivered to customers"*.

A supply chain is defined by tecc.com.au (2002) as *"a chain or progression beginning with raw materials and ending with the sale of the finished product"*.

Bridgefield Group (2006) defines a supply chain as *"a linked set of resources and processes that begins with the sourcing of raw materials and extends through the delivery of end items to the final customer"*.

Pienaar (2009b) defines a supply chain as *"a generic description of the process integration involving organisations to convert raw materials into finished products and to convey them to the end-user"*.

All the definitions given above focus on the core factors of a supply chain. They imply the need for an origin and a destination between which products flow and adopt the concept that supply chains start with raw materials, incorporate a number of value adding activities and end with the delivery of a finished product to a customer or consumer.

The following definitions are more complex. They encompass a broader view of a supply chain and incorporate additional activities in the function of the supply chain.

Little (1999) defines a supply chain as *"the integrated and coordinated flows of goods from source to destination, as well as the information and money flows that are associated with it"*.

A supply chain is defined by Chow & Heaver (1999) as *"the collection of all producers, suppliers, distributors, retailers and transportation, information and other logistics providers that are involved in providing goods to end consumers. A supply chain includes both the internal and external participants for the firm"*.

Ayers (2001) defines a supply chain as *"life cycle processes comprising physical, information, financial and knowledge flows whose purpose is to satisfy end-user requirements with products and services from multiple, linked suppliers"*.

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[1] added by author.

Mentzer et al. (2001) defines a supply chain as *"a set of three or more entities (organisations or individuals) directly involved in the upstream (i.e. supply) and downstream (i.e. distribution) flows of products, services, finances, and/or information from a source to a customer"*.

The difference in concept between the first and second groups of four definitions and the all-embracing descriptions incorporated in the latter render it difficult to identify a supply chain in practice if any of the definitions are to apply. Many systems of distribution organised to function through transport links and nodes and known as supply chains in industry do not comply with any of these definitions. For the purpose of this study, it is accepted that the core function of a supply chain is to add value to a product by moving it from one place to another, during which the product may be changed through processing. In the remainder of this dissertation, the somewhat more restrictive definition will be adopted, although that will be relaxed to end the chain with intermediate users in particular circumstances. All the mathematical formulae in this thesis are formulated according to this definition.

## 3.4 Supply Chain Management Defined

The links and nodes in a supply chain fulfil functions that contribute to the value of the product moving through the chain and thus its success. Any link that does not perform well reduces the overall efficiency of the entire supply chain.

The concept of supply chain management as used in most literature is usually associated with the globalisation of industry and the tendency for producers to source their inputs worldwide, which requires management of cost-effective ways of co-ordinating global flows of inputs or outputs. The main focus of market competition in such circumstances is not only between products, but between the supply chains delivering the products. As competition in world markets is increasingly dependent upon the timeous arrival of products as well as their quality, co-ordination between suppliers and professional distributors has become an essential feature of the chain of supply. As the satisfaction of the consumer is an important measure of the success of the chain, effective management of the link processes is crucial (Trkman, Stemberger & Jaklic, 2005). Furthermore, market uncertainty requires supply chains to be readily adaptable to changes in the circumstance of trade. Such flexibility in supply necessitates alert and efficient management of the supply chain.

Supply chain management is an approach to analysing and/or managing logistics networks (supply chains) (Langley et al., 2008). The underlying rationale for this concept, and the vision of the proponents of supply chain management, is the opportunity for cost savings (efficiency) and/or better customer service (effectiveness). An important objective is to improve a company's competitive position in the global marketplace and to sustain that position in spite of intensive competitive forces and rapidly changing customer needs (Langley et al., 2008).

As with supply chains, numerous different definitions of supply chain management are found in literature and business practice.

One definition of effective supply chain management is *"the act of optimizing all activities throughout the supply chain, and it is the key to a competitive business advantage"* (Alberta efuturecentre).

Ayers (2001) defines supply chain management *"as the design, maintenance, and operation of supply chain processes for satisfaction of end users needs".*

Grant et al. (2006) define supply chain management as *"the integration of business processes from end user through original suppliers that provides products, services and information that add value for customers".*

The Supply Chain Forum defines supply chain management as follows: *"Supply chain management is the integration of key business processes from end user through original suppliers that provide products, services and information that add value for customers and other stakeholders".*

According to the Council of Supply Chain Management Professionals (2009), *"supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers and customers. In essence, supply chain management integrates supply and demand management within and across companies".*

Table 3.1 contains further definitions in a summary of supply chain schools of thought prepared by Bechtel & Jayaram (1997).

Table 3.1: A summary of supply chain schools of thought[2].

| **Author(s)** | **Definition** |
|---|---|
| **Chain Awareness School** | |
| Jones & Riley (1985) | "Supply chain management deals with the total flow of materials from suppliers through end users."(p.19) |
| Houlihan (1988) | "Supply chain management covers the flow of goods from supplier through manufacturer and distributor to the end user." (p.4) |
| Stevens (1990) | "Control the flow of material from suppliers, through the value-adding (production) processes and distribution channels, to customers." |
| Langley & Holcomb (1991) | "Supply chain management focuses attention on the interactions of channel members to produce an end product/service that will provide best comparative value for the end user." (p.14) |
| Gavinato (1991) | "... the entire sourcing, value-added, and marketing activities of the overall link of firm up to final customers." (p.32) |
| Novack & Simco (1991) | "Supply chain management covers the flow of goods from the supplier through the manufacturer and distributor to the end user." (p.32) |
| Lee & Billington (1992) | "Networks of manufacturing and distribution sites that procure raw materials, transform them into intermediate and finished products, and distribute the finished products to customers." (p.65) |
| **Linkage/Logistics School** | |
| Scott & Westbrook (1992) | "...supply chain is used to refer to the chain linking each element of the production and supply process from raw materials through to the end customer." (p.23) |
| Turner (1993) | "... technique that looks at all the links in the chain from raw materials suppliers through various levels of manufacturing to warehousing and distribution to the final customer." (p.52) |

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[2] Source: Reproduced from Bechtel & Jayaram (1997).

| | |
|---|---|
| **Information School** | |
| Towill, Naim & Wikner (1992) | "A supply chain is a system, the constituent parts of which include material suppliers, production facilities, distribution services, customers linked together via the feed-forward of materials and the feedback flow of information." (p.3) |
| Johannson (1994) | "Supply chain management is really an operations approach to procurement. It requires all participants of the supply chain to be properly informed. With SCM, the linkage and information flow between various members of the supply chain are critical to overall performance." |
| Manrodt & Harrington (1995) | "Product and information flow encompassing all parties beginning with the supplier's suppliers and ending with customers or consumers/end users ... flow are bi-directional." |
| **Integration School** | |
| Cooper & Ellram (1990) | "An integrative philosophy to manage the total flow of a distribution channel from the supplier to the ultimate user." (p.1) |
| Hewitt (1992) | "Supply chain integration is only a natural result of redesigned business processes not realignment of existing functional organisations." (p.340) |
| Ellram & Cooper (1993) | "Supply chain management is an approach whereby the entire network from which suppliers through the ultimate customer, is analysed and managed in order to achieve the 'best' outcome for the whole system." (p.1) |
| **Future** | |
| Cavinato (1992) | "The supply chain concept consists of actively managed channels of procurement and distribution. It is the group of firms that add value along product flow from original raw materials to final customer. It concentrates on relational factors rather than transactional ones." (p.285) |
| Farmer (1995) | "Instead of using the term supply chain management, we should use the idea of a seamless demand pipeline." |

Although all the definitions provided above are acceptable, most do not highlight the importance of efficiency in supply chain management. Thus for the purpose of this dissertation, the following definitions were used as the basis for developing the model for measuring supply chain efficiency.

According to Little (1999) *"supply chain management aims at maximising value contribution to the customer while simultaneously optimizing infrastructural and operational costs of the supply chain"*.

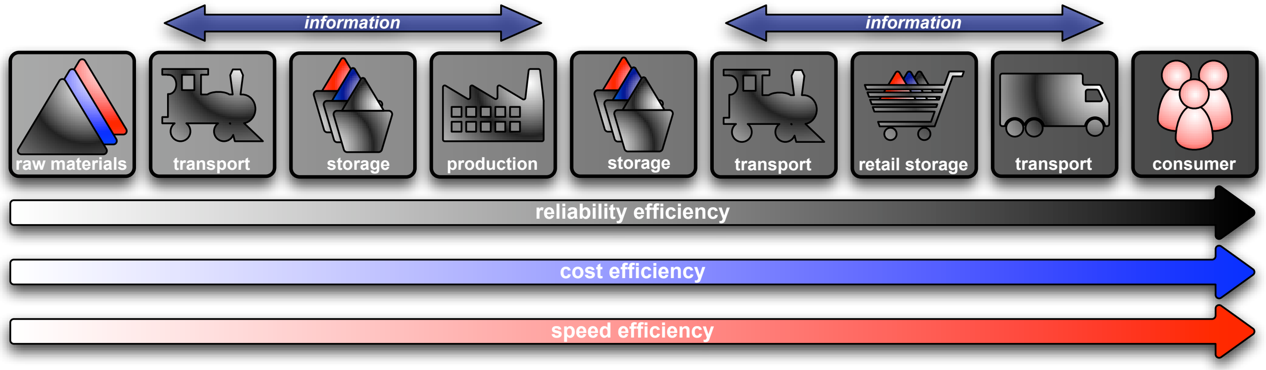
Computerworld (2001) defines supply chain management as *"the management that lets an organization get the right goods and services to the place they're needed at the right time, in the proper quantity and at an acceptable cost. Efficiently managing this process involves overseeing relationships with suppliers and customers, controlling inventory, forecasting demand and getting constant feedback on what's happening at every link in the chain"*.

KEYITSOLUTIONS (2003) defines supply chain management as *"supplying the correct product or service, to the correct place, in the correct quantity, at the correct time and at the correct cost"*.

Simchi-Levi et al. (2003), define supply chain management as *"a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimise system wide costs while satisfying service level requirements"*.

The basic notion of these four definitions is that a supply chain must be managed in order to be fast (under certain circumstances) and reliable, cost-effective, and flexible enough to meet customers' needs as shown in Figure 3.1. Reliability is often more important than speed in the supply chain and it is, therefore, important to temper overall speed with the need for reliability.

**Figure 3.1:** A diagram of a basic supply chain[3].



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[3] Source: Developed by the author for the purpose of this study.

However, there are certain circumstances when speed is important in a supply chain and the importance of speed can therefore not be overlooked. Speed is important in a supply chain under the following circumstances[4]:

- When the goods are:
    - perishable
    - subject to rapid obsolescence
    - needed on short notice
    - valuable in relation to its mass
    - expensive to handle or store
- When the demand for goods is:
    - unpredictable
    - occurs irregularly
    - greater than the local supply for short periods of time
    - seasonal
- When the following problems occur during distribution:
    - risk of theft, breakage or physical deterioration
    - high insurance and/or interest rates for long transit times
    - special care of the goods is required while in transit

Cost is always important, while customer satisfaction is fundamental to continued business. Thus in building the model (see Chapter 7) for measuring supply chain efficiency, the factors used to determine the efficiency of a supply chain are therefore, speed, reliability, cost and customer satisfaction. If speed is not important to the supply chain under investigation, it can simply be left out of the calculation.

In addition to the product flowing down the supply chain, information flows in both directions along the supply chain. For supply chains to function properly, it is important that information flows freely along the supply chain and that the different firms are prepared to share information with one another.

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[4] Source: Pienaar (2007).

## 3.5 Supply Chain Integration Defined

Supply chain integration greatly increases the ability of managers to pinpoint the weaknesses in the chain in order to effect improvements. However, without a reliable method (or model) to assist managers in detecting bottlenecks along the supply chain, it becomes more difficult for managers to gain the knowledge they require in order to benefit fully from supply chain integration. It is with this goal in sight that the model developed is initially designed.

Integrating the links of the supply chain into a holistic functioning system potentially improves the flow of both the products and information in the organisation. That leads to a more efficient supply chain. Thus, irrespective of whether a supply chain comprises links operated by several service providers or it is under the control of a single management link, integration is conducive to the maximisation of efficiency.

The goal of supply chain integration is to coordinate functions across the supply chain in order to improve performance. According to Simchi-Levi, Kaminsky & Simchi-Levi (2008) supply chain integration is best achieved by integrating the front end of the supply chain, customer demand, to the back end of the supply chain, the production and manufacturing portion of the supply chain.

There are two types of integration, namely horizontal and vertical integration. Horizontal integration is defined as “the absorption into a single firm of several firms involved in the same level of production and sharing resources at that level” (Answers.com, 2006a), whilst vertical integration is defined as “the absorption into a single firm of several firms involved in all aspects of a product’s manufacture from raw materials to distribution” (Answers.com, 2006b). The consensus of experts is that vertical integration of supply chains can lead to greater efficiency (Stonebraker & Liao, 2006) if it shortens an inefficiently long supply chain related to insourcing and outsourcing or (make or buy) decisions. Panayides (2006) agrees and adds that integration can contribute to agility along the supply chain. The Agility Forum has defined ‘agility’ as the “ability of an organization to thrive in a continuously changing, unpredictable business environment” (Agility Forum, 1994). From this definition the conclusion can therefore be drawn that agility along a supply chain results in greater flexibility and higher levels of customer satisfaction.

Although academic articles have been written on the importance of supply chain integration, conceptualisation and empirical evidence of what is really meant by integration and how such integration can be measured and quantified is lacking in the literature. There also seems to be a need for further investigation into the extent to which different organisations can and have been integrated along global supply chains and the performance implications (Panayides, 2006).

### 3.5.1 Push-Based Supply Chain

Push-based supply chain systems shift the responsibility of deciding when and how much of a given product must be kept in storage onto the manufacturing firm. Manufacturing and distribution (mainly inventory and transportation) decisions are made based on long-term forecasts of demand and the current levels of stock on-hand. In a push-based supply chain, the manufacturing firm is in control and determines the core factors in the supply process (Pienaar, 2009c).

Manufacturers usually base demand forecasts on orders that are received from wholesalers and retailers. This means that it will take far longer for a push-based supply chain to react to varying end-user market conditions. Possible outcomes of this shortcoming are, firstly, an inability by manufacturers to meet changing consumer demand patterns, and secondly, the obsolescence of a portion of supply chain stock due to the fact that the demand for certain products disappears (Pienaar, 2009c).

### 3.5.2 Pull-Based Supply Chain

In a pull-based supply chain it is the warehousing function that is in control and determines how much of a given product is required and when. The manufacturing and distribution decisions are therefore demand driven. Pull-based supply chains are coordinated by actual demand rather than by forecasted demand, which results in a substantial reduction in the need for inventory (in a pure pull system, the firm carries no product inventory and works from orders received) (Pienaar, 2009c).

A pull-based supply chain provides three main advantages. Firstly, it results in a considerable reduction in system stock levels. Secondly, it supports an enhanced ability to manage resources along a supply chain and finally, it results in lower supply costs than an equivalent push-based supply chain. However, pull-based supply chains are difficult to implement when products have long lead times and they find it more difficult to benefit from economies of scale in manufacturing and transport because they are not planned long in advance (Pienaar, 2009c).

### 3.5.3 Push-Pull Supply Chain

Push-pull supply chains are handled in two parts with the upstream stages of the supply chain handled as a push-based approach and the downstream stages operated as a pull-based approach. The push phase of the supply chain is made up of the standardised (generic) stages, while the pull phase is made up of stages that lead to the differentiation of the product (Pienaar, 2009c).

### 3.5.4 Identifying the Appropriate Supply Chain

According to Simchi-Levi, Kaminsky & Simchi-Levi (2008) with all other things being equal, higher levels of demand uncertainty results in a preference for managing the supply chain based on a realised demand: a pull strategy. Conversely, lower levels of demand uncertainty leads to a desire to manage the supply chain based on a long-term forecast: a push strategy.

In addition, all other things being equal, the greater the role that economies of scale play in reducing cost, the greater the value of aggregating demand, and therefore the greater the benefit of managing the supply chain based on a long-term forecast, a push-based strategy. If economies of scale are not important to the supply chain, aggregation does not reduce cost, so a pull-based strategy will be more beneficial (Simchi-Levi, Kaminsky & Simchi-Levi, 2008).

## 3.6 Efficiency, Effectiveness, Productivity and Performance Defined

The terms efficiency, effectiveness, productivity and performance are often used interchangeably in academic and business literature. However, their meanings are different. In order to differentiate between the terms and use them correctly, definitions found in literature are first discussed. The definition used as a basis for the subsequent research is then given for each term.

Of the four terms, the two that are most often confused are efficiency and effectiveness. Talley (1994) highlights the operational objectives of public transit firms and states that these objectives have been classified as either effectiveness or efficiency objectives. He continues by providing definitions for both these terms. Effectiveness is defined as “how well the transit firm provides service to the user”, while efficiency is defined as “how well the transit firm utilises its available resources”.

Chow, Heaver & Henriksson (1994) extend these definitions by adding their own definitions of the terms efficiency and effectiveness. They define effectiveness as "the extent to which an objective has been achieved" and efficiency as "the degree to which resources have been used economically". Simply put, efficiency is "doing things right" and effectiveness is "doing the right things" (Chow, Heaver & Henriksson, 1994).

According to Schenk (2007), *"the criterion for* ***economic efficiency*** *is* ***value****. A change that increases value is an efficient change and any change that decreases value is an inefficient change. A situation that is economically efficient may be inefficient when judged on different criteria"*. Schenk continues by stating that "efficiency is never absolute; it is always relative to some criterion".

For the purpose of this study a simple definition will be used for each term. The term "effectiveness" will be used to describe the extent to which a purpose is fulfilled, while the term "efficiency" will be used to describe the economy of resource utilisation in achieving goals when judged on specific identified criterion.

The meanings of the terms productivity and efficiency are also quite often confused with each other. As defined by the Bridgefield Group (2006) productivity is "an overall measure based on a quantity of output generated by a given quantity of input". CPE Globalization Briefs agrees with this definition and adds that productivity is most often expressed as a ratio of outputs over inputs. Increased output as a result of the same amount of input (such as labour hours) indicates more efficient use of a given set of resources due to process improvements or other achievements Bridgefield Group (2006). For the purpose of this study, productivity will be regarded as a measure of efficiency.

Performance is defined by the US Agency for International Development (2009) as "the actual output and quality of work performed". Although this definition is somewhat similar to that used for efficiency, it is important to note the key differences. Performance measures output, while efficiency measures the manner in which output is achieved (based on criteria). Performance measurement is defined as the process of quantifying action, where measurement is the process of quantification and action leads to performance (Neely, Gregory & Platts, 1995). Logistics performance measures are indicators of the work performed and the results achieved in an activity, process, or organizational unit (Forbes.com, 2006).

With the development of globalisation countries began to trade more freely. Countries realised that they are better off if they specialise in certain goods and trade their surplus production for the other goods they need. Through specialisation firms become more productive and the world's limited economic resources are used more efficiently. Resources are scarce and therefore care must be taken to use them as efficiently as possible. Because efficiency measures "the economy of resource utilisation in achieving goals when judged on specific identified criterion" it was decided that for the purpose of this dissertation, a supply chain will be measured in terms of efficiency rather than effectiveness. The results achieved by the model developed will assist firms to utilise their resources more efficiently, which will result in increased levels of trade and in so doing will help to grow the economy.

## 3.7 Supply Chain Efficiency Defined

Efficient management of a supply chain has been increasingly recognised as a key factor in differentiating product and service offerings and gaining competitive advantage for firms (Christopher, 1998). It demands close integration of internal functions within a firm and efficient linkages with the external operations of channel members in the chain (Lee, 2000). It is also essential that supply chains do not remain static, but rather evolve continuously based on the changing market and customer needs (Little, 1999).

For the purpose of this study, it is important to define supply chain efficiency in order to understand what the model developed measures. By combining the definitions for a supply chain (section 3.3) and efficiency (section 3.5), the resultant definition of supply chain efficiency is *"the economy in resource utilisation based on specific criterion while products are moved from one place to another, in the course of which movement the products may be changed through processing"*.

Performance of the entire supply chain is a key factor in achieving an efficient supply chain. It is therefore important to utilise the combined resources of the supply chain members in the most efficient way possible to provide competitive and cost-effective products and services. According to Wong & Wong (2007), overall supply chain efficiency is defined as "the efficiency which takes into account the multiple performance measures related to the supply chain members, as well as the integration and coordination of the performances of those members".

The need to improve efficiency in a supply chain has lead to the development of models and methods to measure supply chain efficiency. These models can be used to evaluate the levels of performance along supply chains and help their managers to identify weaknesses in order to improve the overall functioning of the chains.

Although there are a variety of criteria that can be used to measure the efficiency of a supply chain, for the purpose of this study the criteria used are speed, reliability, cost and customer satisfaction (as explained in section 3.3 and 3.4). While, speed, reliability, cost and customer satisfaction on their own are only measures of effectiveness, when considered in terms of the effect they have on resource utilisation in a supply chain they can be used to measure efficiency. For example, if the speed, reliability and other attributes of a link or node in a supply chain satisfy the requirements of its users at the least economic cost (i.e. with the minimum use of resources - capital or infrastructure and equipment, labour, material and energy), that link or node can be regarded as efficient. The "least economic cost" would render the link or node efficient for society. If only the "least financial cost" to the service provider is taken into account (i.e. social costs are excluded), the link or node would be efficient in the business sense. Economic efficiency (and specifically Pareto optimality) should refer to the situation where the trade-off between speed, cost and reliability is also achieved optimally and where, in terms of a supply chain, no component can lead to further improvement without impacting negatively on another component (Pareto optimality is a situation which exists when economic resources and output have been allocated in such a way that no-one can be made better off without sacrificing the well-being of at least one person (Economy Professor, 2006)).

There is a direct relationship between speed and cost and reliability and cost. Therefore, as speed and reliability increase, costs will usually increase and with a decrease in costs, speed and reliability will usually decrease. This means that a firm has to make a trade-off between the different criteria for supply chain efficiency as defined in this dissertation. If these three elements are seen in combination, then supply chain efficiency is achieved, if customer satisfaction is maximised with the optimal combinations of speed, reliability and costs. While, for example, speed may increase in the supply chain, if the marginal costs demanded by the speed increase are in excess of the marginal consumer satisfaction achieved then the supply chain is not efficient at the increased speed.

## 3.8 Existing Supply Chain Performance Measures

In the development of a model to measure the efficiency of a supply chain, it is important to structure the model correctly. Each stage of the model must be carefully constructed and each function of the model must be thoroughly explored to ensure that it achieves what it sets out to do.

As mentioned in section 3.5, there is a difference between a performance measure and an efficiency measure (performance measures output, while efficiency measures the manner in which output is achieved). However, performance measures can be used in combination with efficiency measures to evaluate the efficiency of an overall supply chain. Therefore, for the purpose of this dissertation, performance measures that are currently in use, will be investigated (see Chapter 4) and those which are considered relevant to the purpose of this research will be included as the first stage in the model developed to measure overall supply chain efficiency.

Performance measures provide a basis to evaluate alternatives and identify decision criteria (Abu-Suleiman, Boardman & Priest, 2004). The information collected through performance measurements can be used to assist the firm in making educated decisions and help ensure that the firm continues to improve its position in the market.

Feedback is an integral part of any process. An effective supply chain performance measurement system allows proper monitoring of business processes (Abu-Suleiman, Boardman & Priest, 2004). The feedback received is used to compare actual progress to planned or budgeted values, facilitate benchmarking against industry best practices, and to identify poor performance or improvement opportunities.

Lastly, performance measurement has to direct employees towards higher productivity by motivating and rewarding them for good performance (Kussing, 2009). Performance measurement must encourage employees to strive towards excellence and in so doing identify weak points in the chain.

The purposes of a performance system are as follows (Rolstadås, 1995):

- It should support the decision-making process, by indicating where to act and how to act, and by monitoring the effect of implemented action plans.
- The system should monitor the effect of strategic plans, so that corrections can be made to ensure the achievement of long-term goals and objectives.
- Performance evaluation is required for internal purposes and for satisfying requirements from various external stakeholders.
- The system should have diagnostic properties, so that warning can be given in advance of decreasing business performance.
- Performance measurement is part of a continuous improvement process.

- Measurement of progress has a motivational effect on the labour force of a business and is necessary to justify further effort in any improvement process.
- The measuring of performance is necessary for comparison and for identifying performance gaps.
- Records should be kept of all business activities, so that they can be supplied on demand to, for example, customers and suppliers. A record of supplier performance could, for example, be used to give input to their improvement processes.

This list of purposes should be taken into account during the development of a performance measurement system (Rolstadås, 1995).

## 3.9 Existing Supply Chain Efficiency Measures

All the elements of the supply chain interact to meet the needs of the buyers and the sellers of the products moving through the chain. Those elements are interdependent and have a cause-and-effect relationship with one another. Thus for each element to achieve its maximum value and at the same time contribute to the optimisation of the value of co-elements in the supply chain, there must be a high degree of integration between the elements (Qukula, 2000). A weak link in the supply chain has a negative effect on the performance of all the elements throughout the supply chain. Therefore the efficiency of each individual element must be evaluated in order to assess the efficiency of the entire supply chain. However, in order to raise the level of efficiency in the supply chain, it is necessary to be able to measure that level throughout all the links. Spekman et al. (1994) argue that this presents a challenge for measurement (as the chain efficiency cannot be measured by measuring single transactions, but only through the evaluation of the efficiency of all the transactions together along the entire supply chain). Therefore, when devising a model for measuring supply chain efficiency, it is important to choose one that takes all relevant transactions into account.

Little (1999) highlights a second obstacle to measuring supply chain efficiency; namely, that the measures of efficiency are not always used in a balanced way to reflect overall efficiency. Frequently, one measurement or another is over-emphasized leading to inaccurate overall measurement or sub-optimisation of the supply chain efficiency. Little (1999) continues by saying that the risk of this increases when no single body oversees the entire chain. Thus, when measuring the supply chain, the method devised must evaluate each link in terms of the correct ratio of importance to the overall efficiency of the supply chain.

From a marketing perspective, firms achieve their goals by satisfying their customers with greater efficiency and effectiveness than their competitors (Kotler, 1984). Therefore firms can benefit from measuring the level of efficiency and effectiveness throughout their entire supply chains.

Firms deal in different commodities, and supply chains exist for every commodity. Little (1999) points out that supply chains in different sectors (of industry) have different characteristics that vary within those sectors. Thus, supply chain design must clearly be tailored both to the specific industry and to the individual circumstances of each business (Little, 1999). It is also important that each service provider in a supply chain should use the same method for measuring efficiency in order to provide meaningful comparisons of the efficiency of the links. Therefore, when selecting a model for measuring supply chain efficiency, it is important that firms choose a model that can be applied throughout all the links and nodes of the supply chain.

Another consideration when measuring supply chain efficiency is the strategy for the growth of the supply chain. Supply chains that work well for current throughput might become "Achilles heels" if flexibility, responsiveness and scalability have not been designed into the system (Barloworld Logistics, 2005). Thus it is important to plan supply chains so that they maintain their efficiency as throughput changes.

The measures used to determine efficiency should also be broad in the nature of the information they analyse. Often quantitative measures are the only ones used, as they are the easiest to compile (Potter, Mason & Lalwani, 2002). However, by focusing only upon information that can be quantified, attention is taken away from some of the more qualitative factors, such as product quality (Cousins & Hampson, 2000). Thus, it is important to use both qualitative and quantitative measures when determining supply chain efficiency.

The lack of a widely accepted definition for supply chain management and the complexity associated with overlapping supply chains make supply chain efficiency measurement difficult (Lambert & Pohlen, 2001). In addition, the lack of supply chain orientation, the complexity of capturing measurements across multiple links, the unwillingness to share information among companies, and the inability to capture performance by customer, product or supply chain (Lambert & Pohlen, 2001) make accurate supply chain efficiency measurement more complex. Another major contributor to the lack of meaningful supply chain efficiency measures is the absence of an approach for developing and designing such measures (Lambert & Pohlen, 2001).

## 3.10 Conclusion

International supply chains are an important part of global trade. However, a supply chain in itself is not sufficient. Only those that are efficient will prosper. In order for a supply chain to be efficient, it is important to be aware of its main functions as well as the role that each function plays in the overall efficiency of the supply chain. Achieving this makes it easier to identify bottlenecks and effect the necessary improvements.

The literature review in this chapter serves as the basis for the development of the study. It introduces important terminology that is used throughout the dissertation. In order to simplify the research each of the terms is defined in the context in which it is used throughout the report. The criteria on which the measurement of supply chain efficiency will be based for this dissertation are identified and important factors that must be taken into account when developing an efficiency measurement are highlighted.

# CHAPTER 4

# Logistics Performance and Efficiency Measures

## 4.1 Introduction

This chapter identifies different formulas and methods for measuring supply chain performance and supply chain efficiency. The different formulas and methods available are discussed and the strengths of each are identified so that they can be included in the model developed. Performance measures are included in the study as they form part of the first stage of the model that is developed in the dissertation. Methods for measuring supply chain efficiency are used in stages two and three of the model.

An important objective is to improve an entity's competitive position in the global market place, whether it is a private or public entity, and to maintain that position while accommodating changing customer needs. Efficient supply chain management takes advantage of all opportunities to implement improvements in the logistical structures and strategies of the chains.

The first step in logistics performance measurement is the definition of the system that needs to be measured as well as its components. After the functional requirements of the system have been determined, performance measures that can quantitatively measure the functional requirements have to be identified (Kussing, 2009).

Beamon (1996) presents a number of characteristics that are found in performance management systems and can therefore be used in the evaluation of these measurement systems. These categories include: inclusiveness (measurement of all pertinent aspects), universality (allow for comparison under various operating conditions), measurability (data required are measurable), and consistency (measures consistent with organisation's goals) (Beamon, 1999).

Cost, speed, reliability and customer satisfaction can all be used as measures of supply chain performance and supply chain efficiency. They can either be used as measures by themselves that focus on only one aspect of supply chain performance or they can be combined to cover all four variables. The use of a single performance measure is attractive because of its simplicity. However, one must ensure that if a single performance measure is utilized, this measure adequately describes the system performance (Beamon, 1999).

## 4.2 Performance Measures

In modern times, organisations compete in complex environments and an accurate understanding of their goals and of the methods for attaining them is therefore essential (Kaplan & Norton, 1996). By identifying specific goals that the firm would like to achieve and then developing methods and strategies for achieving the goals, a company takes the first few steps towards success. However, it is essential that the firm undertake thorough investigations to determine what customers and other stakeholders find important and that they choose a measurement system that will provide them with meaningful information. When considering the entire supply chain, a measurement system should be more than an unrelated collection of individual metrics. It has to be valid, robust, useful, integrative, economical, with an adequate level of detail for its purpose, as well as behaviourally sound (Caplice & Sheffi, 1994).

According to Rafele (2004), two basic aspects are detected in every single step of the supply chain: the first is internal to the firm, called the intra-firm aspect; the second one ties together suppliers and clients, creating the inter-firm aspect. Thus, it is important when studying supply chains to analyse how a firm is organised and managed internally, but it is also significant to evaluate its behaviour with its suppliers (Rafele, 2004).

The following sections (4.2.1 - 4.2.7) provide formulas that can be used to measure the performance of a supply chain. They can either be used individually as many pertinent aspects of supply chain performance as possible. The equations given in sections (4.2.1 - 4.2.7) below will be used as the initial step in the model to be developed. (A large portion of the following sections (4.2.1 - 4.2.7) has been based on the chapter entitled "Controlling Logistics Performance" (Kussing, 2009)).

### 4.2.1 General Non-Financial Performance Measures

- Asset utilisation - the percentage of time that assets are being used effectively to generate the desired output, while taking into account the effects of transport, warehousing, production, etc.:

$$Asset\ utilisation\ (\%) = \frac{Actual\ hours\ worked\ in\ a\ period}{Total\ number\ of\ hours\ in\ a\ period} \times \frac{100}{1} \tag{4.1}$$

- Total cycle time - the time that passes from when a customer places an order for a product until the product is received by the customer:

$$\begin{aligned} Total\ cycle\ time\ (hours) = {} & maximum\ of\ (order\ processing\ time \\ & + manufacturing\ lead\ time + transportation\ time)\ and \\ & (order\ processing\ time + delivery\ time\ from\ warehouse) \end{aligned} \tag{4.2}$$

- System uptime - the time during which a system is functioning or available for use

$$System\ uptime\ (\%) = \frac{Hours\ that\ system\ is\ available\ in\ a\ period}{Total\ hours\ in\ that\ period} \times \frac{100}{1} \tag{4.3}$$

- Percentage defective - measures the percentage of defective products that are shipped and in so doing provides an indication of the quality control of the business:

$$Percentage\ defective\ (\%) = \frac{Total\ number\ of\ defectives\ shipped}{Total\ number\ of\ items\ shipped} \times \frac{100}{1} \tag{4.4}$$

- Percentage of demand met - this provides an indication of the operational capability of a business, as demand may not be met if one or more of the following activities - forecasting, production, warehousing, inventory management or distribution - are not functioning properly:

$$Percentage\ of\ demand\ met\ (\%) = \frac{Number\ of\ orders\ fulfilled}{Total\ demand} \times \frac{100}{1} \tag{4.5}$$

- Safety - safety can be measured by determining the frequency rate in terms of the number of disabling injuries per million man-hours or the severity rate in terms of the number of lost man-days per million man-hours worked:

$$Frequency\ rate = \frac{Number\ of\ lost\ time\ injuries}{Number\ of\ man\text{-}hours\ worked} \times 1000000 \tag{4.6}$$

$$Severity\ rate = \frac{Number\ of\ lost\ man\text{-}days}{Number\ of\ man\text{-}hours\ worked} \times 1000000 \tag{4.7}$$

### 4.2.2 Performance Measures for Procurement

- Price reduction quota - gives an indication of how good the purchasing staff are at negotiating with suppliers to achieve prices that are lower than those paid on the open market:

$$Price\ reduction\ quota\ (\%) = \frac{Realised\ object\ price\ reductions\ (Rands)}{Market\ price\ (index)\ (Rands)} \times \frac{100}{1} \tag{4.8}$$

- Average cost per order - is represented by the sum of all annual purchasing function costs divided by the number of purchases made per year to get an average cost per order.

$$Average\ cost\ per\ order\ (Rands) = \frac{Total\ cost\ of\ orders\ (Rands)}{Total\ number\ of\ orders} \tag{4.9}$$

- Standardisation quota - provides an indication of the degree of standardisation in the procurement process. The higher the degree of standardisation in the procurement process, the shorter the order time and the lower the cost:

$$Standardisation\ quota\ (\%) = \frac{Number\ of\ standardised\ procurement\ objects}{Number\ of\ objects\ delivered} \times \frac{100}{1} \tag{4.10}$$

- Regional market quota - this gives an indication of supply risk, as items that are procured internationally will have longer, and more variable lead times and be more prone to disruptions of supply:

$$Regional\ market\ quota\ (\%) = \frac{Purchasing\ volume\ in\ regional\ markets}{Total\ purchasing\ volume} \times \frac{100}{1} \tag{4.11}$$

### 4.2.3 Performance Measures for Production Plants

- System uptime - this will give an indication of the percentage of time that the production plant is operational.

$$System\ uptime\ (\%) = \frac{Hours\ that\ system\ is\ available\ in\ a\ period}{Total\ hours\ in\ a\ period} \times \frac{100}{1} \tag{4.12}$$

- Percentage defective - measures the percentage of defective products that are produced and in so doing provides an indication of the quality control of the business:

$$Percentage\ defective\ (\%) = \frac{Total\ number\ of\ defectives\ produced}{Total\ number\ of\ items\ produced} \times \frac{100}{1} \tag{4.13}$$

- Production cost per unit or extraction cost per ton - indicates the cost per product unit produced or the cost per ton of product mined.

$$Production\ cost\ per\ unit\ (Rand/unit) = \frac{Total\ costs\ of\ goods\ produced}{Total\ number\ of\ goods\ produced} \tag{4.14}$$

or

$$Extraction\ cost\ per\ ton\ (Rand/ton) = \frac{Total\ costs\ of\ product\ mined}{Total\ tons\ of\ product\ mined} \tag{4.15}$$

- Total production time - indicates the total time that it takes to produce/extract a product.

$$Total\ production\ time(hours) = Actual\ operating\ time + downtime \tag{4.16}$$

In South Africa firms specifically focus on the availability of equipment due to the problems associated with imported heavy equipment. Measurements of *planned maintenance*, *unplanned maintenance*, *engineering availability*, *waiting time* and *downtime* can be included here. These measurements can be seen as a function of *system uptime* and therefore the details are not covered here, but they can be included if the performance for *system uptime* is lower than expected.

### 4.2.4 Performance Measures for Supplier Selection

- Delivery reliability - indicates the variability of delivery times. Although speed is important, research has shown that customers prefer slower, more reliable service over faster, unreliable service.

$$Delivery\ reliability\ (\%) = \frac{Maximum\ delivery\ time - Minimum\ delivery\ time\ (hours)}{Average\ delivery\ time\ (hours)} \times \frac{100}{1} \tag{4.17}$$

- Complete shipments - measures the percentage of shipments that are delivered according to the desired requirements, without the customer having to wait for backorders:

$$Complete\ shipments\ (\%) = \frac{Number\ of\ orders\ delivered\ in\ full}{Total\ number\ of\ orders} \times \frac{100}{1} \tag{4.18}$$

- Percentage good parts - measures the quality of parts delivered by the supplier:

$$Percentage\ good\ parts\ (\%) = \frac{Total\ quantity\ supplied - Number\ of\ defectives}{Total\ quantity\ supplied} \times \frac{100}{1} \tag{4.19}$$

- Price charged by suppliers - indicates the cost charged by suppliers for their respective goods and/or services.

$$Price\ of\ suppliers\ (Rands) = Rates\ charged\ by\ suppliers\ for\ their\ goods\ and/or\ services \tag{4.20}$$

- Total cycle time - the time that passes from when a customer places an order for a product until the customer receives the product:

$$\begin{aligned} Total\ cycle\ time\ (hours) = {} & maximum\ of\ (order\ processing\ time \\ & + manufacturing\ lead\ time + transportation\ time)\ and \\ & (order\ processing\ time + delivery\ time\ from\ warehouse) \end{aligned} \tag{4.21}$$

### 4.2.5 Performance Measures for Warehousing

- Order picking time - "refers to the time it takes to select all items on a customers order, including order processing time (time taken to locate the items and plan a routing sequence to pick them up) and interference time (time spent waiting for equipment and interruptions in movement due to congestion)":

$$Order\ picking\ time\ (hours) = \begin{array}{l} order\ processing\ time + travel\ time\ to\ first\ location\ + \\ inter\text{-}location\ travel\ time + travel\ from\ last\ location\ + \\ pick\text{-}up\ time + interference\ time \end{array} \tag{4.22}$$

- Warehouse throughput - measures the number of loads that a storage system can handle:

$$Warehouse\ thoughput\ (loads/hour) = \frac{Number\ of\ loads\ received,\ stored\ and\ retrieved}{Number\ of\ hours} \tag{4.23}$$

- Percentage of goods damaged - measures the number of goods that are damaged during storage.

$$Percentage\ damaged\ (\%) = \frac{Number\ of\ goods\ damaged\ in\ storage}{Total\ number\ of\ goods\ stored} \times \frac{100}{1} \tag{4.24}$$

- Utilisation of warehouse equipment and warehouse operating cost per unit can also be used as measures of warehousing performance. The units can be measured in terms of weight (kg) or volume ($m^3$).

$$Warehouse\ equipment\ utilisation\ (\%) = \frac{Duration\ of\ delays\ incurred}{Total\ time\ equipment\ was\ employed} \times \frac{100}{1} \tag{4.25}$$

$$Warehouse\ operating\ cost\ per\ unit\ (Rands/unit) = \frac{Total\ operating\ cost\ in\ warehouse}{Number\ of\ units\ handled} \tag{4.26}$$

### 4.2.6 Performance Measures for Transport

- Total transit time - measures the time period for cargo to move from origin to destination (i.e., from supplier to customer).

$$Total\ transit\ time\ (hours) = \begin{array}{l} Travel\ time + Waiting\ time\ at\ terminals\ or\ docks\ + \\ Transfer\ time + Handling\ time \end{array} \tag{4.27}$$

- Transit time variability - measures the reliability of the transport function. Companies strive for or hire hauliers with low levels of variability in their service delivery, because it allows them to plan their logistics functions more easily.

$$\begin{array}{l} Variability\ as\ a\ \% \\ of\ transit\ time \end{array} = \frac{Max\ transit\ time\ (hours) - Min\ transit\ time\ (hours)}{Average\ transit\ time\ (hours)} \times \frac{100}{1} \tag{4.28}$$

- Percentage of perfect shipments - measures the overall quality of the transport function, by calculating the percentage of shipments that arrived at the final destination at the correct time, without any problems, i.e. all parts present and damage-free, and with complete documentation attached:

$$Perfect\ shipments\ (\%) = \frac{Number\ of\ perfect\ shipments}{Total\ number\ of\ shipments} \times \frac{100}{1} \tag{4.29}$$

- Average transport cost per ton of cargo transported measures the transport cost incurred per ton of cargo transported.

$$Cost\ per\ ton\ of\ cargo\ transported (Rands/ton) = \frac{Total\ transport\ cost\ (Rands)}{Tons\ of\ cargo\ transported\ (tons)} \tag{4.30}$$

- Utilisation of transport means - measures the percentage of utilisation because of insufficient transport means being available.

$$\begin{array}{l} Utilisation\ of \\ transport\ means\ (\%) \end{array} = \frac{Delays\ incurred\ (hours)}{Time\ transport\ means\ were\ employed\ (hours)} \times \frac{100}{1} \tag{4.31}$$

### 4.2.7 Performance Measures for Customer Service

- Service reliability - measures how often shipments are delivered within or close to the delivery time that was promised:

$$Service\ reliability\ (\%) = \frac{Number\ of\ shipments\ within\ ``x"\ hours\ of\ promised\ delivery\ time}{Total\ number\ of\ shipments} \times \frac{100}{1} \tag{4.32}$$

- Fill rate - indicates what percentage of units is available when requested by the customer. It can be measured in a variety of ways, for example:

$$Line\ count\ fill\ rate\ (\%) = \frac{Number\ of\ order\ lines\ shipped\ on\ initial\ order}{Total\ number\ of\ order\ lines\ ordered} \times \frac{100}{1} \tag{4.33}$$

$$SKU^1\ fill\ rate\ (\%) = \frac{Number\ of\ SKUs\ shipped\ on\ initial\ order}{Total\ number\ of\ SKUs\ ordered} \times \frac{100}{1} \tag{4.34}$$

- Customer complaints - records should be kept of the total number of complaints during a fixed period of time.

The criteria, norms, standards or measurements used to measure the performance of a firm must be based on what the market or customer values as important. Figure 4.1 shows a representation of the logistics performance measures that can be used to measure the performance of a supply chain.

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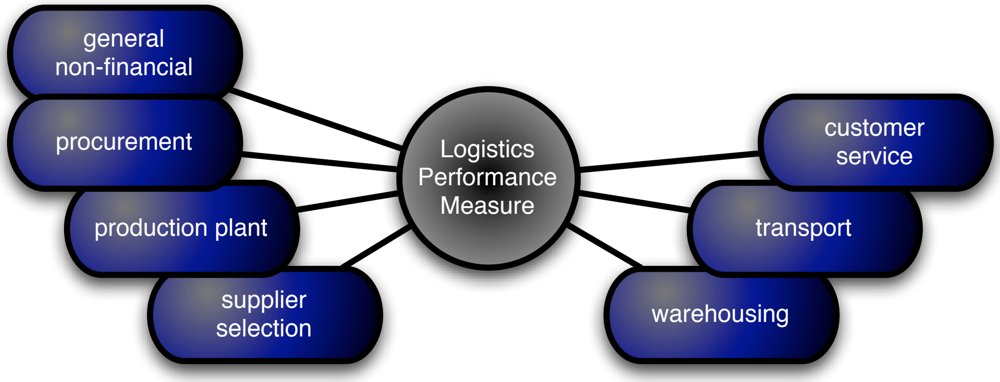
[1] An SKU is a Stock Keeping Unit and it represents the number of one specific product available for sale (TechWeb, 2007)

**Figure 4.1:** Logistics Performance Measure[2].



## 4.3 Evaluation of Supply Chain Performance Measures

After careful consideration of all the performance measures presented above, it can be concluded that when the performance measures are used separately they are incapable of measuring total supply chain performance, because they do not cover all the pertinent aspects of the supply chain. However, when they are used in combination with each other, they provide a much more reliable measurement for total supply chain performance.

## 4.4 Existing Models for Measuring Supply Chain Performance

In sections 4.2.1 - 4.2.7 formulas in the form of ratios were identified for measuring supply chain performance. Ratios are good at comparing quantities relative to each other; however, they do not always have the ability to evaluate a situation that has numerous variables. Therefore more advanced models are developed to assess more complex circumstances. A few models that are already available to measure different aspects or sections of supply chain performance are identified below.

When designing a model for measuring supply chain performance, the first step is to define a real supply chain and its business objectives. Next, an analysis of the various input and output factors must be carried out and the conceptual models are developed. This is followed by the quantitative phase, which deals with more technical problems e.g. development and analysis of mathematical and simulation models and control theory techniques (Laurikkala et al., 2003). Figure 4.2 shows the

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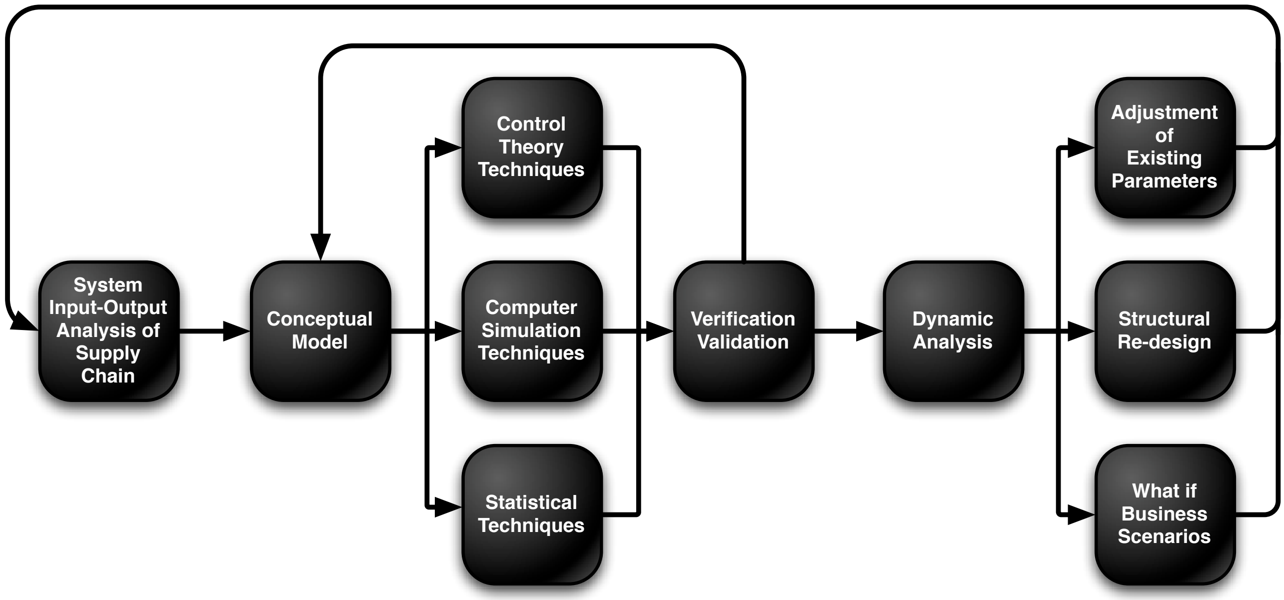
[2] Source: Developed by the author for the purpose of this study.

research structure of supply chain modelling.

**Figure 4.2:** Research Structure for Supply Chain Modelling[3].



### 4.4.1 Process Maps

A common method used to model and analyse business processes is a technique known as Process Maps. A Process Map provides a method of communicating information about activities that occur during the various processes in a supply chain, i.e. it shows how a group of people or an organisation completes a specific task. One of the main advantages of Process Maps is that little training is required for people to create and evaluate the process models (Chen, 1999). Another major advantage of this technique is that it helps to identify the crossing of organisational boundaries, as it shows which company and which organisational unit is responsible for each activity (Trkman, Stemberger & Jaklic, 2005). However, as with collaborative forecasting, process maps do not provide the actual mathematical calculations and therefore still rely on an additional method or model to be able to provide a quantitative measure of performance along the entire chain.

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[3] Source: (Laurikkala et al., 2003).

### 4.4.2 Multi-Stage Models

#### Deterministic Analytical Models

According to Beamon (1998) multi-stage models for supply chain design and analysis can be divided into four categories, namely, (1) deterministic analytical models, (2) stochastic analytical models, (3) economic models and (4) simulation models.

A deterministic analytical model is one in which the variables are known and specified (no uncertainty is included (Forbes.com, 2006)), and the goal is to achieve a closed-form analytical solution through mathematical programming techniques (Ganapathy, Narayanan & Srinivasan, 2003). These models provide prescriptive solutions under certain assumptions, but are limited to static system representation (Ganapathy, Narayanan & Srinivasan, 2003).

Over the years, many formulas and algorithms have been created to assist businesses and manufacturers in determining what quantity of a given item to order. Of these the simplest formula is the most used: The EOQ (economic order quantity) or Lot Size formula. The EOQ formula has been independently discovered many times and can be summarized as determining the order quantity Q, that balances the order cost C and the holding costs h (C-h = 0) to minimize total costs.

Although the EOQ formula is used effectively in simple situations, it is restricted in what it is able to measure (it only provides the optimal solution for the quantity of a particular item that must be ordered). Therefore, when developing a model to measure the efficiency across an entire supply chain, it is not a very effective measure.

Williams (1981) presents seven heuristic algorithms for scheduling production and distribution operations in an assembly supply chain network. The objective of each heuristic algorithm is to determine a minimum-cost production and/or product distribution schedule that satisfies final product demand and minimizes the sum of the average inventory holding costs and average fixed charges for processing, per period, over an infinite planning horizon (Williams, 1981). Finally, the average performance of each heuristic is compared using a wide range of empirical experiments, and recommendations are made on the bases of solution quality and network structure (Beamon, 1998).

Although these algorithms are helpful in measuring the performance of the supply chain in terms of cost and provide a product distribution schedule that satisfies final product demand, it is the aim of this research to develop a more inclusive model for measuring supply chain efficiency. Therefore, the model devised in this research measures speed, reliability and customer service in addition to cost and takes the calculations further by giving an overall measure for efficiency rather than just for performance.

Williams (1983) develops a dynamic programming algorithm for simultaneous determination of production batch sizes in an assembly network and distribution batch sizes in a conjoined distribution network. The objective is to minimize average cost per period over an infinite horizon, where the average cost is a function of the processing costs and inventory holding costs for each node in the network (Beamon, 1998).

Here again, the information collected, though important, is very limited in its scope. The algorithm focuses mainly on performance in terms of costs and does not take any other factors into account.

Beamon (1998) develops a mathematical model designed to improve efficiency and responsiveness in a supply chain. The model maximizes system flexibility, as measured by the time-based sum of instantaneous disparity between the capacities and utilizations of two types of resources: inventory resources and activity resources. Inventory resources are resources directly associated with the amount of inventory held; activity resources, then, are resources that are required to maintain material flow. The model requires, as input, product-based resource consumption data and bill-of-material information, and generates as output: (1) production, shipping, and delivery schedules for each product and (2) target inventory levels for each product (Beamon, 1998).

The model developed by Voudouris (1996) focuses on improving the efficiency of a supply chain rather than measuring the efficiency. Although the information is useful, the scope of the measurement is limited to a manufacturing supply chain. The model developed has the ability to measure the efficiency of a supply chain and point out areas of weakness. In addition, it is a generic model that is able to be applied to any South Africa supply chain (with minimal changes).

Smith et al. (2000) developed a linear programming model in conjunction with Delta and Pine Land Company (D&PL) which D&PL can use in order to derive a more economical strategy for distributing cottonseed to its customers. The research conducted and the model developed highlights the potential for using linear programming in managing large-scale transportation and distribution problems. The model resulted in the creation of new ratios for measuring performance, the model helped identify conditions that result in inventory shortages and the model led to the discovery of inaccuracies in D&PL distribution reports (Smith, Cassady, Bowden & Ainsworth, 2000). The model to be developed will include linear programming.

### Stochastic Analytical Models

A stochastic analytical model is one in which at least one of the variables is unknown, and is assumed to follow a particular statistical distribution (Beamon, 1998). They are models where uncertainty is explicitly considered in the analysis (Forbes.com, 2006). Those models embody more realistic features of a supply chain in the form of stochastic representations. However, they are not dynamic because they do not account for real time updates of the entities and interactions of the system (Ganapathy, Narayanan & Srinivasan, 2003).

Kwon, Im & Lee (2005) employ a multi-agent and Case Based Reasoning (CBR) approach to solving production planning optimization problems. They recommend the multi-agent collaboration engine for supply chain management (MACE-SCM) to manage two decision support levels that reflect different types of relationships among the firms in a supply chain (Kwon, Im & Lee, 2005). The MACE-SCM, based on CBR, is implemented as a web service to facilitate communications among agents. First, they create the model for the MACE-SCM using multi-agent and CBR. Then an equivalent mixed integer-programming model for benchmarking is developed. The model's performance is compared by changing demand quantity, demand uncertainty, demand utility function, and the number of competitors.

### Economic models

Economic models focus mainly on the buyer-supplier relationship in a supply chain from a cost perspective (Ganapathy, Narayanan & Srinivasan, 2003).

Christy & Grout (1994) developed an economic, game theoretical framework for modelling the buyer-supplier relationship in a supply chain. The basis of this work is a 2 x 2 supply chain relationship matrix, which may be used to identify conditions under which each type of relationship is desired. These conditions range from high to low process specificity and from high to low project specificity. Thus, the relative risks assumed by the buyer and the supplier are captured within the matrix. For example, if the process specificity is low, then the buyer assumes the risk; if the product specificity is low, then the supplier assumes the risk (Christy & Grout, 1994).

The framework developed by Christy and Grout provides a clear view of the buyer-seller relationship and is therefore an important measurement of supply chain performance. However, its scope is restricted to performance from a cost perspective and therefore does not encompass the full range of variables that will be considered in this dissertation.

### Simulation models

Simulation has been identified as one of the best methods to analyse and overcome the presence of stochastic events and relationships between events in a supply chain. Its capability of capturing uncertainty, complex system dynamics and large-scale systems makes it attractive for supply chain study.

Simulation models use computer representations to model the real-world interactions and are useful for what-if analysis (Ganapathy, Narayanan & Srinivasan, 2003). They involve a mathematical technique for testing the performance of a system due to uncertain inputs and/or uncertain system configuration options (Forbes.com, 2006). Simulation methods have also been adopted for analysing more complex problem settings that include a larger number of decision variables where optimal solutions may not be possible (Chen & Paulraj, 2004). Simulation produces probability distributions for the behavior (outputs) of a system. A company may build a simulation model of its build plan process to evaluate the performance of the build plan under multiple scenarios on product demand (Forbes.com, 2006).

Ganapathy, Narayanan & Srinivasan (2003) have developed a model that features a decision support system and studies the role of such a decision support system in enhancing the performance of the supply chain logistics system. The model is object oriented in nature, which helps in rapid prototyping of the different components of the system.

Dowlman et al. (2004) have developed a model, using Monte Carlo simulation of a clinical supply chain, managed by an Interactive Voice Response (IVR), in order to get drugs to the market faster. The model mimics aspects of the drug distribution process, which allows for effective optimization of medication management strategies, as well as identification of how much material is required for an upcoming clinical trial by evaluating different supply chain scenarios. The Monte Carlo simulation approach enables the model to answer practical questions and concerns[4]:

- Ideal shipment sizes, to minimize any potential issues versus stock availability at the beginning of the trial
- Optimal trigger/re-supply settings
- Optimal prediction windows in multiple dispensation studies
- The impact of trigger and re-supply levels on the number of shipments

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[4] Source: Dowlman, Lang, McEntegart, Nicholls, Bacon, Star & Byrom (2004).

- The best time to plan subsequent production runs
- How much material to pack, given a particular study and pack design
- How expiry may impact on a study
- What impact different randomization methodologies will have on the available supply material?
- Investigating the use of local depots versus direct-to-site shipments
- Costs and benefits of frequent small shipments or fewer larger shipments versus drug cost and availability
- Benefits of using IVR in a trial.

Although simulation is an extremely effective tool for measuring performance in supply chains, it involves advanced techniques and requires a high level of understanding in order to benefit from its results. The aim of the research in this thesis is to develop a model that can easily be understood and is therefore user-friendly at all levels of management within a firm.

### 4.4.3 Existing Frameworks for Measuring Overall Supply Chain Performance

A common problem that is facing many firms is the fact that a supply chain is often composed of independent business units and legal entities with separate owners and managers, each with differing business goals and objectives. However, sufficient evidence exists that supports the notion that both private and public firms can benefit when cross-enterprise processes are integrated and synchronized, and separate firms cooperate to optimize the supply chain. Because of this recognition, numerous efforts have been made to develop methods for measuring system-wide supply chain performance. Three of the best known proposals for co-ordinated chain-wide performance measurement are (Davis & Spekman, 2004):

- The SCOR model
- The Supply Chain Performance Scorecard developed by the Performance Measurement Group (PMG)
- The Balanced Scorecard (BSC) for SCM

The supply chain operations reference (SCOR) model, developed by the Supply Chain Council, is a strategic planning tool that allows senior managers to simplify the complexity of supply chain management (Huan, Sheoran & Wang, 2004). The aim of the SCOR model is to provide a standardized method of measuring supply chain performance and to use a common set of metrics to benchmark against other organizations (Forbes.com, 2006).

The initial measure of the SCOR model is that of the current state of the process being examined. This information is then used to determine the desired future state of the process. After this, the operational performance has to be quantified and compared to that of similar companies, in order to establish internal targets based on "best-in-class" results. Finally, best practice analysis has to be performed, in which management practices and software solutions are identified that can result in "best-in-class" performance. The main goal of SCOR is the description, measurement and analysis of supply-chain configurations (Kussing, 2009).

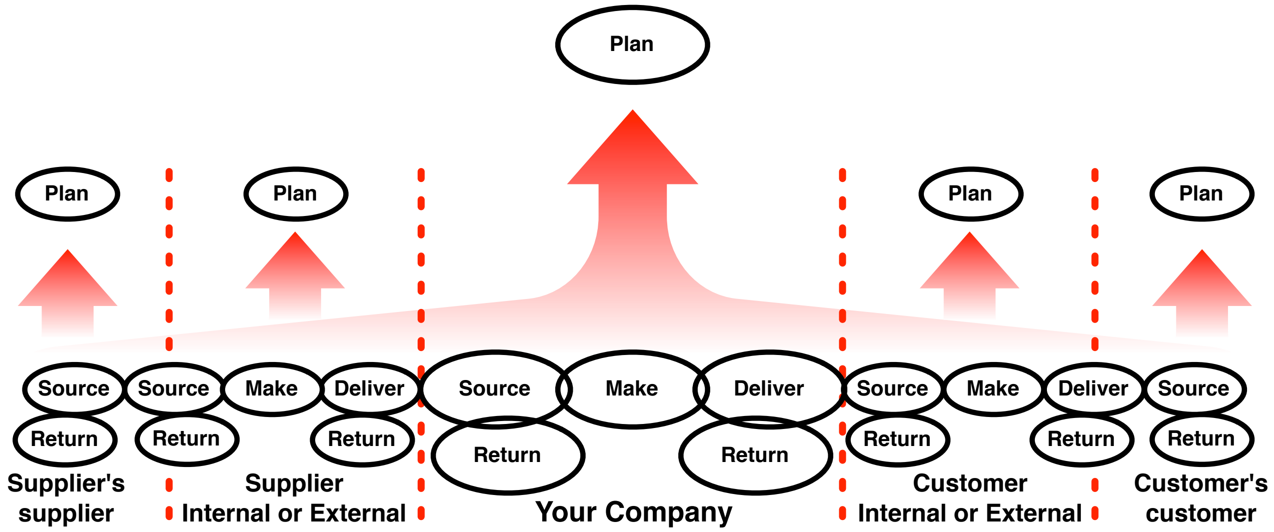
SCOR is based on five distinct management processes: Plan, Source, Make, Deliver, and Return. It also facilitates inter and intra supply chain collaboration and horizontal process integration, by explaining the relationships between processes (i.e., Plan-Source, Plan-Make) (Badr & Stephan, 2007). In addition, the SCOR model is beneficial for inputting data in order to analyze various configuration options better, such as Make-To-Order and Make-To-Stock. The SCOR model makes this possible by describing, measuring, and evaluating the supply chain. It also supports strategic planning and encourages continual improvement of the chain. A schematic representation of the SCOR model is given in Figure 4.3.

According to Wong & Wong (2008) SCOR fails to address the issue of integration synchronization. One of the findings highlighted by Samuel, Sunl & Wang (2004) was that, "although the SCOR model provides a common supply-chain framework, standard terminology, common metrics associated benchmarks and best practices, the approach on the utilization of SCOR seems to be rather rigid and needs further enhancement".

As supply chains become increasingly complex and more and more competitive with one another, firms are looking for a way to achieve or maintain a competitive advantage. One solution to the problem is a performance measurement that is dynamic and able to evaluate various different variables and scenarios. However, SCOR does not currently have the ability to meet those needs.

According to Wong & Wong (2008), SCOR needs a network modelling tool to support the change management decision. This goes hand-in-hand with a firm's need to address supply chain benchmark-

**Figure 4.3:** SCOR Model[5].



ing from a holistic approach. Thus in order for the SCOR model to be more accurate in evaluating integrated supply chains it is important to include some change management. To date, SCOR has only been using deterministic performance metrics, measures which managers can control and determine accurately (Wong & Wong, 2008). However, in an integrated supply chain, the levels of the chain become more complicated and managers have to be accountable for various performance measures.

The SCOR model is currently used as cross-industry standard for supply chain management both internationally and in South Africa. Although it can be used successfully to measure supply chain performance, it does not measure supply chain efficiency. The scope of the research in this thesis is to develop a model for measuring the efficiency across the entire supply chain. Therefore, the SCOR model will be used as a basis for comparative purposes (i.e. the strengths of the SCOR model will be used as a guideline on which to base the structure of the model developed), but the latter (see Chapter 7) measures the efficiency of the supply chain and not just its performance.

Table 4.1 shows a subset of metrics proposed for use with the SCOR model, intended to be applied to all enterprises along a particular supply chain (Davis & Spekman, 2004).

The Supply Chain Performance Scorecard was developed by the Performance Measurement Group (PMG) in 1994. Four broad areas of performance measurement were addressed (Davis & Spekman, 2004):

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[5] Source: Supply-Chain Council (2009).

**Table 4.1:** SCOR Metrics for Supply Chain-wide Performance Measure[6].

| Attribute | Attribute Definition | Measurement |
|---|---|---|
| Supply chain delivery reliability | The performance of the supply chain in delivering the correct product to the correct place, at the correct time, in the correct condition and packaging, in the correct quantity, and with the correct documentation to the correct customer. | Delivery performance<br>Fill rates<br>Perfect order fulfilment |
| Supply chain responsiveness | The velocity at which a supply chain provides products to the customer. | Order fulfilment lead times |
| Supply chain flexibility | The agility of a supply chain in responding to marketplace changes to gain or maintain competitive advantage. | Supply chain response time<br>Production flexibility |
| Supply chain costs | The costs associated with operating the supply chain. | Cost of goods sold<br>Total supply chain management costs<br>Value-added productivity<br>Warranty/returns processing costs |
| Supply chain asset management efficiency | The effectiveness of an organization in managing assets to support demand satisfaction. This includes the management of all assets, fixed and working capital. | Cash-to-cash cycle time<br>Inventory days of supply<br>Asset returns |

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Source: Supply-Chain Council (2009).

- Customer satisfaction/quality
- Cost
- Time
- Assets

A total of eight primary measures and ten secondary measures are proposed by the group to measure performance across these four areas. Table 4.2 shows an early version of the PMG scorecard.

**Table 4.2:** An Early version of the PMG Scorecard[7].

| **Performance Measure** | **Customer-Facing** | | **Internally Facing** | |
|---|---|---|---|---|
| | **Delivery** | **Responsiveness** | **Cost** | **Assets** |
| Delivery performance to request | × | | | |
| Delivery performance to commit | × | | | |
| Order fulfilment lead time | | × | | |
| Upside production flexibility | | × | | |
| Total SCM cost | | | × | |
| Cash-to-Cash cycle time | | | | × |
| Total inventory day's supply | | | | × |
| Net asset turns | | | | × |

Originally containing the eight measurements shown in Table 4.2, the scorecard has evolved into a balanced set of the four measurements highlighted in the table. These include two customer-facing (delivery performance to commit and upside production flexibility) and two internally-facing metrics (cash-to-cash cycle time and net asset turns) (Davis & Spekman, 2004).

The Balanced Scorecard method was developed by Kaplan and Norton during the early nineties. The balanced scorecard is more than just a measurement system. It is a management system that enables organisations to identify their goals and then develop a strategy that helps to convert ideas into actions. It provides feedback around both the internal business processes and external outcomes in order to improve strategic performance and results continuously, and since managers can view all the important aspects of the business, the tendency to improve one area of the business at the expense of another is minimised (Abu-Suleiman, Boardman & Priest, 2004). However, the balanced scorecard has a serious flaw in that it does not take competitors into account (Neely, Gregory & Platts, 1995).

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[7] Source: Davis & Spekman (2004).

The model developed includes the benefits of the balanced scorecard method, i.e. it ensures that one link or node in the supply chain is not improved at the expense of another, however, it also takes competitors into account.

## 4.5 Benchmarking

Benchmarking is a form of performance measurement, where a business compares the performance of its activities against the performance of other businesses. It is thus rather an exercise of performance comparison rather than performance measurement (Kussing, 2009). Benchmarking is a management tool that has been developed around the viewpoint of continual improvement and change, characteristic of the total quality management approach (Carpinetti & Melo, 2002), with the aim of improving productivity and company performance (Cuadrado, Frasquet & Cervera, 2004). Bemowski (1991) defines benchmarking as "the measurement of a company's performance in comparison to the best, determining how those companies achieve superior performance and using that information as the basis to decide on and implement objectives and strategies". Thus, benchmarking is useful because it gives a firm an indication of where it stands in the market.

Benchmarking is a continuous process of the measurement of products, services and work processes, against those recognised as leaders in the industry. The goal of benchmarking is to assist companies in achieving best practices within the organisation. Although no two benchmarking exercises will follow exactly the same procedure, they will have the following characteristics in common (Kussing, 2009)[8]:

- **Continuous** - Benchmarking is a process that takes place over an extended period; it's not a one-time panacea.
- **Systematic** - For any benchmark effort to prove successful there must be a consistency among organizational functions and locations and a common set of expectations regarding realistic outcomes.
- **Process** - Benchmarking involves a series of actions that define issues, problems or opportunities. The benchmark process also measures internal and external performance and draws conclusions based on an analysis of the information collected. The underlying goal of benchmarking is to stimulate organizational change and improvement.

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[8] Source: (Spendolini, 1992).

- **Evaluation** - While benchmarking does not deliver answers, it is considered a useful tool that helps people learn about themselves and others.
- **Work processes** - Benchmarking is useful in understanding work processes as well as the finished products or services these processes produce.
- **Organizations** - Benchmarking can be applied to any organization that engages in similar business practices or that manufactures similar products.
- **Recognition** - Benchmarking involves an initial investigation to determine which companies are considered vastly superior in the area or process under evaluation.
- **Best practices** - To maximize the potential for rewarding results, the organizations chosen for investigation and analysis should be considered on a world-class level in terms of the subject being benchmarked.
- **Organizational improvement** - Generally speaking, the purpose of benchmarking usually includes some reference to comparisons and change. Any successful benchmark effort should culminate with a clarion call to action.

Supply chain benchmarking has certain distinct characteristics and features that distinguish it from other fields (Wong & Wong, 2008). By focusing on the definition of a supply chain used in this dissertation that *"the core function of a supply chain is to add value to a product by moving it from one place to another, in the course of which movement the product may be changed through processing"*, supply chain benchmarking can be viewed as comparing these movements against the relevant metrics of successful firms or chains. Hence, benchmarking of a supply chain covers various aspects such as processes, products, performances and strategies. Thus, supply chain benchmarking can be viewed as an integrated form of benchmarking, giving a holistic examination for the whole entity (Gilmour, 1999).

## 4.6 Methods and Models for Measuring Supply Chain Efficiency

An important measure of efficiency within and along a supply chain is the amount of idle time at each stage of the supply chain. In addition, throughput, turnaround times and utilisation of the facilities within the supply chain will also have a major impact on the overall efficiency of the chain. Thus a number of methods have been formulated to determine the idle time, throughput, turnaround times and utilization of the facilities in a supply chain. Talley (1994), points out that seaports have traditionally been evaluated by comparing their actual throughput (e.g. tonnage or containers handled) with their optimum throughput for a specified time period. If actual throughput is approaching the optimum throughput over time, a port's performance is said to be improving or, alternatively it is classified as deteriorating. Talley (1994) continues, by highlighting a few of the methods used in Australia to measure performance within a seaport.

"Stevedoring performance indicators measure productivity and utilization of equipment and labour resources across container, Roll-On-Roll-Off (RO-RO), conventional and bulk handling stevedoring operations. These indicators from an equipment perspective include:

- the number of ships and cargo handled (an indicator of the output work load)
- cargo handling rate (the rate at which ships are loaded and discharged)
- containers handled per crane (the rate at which cranes are worked)
- units per man-shift (total cargo handled divided by the number of man-shifts paid for to accomplish the work)"

"The indicators from a labour perspective include: number of employees;

- average age of the total labour force;
- average hours worked per week; and
- idle time percentages (the percentage of time employees are available for work but are not required to work)"

"Shipping line performance indicators are concerned with delays experienced by ships. These indicators include:

- average delay to ships awaiting berths and
- average delay to ships whilst alongside berths"

"Port Authority performance indicators measure port facility utilisation and throughput. These indicators include:

- facility utilisation (as a percentage of total available time),
- tonnage handled (or port throughput) and
- truck turnaround time and queuing (i.e. performance interface in container terminals)" (Talley, 1994)

### 4.6.1 Simple Methods for Measuring Supply Chain Efficiency

There is currently a wide variety of literature available on supply chain efficiency and the important role that an efficient supply chain fulfils in a successful organization. Some of the more common tools used to measure supply chain efficiency include the "spider" or "radar" diagram (a spider or radar diagram is used to display graphically the comparative values of multiple variables in a data set; to display values of different categories of data on a single chart; and to aid in the identification of composite performance measure elements needing improvement (Performance Improvement Network, 2005)) and the "Z" chart (The Z-chart is a combination chart that shows three perspectives in a single picture (Syque.com, 2007)). These tools are based on gap analysis techniques and they are graphical in nature (Wong & Wong, 2007). Although the graphical nature of the techniques makes them easy to understand, it also limits them in their ability to handle complex situations. In other words, it is not feasible to measure the efficiency of a supply chain using these tools when there are multiple inputs or outputs (Wong & Wong, 2007).

Another popular method used for measuring supply chain efficiency is the ratio. It calculates the efficiency of the supply chain by comparing the relative efficiencies of the outputs against different combinations of inputs. For example, in the past supply chain efficiency was measured by taking the ratio of revenue over the total supply chain operational costs (Wong & Wong, 2007). The main strength of ratios is that they are easy to calculate and can be understood by employees with a limited understanding of mathematics. However, a shortfall in the method of using ratios to calculate efficiency across an entire supply chain is that there are multiple inputs and outputs to be considered, and therefore many different ratios need to be calculated. To date, there is no model available to combine the entire set of ratios into a single answer and therefore the ratios cannot give a reliable conclusion. However, the model developed in this dissertation uses the simplicity of ratios as a starting point and devises a mathematical method for combining them in order to provide a measurement for supply chain efficiency.

Single output to input financial ratios such as return on sales and return on investment are not adequate for use as indices to characterize the overall supply chain efficiency. Hence, the traditional tools that are currently in use, which do not take multiple concepts into account, are not able to provide a good measure of supply chain efficiency (Wong & Wong, 2007). The model devised incorporates ratios that measure speed, reliability and customer service efficiency in addition to cost efficiency and therefore provides a more inclusive measure for supply chain efficiency.

Since supply chain efficiency is a complex phenomenon requiring more than a single criterion to be characterized, a number of studies have suggested that a multi-factor performance measurement model may be applied for the evaluation of supply chain efficiency (Zhu, 2000). The development of a multi-factor performance measure, which reflects the efficiency of functional units and technologies implemented in a supply chain, is important to policy makers for knowing how far a particular industry or firm can be expected to increase its multiple outputs and decrease its input level through the improvement of its efficiency (Wong & Wong, 2007). Data envelopment Analysis (DEA) has become the main topic of interest as a mathematical tool to measure efficiency in a supply chain. The next section will give a brief review of DEA.

### 4.6.2 Review of DEA and its Applications in Measuring Supply Chain Efficiency

DEA was first introduced by Charnes, Cooper & Rhodes (1978) as a linear programming (LP)-based methodology for performing the analysis of how efficiently a firm operates (Wong & Wong, 2007). DEA is a data-oriented approach for evaluating the performance of a set of peer entities called Decision Making Units (DMU) which convert multiple inputs into multiple outputs (Cooper, Seiford & Zhu, 2004). It is a nonparametric approach to frontier estimation. In other words, it means that DEA does not rely on the definition of the specific role that the variables perform in order to specify the relationships or trade-offs among the performance measures in the calculation of efficiency and it utilizes the concept of efficient frontier as an empirical benchmark (Mathematically the efficient frontier "is the intersection of the set of portfolios with minimum variance and the set of portfolios with maximum return" (Chen, Chung, Ho & Hsu, 2008)). It is defined by Granite Financial Group (2009) as "a statistical result from the analysis of the risk and return for a given set of assets that indicates the balance of assets that may, under certain assumptions, achieve the best return for a given level of risk"). These advantages of DEA enable managers to evaluate any measures efficiently as they do not need to find any relationship that relates to them (Wong & Wong, 2007).

*Before DEA can be used to calculate efficiency it is important to define the conditions for efficiency. According to Charnes & Cooper (1984) 100% efficiency is attained for any DMU only when:*

- *None of its outputs can be increased without either*
    - *increasing one or more of its inputs or*
    - *decreasing some of its other outputs.*
- *None of its inputs can be decreased without either*
    - *decreasing one or more of its outputs or*
    - *increasing some of its other inputs.*

Thus efficiency is represented by the attainment of Pareto optimality. Output or input inefficiency corrections are allowed under this definition without worsening any other input or output and the need for assigning measures of relative importance to the different inputs and outputs is thereby avoided (Charnes & Cooper, 1984).

The aforementioned definition is formulated so that efficiency can be determined relative to prior theoretical knowledge. Such knowledge of true or theoretical efficiency is not available for all situations and therefore in such cases, the above definition must be extended to one which involves only *relative* efficiency as determined from the kind of data that are likely to be available.

*100% relative efficiency is attained by any Decision Making Unit (DMU) only when comparisons with other relevant DMUs do not provide evidence of inefficiency in the use of any input or output.*

Under the conditions described, the preceding definition is expanded to include situations when all the required information is not freely available.

A common statistical approach is portrayed as a central tendency approach and it evaluates variables relative to an average variable. In contrast, DEA is an extreme point method and compares each variable with only the "best" variable (University of Phoenix, 1996). Because it requires very few assumptions, DEA has also opened up possibilities for use in cases which have been resistant to other approaches because of the complex (often unknown) nature of the relationships between the multiple inputs and multiple outputs involved in DMUs (Cooper, Seiford & Zhu, 2004).

The core of DEA rests in finding the optimal virtual variable for each real variable. If the virtual variable is better than the original variable by either making more output with the same input or making the same output with less input then the original variable is inefficient.

DEA does not require assigned numeric weights or modelling preferences for analysis. However, these could be introduced if the information is available and it is deemed helpful. The DEA model automatically computes weights that give the highest possible efficiency score to a DMU while keeping the efficiency scores of all DMUs less than or equal to one under the same set of weights (Wong & Wong, 2007). This helps to prevent discrimination of criteria used in the analysis based on the different analysts' individual perspectives (Wong & Wong, 2007).

### 4.6.3 Current DEA Models used for Measuring Supply Chain Efficiency

Data Envelopment Analysis (DEA) is becoming more and more popular as a means to calculate efficiency within and along supply chains. It was therefore chosen as the mathematical method used in the model developed. The following section will describe the models that were incorporated (either in part or in full) within the model developed as well as a few additional models that are used in practice, but were not included in this research's model. The reason for the inclusion of the latter models is to verify the fact that data envelopment analysis can be used to calculate efficiency across an entire supply chain.

Weber & Desai (1996) and Weber et al. (1998) investigated the subject of supplier selection and supplier negotiation along a supply chain and the effect that it has on overall supply chain efficiency with the help of DEA modelling. However, on both occasions, the research conducted was mainly focused on input analysis, i.e. they did not specifically investigate any output variable except for a constant, one unit of product as output. In order to obtain a complete assessment of supplier performance, the use of both input and output variables is important. Mention is made of this research in order to highlight the importance of carefully selected inputs and outputs in the development of a model in order to provide a reliable evaluation of the efficiency and productivity of a supply chain.

Liang, Yang & Cook (2006) develop a number of DEA models for characterizing and measuring supply chain efficiency when intermediate measures are incorporated into the performance evaluation. Because conventional DEA models cannot be directly applied to evaluating multi-member supply chain operations, the models they developed become important tools for managers when monitoring and planning their supply chain operations and can significantly aid in making supply chains more efficient. The relevant concepts discussed in their research are included in the model developed.

Seth, Deshmukh & Vrat (2006) highlighted the importance of service quality in supply chain efficiency and developed a conceptual framework for its measurement using DEA modelling. Their research showed that service quality not only has an impact on suppliers/distributors, employees and customers, but it also affects the overall business and growth of the organization. Due to its importance in the overall efficiency of a supply chain, service quality is included in the model that is developed in Chapter 7. It forms part of the first stage of the measurement process.

Min & Joo (2006) use DEA to measure the operational efficiency of various profit and non-profit organizations in order to improve the productivity of third party logistics providers (3PLs) in the increasingly competitive logistics market. The proposed DEA model also helps 3PLs identify potential sources of inefficiency and provide useful hindsight for the continuous improvement of operational efficiency (Min & Joo, 2006). Although the finding of the research completed by Min and Jong Joo is not used directly in the model developed in Chapter 7, it is included to back up the notion that DEA can successfully be implemented to calculate efficiency in supply chains and, therefore, adds weight to this research.

Wong & Wong (2007) developed two DEA models, i.e. a technical efficiency model and a cost efficiency model, for measuring internal supply chain efficiency. The information obtained from the DEA models can be used to help managers identify the inefficient operations and take the correct curative actions for continuous improvement. In addition, the cost efficiency model calculates the opportunity costs (forgone profit) which can be used as a guide by managers when they have to make important resource allocation decisions (Wong & Wong, 2007). The mathematical method implemented in the article by Wong and Wong is applied in the model developed in Chapter 7. However, different input and output variables have been selected and will therefore provide managers with a different method for measuring supply chain efficiency.

## 4.7 Conclusion

In an attempt to develop a model that can measure the efficiency across an entire supply chain it is important at first to determine the types of measures that are already available in practice. This chapter presents various measures and models that are currently in use in the field of supply chains. The majority of the measures are focused only on determining the efficiency within a single link or node in a supply chain and therefore creates the opportunity for developing a model that can determine efficiency throughout a supply chain. Many of the measures or models described in this chapter are used in the development of the model in Chapter 7.

# CHAPTER 5

# Factors that influence supply chain efficiency

## 5.1 Introduction

South Africa is classified as a developing country, because the majority of people have a lower standard of living with access to fewer goods and services than most people in high-income, first world countries (European Commission, 2007). Another view is that a developing country is one that exports raw materials instead of beneficiating them and becomes developed when it relies on imported resources to produce its exports. South Africa also has a high level of unemployment at 26,7% in September 2005 (Statistics South Africa, 2005). Thus, South Africa faces the dilemma that improved efficiency usually means an increase in technology, but an increase in technology often results in job losses. It is therefore important to find ways of improving efficiency along supply chains without extensive job losses.

The development of the South African economy relies heavily upon earnings from physical exports, which depend increasingly upon the competitiveness in global markets of the maritime supply chains that serve the country. In accordance with world best practice those chains need to function as entities structured to serve their logistical purpose. This chapter identifies some of those factors that have a large influence on the overall efficiency of a supply chain and introduces formulae for measuring them.

These are not the only factors that influence supply chain efficiency. In fact, there are numerous other factors that could influence the efficiency of a supply chain but it is not feasible to include all of them in this study. However, the factors that are included are believed to be the main factors that influence the efficiency of many South African supply chains (as were identified through the personal interviews with experts in the field). Furthermore, all the necessary steps for calculating the influence of any supplementary factors are provided in the development of the model. Because of the generic nature of the model developed, it is possible for firms using the model to make the necessary adaptations to the model.

## 5.2 Idle Time in the Supply Chain

Idle time is defined by the Saskatoon and District Labour Council (2006) as "non-productive time resulting from waiting for work, machinery or other breakdowns and the like". It is defined by Pcmag.com (2007) as "the duration of time a device is in an idle state, which means that it is operational, but not being used". From the definitions, it is clear that idle time can be detrimental to the efficiency of the supply chain. Thus steps must be taken to ensure that idle time is kept to a minimum at every stage in the supply chain.

According to WordNet (2009), efficiency can be defined as "skilfulness in avoiding wasted time and effort". Although this definition differs from the definition for efficiency used in this dissertation, the definition supports the notion that time can be one of the criterions laid down in order to determine efficiency within a supply chain. Thus maximising efficiency would reduce the amount of idle time in the supply chain and since time has value, reducing idle time adds value to the chain.

Talley (1994) provides a ratio of the time available for work and work being done to the time available for work and no work being completed.

$$Idle\ time^{1}\ (\%) = \begin{array}{l} The\ percentage\ of\ time\ employees\ and\ equipment\ are\ available\ for\ work \\ but\ do\ not\ work \end{array} \tag{5.1}$$

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[1] possible reasons for idle time include "loafing" on the job, extended lunch and tea breaks, doing personal business instead of the job requirements, waiting for inputs and phoning friends

According to the parameters chosen for this study (refer to sections 3.4 and 3.6) idle time affects both the speed and the reliability of a supply chain. The importance of this measure lies in the ability to identify possible non-optimal worker and equipment time allocation. If the amount of idle time in the supply chain under review is fixed then it will affect the overall speed of the supply chain. However, if the amount of idle time varies then it will affect the reliability of the supply chain. In both cases, the same formula can be used to determine the measure of idle time in the supply chain. The form of idle time will determine whether the measurement is included under the reliability or speed efficiency measurement when calculating the overall efficiency of the supply chain.

## 5.3 Infrastructure Availability and Utilisation

Academic literature and business reports show that productivity differs between countries at the industry level. Causal observation in developing countries suggests that poor infrastructure contributes to low levels of productivity (Yeaple & Golub, 2004). Power outages, weak telecommunication systems and lack of adequate transport infrastructure are all obstacles to investment, growth and poverty alleviation in developing countries (World Bank, 2002).

When referring to transport infrastructure, reference is made to the durable capital of a city, region and the country and its location is fixed. It includes roads, railways, canals, ports, airports, communication links (e.g. air traffic control installations) and terminals and other interchanges (Banister & Berechman, 2003). In addition, Kay (1993) states that transport and other infrastructure have the following characteristics:

- Constituting networks involving delivery systems that are substantial interactions in the provision of services to individual customers.
- Forming a small but indispensable part of the total costs of a wide range of products in which they are used, thus the losses that result from service failure are often very large relative to the basic cost of service provision.
- Substantial elements of natural monopoly exist and competitive provision of infrastructure is costly, often prohibitively so, not to exclude competition in the use of infrastructure.
- Relative to the running cost of infrastructure, the capital cost thereof is generally large.

- Sunk costs of establishing infrastructure are substantial and so a high proportion of the total cost of a service relying on the infrastructure has already been incurred before that service is offered.

The Government prior to 1940 developed an extensive rail and port network and at one stage the railways and ports of South Africa were among the most efficient in the world, especially in the conveyance of bulk exports. Even during sanctions, raw materials were exported without problems and record rail loads were achieved. However, during the past twenty years South Africa's rail network and ports have been neglected as the Government focused on building a well-developed road transport infrastructure in order to support domestic markets.

Since South Africa's re-entry into the world markets the focus has shifted away from local trade towards international trade and both the private and public sector have realised the importance of improving the entire spectrum of South Africa's transport infrastructure. South Africa is now striving to increase its exports not only with the rest of the African continent, but with the rest of the world. Additional pressure is being placed on the already strained logistics infrastructure by the fast growing economy, and the resultant increase in freight movement and traffic volumes. In addition, the demands of the 2010 Soccer World Cup have identified areas of weakness in South Africa's infrastructure. The situation is made worse by the total lack of adequate public transport and record private motor vehicle sales (Ittmann, 2007b).

The basis for future infrastructure investments in South Africa's ports is driven by the cargo volumes that are handled through the ports. Cargo forecasts are used to determine infrastructure capacity requirements. The capacity of any terminal in the port is restricted by the function or operation that has the lowest capacity. From an investment perspective it is therefore important to ensure that there is a matching of capacity provided in the links between the ships' cargo handling system, storage and onward transportation (National Ports Authority, 2005). Marlow & Paixo (2002) agree by highlighting that modern ports require agility in order to function properly and that agility can only be achieved through the provision of sufficient infrastructure (agility is defined as "the ability to be reliable in an uncertain and changing environment by being able to respond quickly to changes" (Prater, Biehl & Smith, 2001). Clark, Dollar & Micco (2004) support this argument by highlighting the fact that onshore infrastructure is an important one, and that countries with good infrastructure have lower port costs.

In research conducted by Schoeman (2007) one of the major complaints of South Africa's fast moving consumer goods industry is the poor levels of port and rail infrastructure in the country. The research identifies a shortage of skills, the suboptimal utilization of assets and inefficient processes as the main causes for the inefficiencies in rail and port infrastructure (Schoeman, 2007). The research also identified that there is a lack of infrastructure to link supply chains with the informal sector (Small, Medium and Micro enterprises (SMME's)) in South Africa. This limits South Africa's ability to reduce unemployment and alleviate poverty.

The Moving South Africa (MSA) (Department of Transport, 1998) strategy promotes the notion that exporters can benefit from lower transport costs through the consolidation of freight flows into a limited number of corridors. This consolidation would result in substantial costs savings in the provision of land-based infrastructure.

According to Saxton (2006) *"A revamping of South Africa's internal and external logistics infrastructures and systems is therefore critical to our future, both for African and for international competitiveness. The reality is that South Africa will take some years before it is able to re-engineer this infrastructure. During these years of re-engineering and reconstruction, South Africa, its businesses and its industries, will need to find ways and means of reducing its costs of logistics, and being able to provide its customers and its markets with the competitive advantage that comes from supply chain management focus and logistical integration..."* (Ittmann, 2007b).

South Africa must plan and provide infrastructure for the long-term. Stakeholders need to think big, be bold and consider a 50-year time horizon at minimum. There are enormous challenges facing the country in the short term in order to meet the requirements of 2010. However, it is critical to plan for and develop the infrastructure way beyond 2010 (Ittmann, 2007b).

There are numerous situations that can cause disruptions to supply chains. One of the causes is lack of sufficient infrastructure to handle the demand of the supply chain. If the demand for a commodity grows rapidly, the available capacity may be unable to handle the increase in demand and may cause delays. When supply and demand is finely balanced, even a relatively minor interruption in flow can throw a supply chain into crisis, particularly in global markets. The potential vulnerability to such disruptions needs to be understood and firms need to plan properly in order to prevent disruptions due to insufficient infrastructure capacity.

The availability of infrastructure, both physical and technological, plays a very important role in determining the overall efficiency of a supply chain. Insufficient infrastructure leads to congestion and delays, which will ultimately result in lower customer satisfaction and reduced sales, while the oversupply of infrastructure leads to unnecessary costs. It is unnecessary to supply infrastructure for the peaks in demand, because this will only result in an excess of infrastructure at other times. Thus, it is important to determine the optimal supply of infrastructure, which can be achieved by implementing cost benefit analyses.

According to the parameters chosen in this study for the measurement of efficiency across an entire supply chain (refer to sections 3.4 and 3.6), the availability of infrastructure must be measured according to its effect on the reliability, cost and overall speed of the supply chain. Insufficient infrastructure will affect the reliability of the supply chain as it will cause delays, while the infrastructure provided will affect the costs of the supply chain (more infrastructure provided will result in greater costs). Thus both aspects must be measured when determining the overall efficiency of a supply chain. The formulae used in the calculations are given below.

$$\begin{array}{l}\textit{Reduction in production due to lack}\\ \textit{of necessary infrastructure}\ (\%)\end{array} = \frac{\textit{Production decrease from lack of infrastructure}}{\textit{Total produced if there was no shortage}} \times \frac{100}{1} \tag{5.2}$$

$$\begin{array}{l}\textit{Reduction in storage due to lack}\\ \textit{of necessary infrastructure}\ (\%)\end{array} = \frac{\textit{Storage decrease from lack of infrastructure}}{\textit{Total stored if there was no shortage}} \times \frac{100}{1} \tag{5.3}$$

$$\begin{array}{l}\textit{Reduction in transport due to lack}\\ \textit{of necessary infrastructure}\ (\%)\end{array} = \frac{\textit{Transport decrease from lack of infrastructure}}{\textit{Total transport if there was no shortage}} \times \frac{100}{1} \tag{5.4}$$

$$\begin{array}{l}\textit{Cost to balance production resources}\\ \textit{with production requirements}\end{array} = \begin{array}{l}\textit{Sum of costs associated with the balance of}\\ \textit{production resources with production requirements}\end{array} \tag{5.5}$$

$$\begin{array}{l}\textit{Cost to balance storage resources}\\ \textit{with storage requirements}\end{array} = \begin{array}{l}\textit{Sum of costs associated with the balance of}\\ \textit{storage resources with storage requirements}\end{array} \tag{5.6}$$

$$\begin{array}{l}\textit{Cost to balance transport resources}\\ \textit{with transport requirements}\end{array} = \begin{array}{l}\textit{Sum of costs associated with the balance of}\\ \textit{transport resources with transport requirements}\end{array} \tag{5.7}$$

## 5.4 Transport Productivity

Transport is an essential part of most supply chains and therefore problems experienced in the transport legs of a supply chain can have a substantial impact on the overall efficiency of a supply chain. Low transport productivity is a problem facing a number of South African supply chains. The causes of low transport productivity vary from congestion on South Africa's roads, lack of sufficient transport infrastructure and lack of vehicle scheduling and route planning to lack of driver skills and poor management and administration of the transport function with a supply chain.

The overuse of the national and urban road network represents a barrier to both domestic and international logistics competitiveness (Ittmann, 2007b). Congestion, on especially urban roads, is severely impacting freight movements, and is resulting in increased logistics costs. Road freight carriers are continuously gaining market share on long distance links where rail transport is the more cost efficient mode. The greater value added by road freight carriers in comparison with rail transport through service effectiveness is often greater than the cost premium paid for utilizing their service rather than making use of rail transport (Pienaar, 2007). These conditions are expected to worsen in the short term, and South African industry is facing severe logistics challenges (Saxton, 2006). Thus steps have to be taken to improve the efficiency of South Africa's rail transport system as this will help to shift a portion of the freight away from the national and urban road network and in so doing will not only reduce the congestion on the national and urban roads, but will result in a more cost effective land transport supply chain.

A lack of vehicle scheduling and route planning causes many problems for some supply chains. Although it will have no effect on bulk supply chains that make use of rail transport and cover the same route on every trip, it can have a large impact on a commodity like those from the pharmaceutical industry. For example, a pharmacy receives prescriptions for various different types of medicines throughout the day. If they do not have the medicine that is requested on their shelves, they have to get the medicine from their suppliers (or other branches of the pharmacy). It then becomes a routing and scheduling problem to determine whether to try and fill the prescription every time there is no stock available or to only make the trip once a day at the end of the day. Making numerous trips increases customer satisfaction, but also increases costs and the two must therefore be traded off against each other in order to make the decision that is best for the supply chain.

In the third state of Logistics Survey for South Africa conducted by Ittmann et al. (2007), it was found that low transport productivity was one of the main problem areas in the fast moving consumer goods

(FMCG) industry in South Africa. The causes of inefficiency in a FMCG supply chain are described in Table 5.1.

**Table 5.1:** Low Transport Productivity Inefficiencies based on FMCG Industry Self Analysis[2].

| Inefficiency | Cause |
|---|---|
| Backdoor congestion | Poor receiving bay infrastructure<br>Poor management / administrative discipline<br>Inefficient replenishment policy / merchandising<br>Unloading: inefficient planning and operations<br>Multiple single consignment deliveries<br>Lack of vehicle scheduling and route planning<br>Incorrect bar-coding by manufacturers undermine IT initiatives at backdoors causing delays |
| Reverse logistics | Credit note trading terms: high cost of return items |
| Inefficient vehicle utilization and infrequent delivery | Inefficient replenishment policy / merchandising<br>Lack of vehicle scheduling and route planning<br>Sub-optimal distribution fleet configuration |
| Road congestion | Limited delivery timeframe (security and working hour constraints)<br>Commercial development in high-density residential areas<br>Lack of truck driver skills |

The formulae for calculating transport efficiency are given below.

$$\begin{array}{l} Transportation\ efficiency\ in\ terms \\ of\ maritime\ transportation\ (\%) \end{array} = \frac{Actual\ ton\ miles\ undertaken\ for\ transportation}{Planned\ ton\ milesundertaken\ for\ transportation} \times \frac{100}{1} \tag{5.8}$$

$$Land\ based\ transport\ services\ (\%) = \frac{Volume\ delivered\ by\ land\ transportation}{Total\ volume\ planned} \times \frac{100}{1} \tag{5.9}$$

$$Total\ transit\ time\ (hours) = \begin{array}{l} Travel\ time + Waiting\ time\ at\ terminals/docks + \\ Transfer\ time + Handling\ time \end{array} \tag{4.27}$$

$$\begin{array}{l} Variability\ as\ a\ \% \\ of\ transit\ time \end{array} = \frac{Max\ transit\ time\ (hours) - Min\ transit\ time\ (hours)}{Average\ transit\ time\ (hours)} \times \frac{100}{1} \tag{4.28}$$

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[2] Source: Schoeman (2007).

$$Perfect\ shipments\ (\%) = \frac{Number\ of\ perfect\ shipments}{Total\ number\ of\ shipments} \times \frac{100}{1} \tag{4.29}$$

$$Cost\ per\ ton\ of\ cargo\ transported (Rands/ton) = \frac{Total\ transport\ cost\ (Rand)}{Number\ of\ tons\ of\ cargo\ transported\ (tons)} \tag{4.30}$$

$$\begin{array}{l} Utilisation\ of \\ transport\ means\ (\%) \end{array} = \frac{Delays\ incurred\ (hours)}{Time\ transport\ means\ were\ employed\ (hours)} \times \frac{100}{1} \tag{4.31}$$

## 5.5 Method of Freight Handling

Stopford (2009) includes efficient goods handling as one of the four principles of system design, and points to the fact that the use of high productivity handling equipment will essentially contribute to overall efficiency in two ways:

- It lowers unit-costs by eliminating unnecessary handling (cost efficiency), and
- Will lead to faster turnaround time, because of faster loading (speed efficiency).

Goods handling along the supply chain therefore has an impact on the overall efficiency of a supply chain. Measuring goods handling efficiency for a specific supply chain can be achieved through determining the best practice (BP) measure for goods handling in a similar supply chain either locally or internationally and then comparing the supply chain in question to the best practice measure. Due to the nature of goods handling, it is important to include the measurement in terms of both costs and overall supply chain speed. The formulae for the measurements are given below. The formulae were developed by the author for the purpose of this dissertation.

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ cost\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ costs\ (Rands)}{Actual\ goods\ handling\ i.t.o.\ costs\ (Rands)} \times \frac{100}{1} \tag{5.10}$$

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ time^{3}\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)}{Actual\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)} \times \frac{100}{1} \tag{5.11}$$

## 5.6 Throughput, Lead Time and Utilisation of the Supply Chain

The throughput of the supply chain measures the number of commodities that pass through a supply chain in a given period of time. Thus it is very important, when trying to improve the speed of a supply chain, to ensure that the throughput within the supply chain is at the highest level possible. The point in the supply chain with the slowest throughput, will determine the maximum throughput of the entire supply chain, because a supply chain is only as good as its weakest link.

As previously stated port performance was traditionally measured by comparing its actual throughput with its optimal throughput for a specific period (Talley, 1994). This measure can be used at each node along the supply chain in order to determine the throughput efficiency of that function. The throughput efficiency will help to determine the overall efficiency of the supply chain in terms of speed efficiency.

$$Throughput\ efficiency^{4}\ (\%) = \frac{Actual\ throughput}{Best\ Practice\ throughput} \times \frac{100}{1} \tag{5.12}$$

The throughput efficiency of a supply chain is affected by numerous other factors such as idle time, breakages or downtime in the supply chain and the availability of infrastructure in the supply chain. If the throughput efficiency is affected by variable idle time or unplanned delays, then the throughput efficiency will be used to measure the supply chain efficiency in terms of reliability efficiency instead of speed efficiency. The same formula can be used in both cases.

However, when it comes to the overall efficiency of a supply chain, speed must be tempered with cost. The relationship between the availability of infrastructure and the throughput in a supply chain is correlated, i.e. if there is an increase in the availability of infrastructure there could be an increase in the throughput achieved (up to a point where the infrastructure is no longer fully utilized). However,

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[3] time period (t) may be measured in minutes, hours, days, weeks, months or years

[4] The throughput will be determined as units per time period. The units can be measured in terms of weight ($kg$), volume ($m^3$) or Value (Rand). The time period can be measured in terms of hours, days, weeks, months or years.

this will also result in an increase in fixed costs, which will in turn have an affect on the cost efficiency of the supply chain. Therefore, in analysing the optimal level of infrastructure needed, it is important to take the optimal throughput into account. The throughput efficiency in terms of cost can be calculated as follows:

$$\begin{array}{l} Throughput\ efficiency\ i.t.o.\ cost \\ (Rands\ per\ throughput\ unit) \end{array} = \frac{BP\ throughput\ (Rands/unit)}{Actual\ throughput\ (Rands/unit)} \tag{5.13}$$

Terminal turnaround time for loading ships is another measure used for calculating port efficiency (Sanchez et al., 2002). Utilisation of the supply chain refers to "the act of using" (WordNet, 2006) the supply chain. Turnaround time and terminal utilization are positively correlated. This concept is supported by Tongzon (1995) who notes that to improve ship turnaround time, port authorities must maximize berth utilisation. Therefore it is important to ensure that manufacturing equipment, transport means and storage areas along the supply chain are properly utilised. The turnaround time is used to measure the supply chain in terms of reliability efficiency.

$$\begin{array}{l} Utilisation\ efficiency\ of \\ manufacturing\ equipment\ (\%) \end{array} = \left(1 - \frac{Delays\ incurred\ (time\ period\ (t))}{Total\ time\ manufacturing\ equipment\ was\ employed\ (t)}\right) \times \frac{100}{1} \tag{5.14}$$

$$\begin{array}{l} Utilisation\ efficiency\ of \\ warehouse\ equipment\ (\%) \end{array} = \left(1 - \frac{Delays\ incurred\ (time\ period\ (t))}{Total\ time\ warehouse\ equipment\ was\ employed\ (t)}\right) \times \frac{100}{1} \tag{5.15}$$

$$\begin{array}{l} Utilisation\ efficiency\ of \\ transport\ means\ (\%) \end{array} = \left(1 - \frac{Delays\ incurred\ (time\ period\ (t))}{Total\ time\ transport\ means\ was\ employed\ (t)}\right) \times \frac{100}{1} \tag{5.16}$$

Lead time is defined as "the total time a customer, internal or external, must wait to receive a product after placing an order" (Industry Forum, 2003). Here again it is important to try and keep lead time as low as possible, but far more important is to ensure that lead time is predictable and reliable. This ensures that all parties along the supply chain can plan and will ensure that the supply chain runs smoothly.

$$Lead\ time\ (time\ period\ (t)) = \begin{array}{l} Time\ it\ takes\ for\ goods\ to\ arrive\ at\ the\ customer \\ in\ the\ correct\ condition\ after\ the\ order\ has\ been\ placed \end{array} \tag{5.17}$$

Lead time is also a function of frequency. For example, frequent liner services are another way of reducing lead time. Lead time is used to measure the performance of the supply chain in terms of speed reliability. It is usually used as a measure of customer satisfaction.

## 5.7 Interface arrangements

Another major problem with supply chains can result from the transfer of goods at an interface (an interface is the point when goods are transferred between a node and a link or between two links). Complications can result if the product being moved is perishable and could be spoilt if bottlenecks occur. It is therefore important to minimise all potential interface problems in order for a supply chain to function efficiently.

## 5.8 Customer Satisfaction

There are numerous definitions for customer satisfaction. Strategis (2006) defines it as “a measure of the degree to which a product or service meets the customer’s expectations”. The National Business Research Institute defines it as “the company’s ability to fulfill the business, emotional, and psychological needs of its customers” and Beech & Chadwick (2009) define it as “the comparison of expectations versus perception of experience”.

In many, if not most, firms, only a small number of employees have direct contact with external customers, and yet the performance of virtually all of the employees within the firm has an effect on the level of satisfaction of external customers. Furthermore, internal customer relationships play an important role in achieving a high level of external customer satisfaction. Although it remains important to measure the levels of customer satisfaction between the firm and its external customers, the firm must also take steps to measure the internal relationships because they influence the external customer satisfaction. The ability of those involved in direct interaction with external customers to provide quality service is derived from the efficiency and effectiveness of the internal customer/supplier relationships (Swinehart & Smith, 2005). Research conducted by Ittmann et al. (2007) supports this argument. The research found that there is a lack of skills and an inability of firms to comply with individual customer's needs, which is resulting in low levels of customer satisfaction in the supply chains of fast moving consumer goods.

Without customer satisfaction, there is unlikely to be demand for a company's product. Academic research highlights the link between customer satisfaction and customer loyalty. Ellinger, Daugherty & Plair (1998) show through their research that highly satisfied customers are more loyal than less satisfied customers and therefore deduce that an increase in customer satisfaction results in benefits for the firm through higher levels of loyalty.

Read & M.S.Miller (1990) highlight the importance of total customer satisfaction as a parameter in determining supply chain efficiency. Read & M.S.Miller (1990) describe the delivering of perfect customer service as the outcome of a lean port that as a business unit makes the best use of all available resources, thus resulting in an efficient port, while BNET (2007) points out that firms can improve their supply chain efficiency by improving the link between customer information and the value chain. They argue that by collecting information on what is important to customers the firm can ensure a smooth transition from the concept to order process and in so doing increase the level of efficiency in the supply chain. Therefore customer perspective forms part of the external level of performance evaluation used. In addition to reliability, cost and speed efficiency, customer service efficiency is used to determine the overall level of efficiency in the model developed in this dissertation.

$$Service\ reliability\ (\%) = \frac{Number\ of\ shipments\ within\ promised\ delivery\ time}{Total\ number\ of\ shipments} \times \frac{100}{1} \tag{4.32}$$

Customer complaints - records should be kept of the total number of complaints during a fixed period of time (Kussing, 2009).

## 5.9 Labour

Improving the efficiency of a supply chain is 45% dependent on people, 45% dependent on systems and 10% dependent on infrastructure (Ittmann, 2007b). Therefore it is important to have a properly trained, dedicated labour force in order to maximize the efficiency of a supply chain. Low productivity by labour is a major problem for supply chains throughout the world; in particular developing countries. A significant factor that influences terminal efficiency is the motivation and quality of terminal personnel (Tongzon, 1995).

In order to measure the full impact of labour on the efficiency of a supply chain, there are a number of factors that must be taken into account. The most important of these factors include:

- Number of employees
- Skills of the workforce
- Average hours worked per week
- Average age of the total workforce

All these factors are used to measure the efficiency of the supply chain in terms of cost efficiency. The number of employees determines the labour costs of the supply chain, which is often a substantial component of the unit costs of throughput. There are situations however, when fewer workers with higher qualifications result in higher costs than more employees with no or lower qualifications. Thus the skills of the workforce also have to be taken into account. The hours worked per week are important to determine whether overtime must be paid (overtime is usually more expensive than normal working hours and therefore can result in an increase in costs unless it substitutes for additional employees). Finally, the average age of the total workforce affects cost efficiency because older employees with more experience usually earn higher salaries than younger employees with less experience in the same positions. Also, older employees may be nearing retirement, which means that they will have to be replaced. That might increase the costs either through additional training requirements or higher salaries demanded by the new employee, or the replacement of highly competent employees by a greater number of newcomers.

## 5.10 Communication throughout the Supply Chain

Nowadays managers are faced with the problem of being able to make decisions in “real time”. Organisations are exposed to higher risks and may suffer penalties, such as losing a valuable customer or mission-critical supplier, if decisions are incorrect. Therefore, it is essential that they have or can access all the information they need – quickly and accurately.

Information and communications technologies are transforming the scope and scale of e-supply chain infrastructures ("An e-supply chain is a component of e-commerce which encompasses the coordination of order generation, order taking and order fulfillment/distribution of products, services and information using Internet technologies" (Ghayur, 2003)). Online data exchange is changing business practices, allowing managers to capture and track complex data more effectively. The exact position of orders and various products related to those orders can be traced more easily within the supply chain. It is also possible to exchange information among the various role-players within the value chain, thus greatly improving customer-provider relationships.

It is important that systems allow seamless communication and sharing of information across the entire supply chain as well as within the organisation itself. Intelligent application of information technology can also help to eliminate duplicative data entry, provide real-time status information, and help organisations move past a narrow-minded view of their processes to view themselves within the context of larger missions and goals.

A measure of communication efficiency in terms of the reliability in a supply chain can be calculated by determining the number of key communication processes that are integrated through the entire supply chain. This in turn will have to be traded off against the costs incurred for placing the necessary communication equipment along the supply chain. An optimal point will have to be selected based on the requirements of the specific supply chain.

$$Communication\ efficiency = Number\ of\ key\ processes\ integrated\ through\ the\ entire\ supply\ chain \tag{5.18}$$

$$Percentage\ of\ communication\ cost\ (\%) = Communication\ cost\ as\ a\ \%\ of\ revenue \tag{5.19}$$

## 5.11 Damage to Goods and Pilferage in the Supply Chain

Another significant factor affecting the efficiency of a supply chain is the percentage of goods that are damaged or stolen whilst passing through the supply chain. Goods that arrive at the customer in a damaged condition will usually be sent back to the supplier. This causes delays in the supply chain and increases the costs, because not only do the goods have to be returned to the supplier, but new products (in a satisfactory condition) have to be delivered to the customers. In addition to the increase in costs and a reduction in the reliability of the supply chain, it will also result in a lower level of customer satisfaction and may result in customers shifting to competitors for future purchases. The effect of the loss and damage to goods in the supply chain on the overall level of efficiency in the supply chain can be measured as follows:

$$Defective\ goods\ i.t.o.\ costs\ (\%) = \frac{Cost\ of\ defectives\ shipped\ (Rands)}{Total\ cost\ of\ goods\ shipped\ (Rands)} \times \frac{100}{1} \tag{5.20}$$

$$Damaged\ goods\ in\ storage\ i.t.o.\ costs\ (\%) = \frac{Cost\ of\ goods\ damaged\ during\ storage\ (Rands)}{Total\ cost\ of\ goods\ stored\ (Rands)} \times \frac{100}{1} \tag{5.21}$$

$$Damaged\ shipments\ i.t.o.\ costs\ (\%) = \frac{Cost\ of\ goods\ damaged\ during\ shipments\ (Rands)}{Total\ cost\ of\ goods\ shipped\ (Rands)} \times \frac{100}{1} \tag{5.22}$$

$$Defective\ goods\ i.t.o.\ reliability\ (\%) = \frac{Number\ of\ defectives\ shipped^5}{Total\ number\ of\ items\ shipped^5} \times \frac{100}{1} \tag{4.4}$$

$$\begin{array}{l} Damaged\ goods\ in\ storage \\ i.t.o.\ reliability\ (\%) \end{array} = \frac{Number\ of\ goods\ damaged\ during\ storage^5}{Total\ number\ of\ items\ stored^5} \times \frac{100}{1} \tag{4.24}$$

$$Perfect\ shipments\ i.t.o.\ reliability\ (\%) = \frac{Number\ of\ perfect\ shipments^5}{Total\ number\ of\ shipments^5} \times \frac{100}{1} \tag{4.29}$$

## 5.12 Imbalances in cargo flows

Imbalances in cargo flows result in additional obstacles to the movement of goods. There are often greater volumes of goods flowing in one direction than the other. This means that the mode of

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[5] The units can be measured in terms of weight ($kg$), volume ($m^3$) or value ($Rands$).

transport often has to travel empty on the return leg. For example, bulk ore vessels usually return to the Port of Saldanha in ballast after carrying iron ore for export. Therefore, the tariffs charged for the transportation of goods must cover the costs incurred over both legs. This can result in high transport costs that are ultimately borne by the customer. However, if the situation allows, ships are used in cross-trading in order to limit voyages in ballast. Furthermore, the terms of sale determine who bears the shipping costs. Exporters bear the costs of c.i.f. exports, although this might be reflected in the sale price. Thus an imbalance in cargo flows affects the overall level of efficiency of a supply chain in terms of cost efficiency. It can be measured as follows:

$$Imbalance\ in\ cargo\ flows\ (\%) = \frac{Ton.kilometre\ utilised}{Ton.kilometre\ available} \times \frac{100}{1} \tag{5.23}$$

## 5.13 Documentation required throughout the Supply Chain

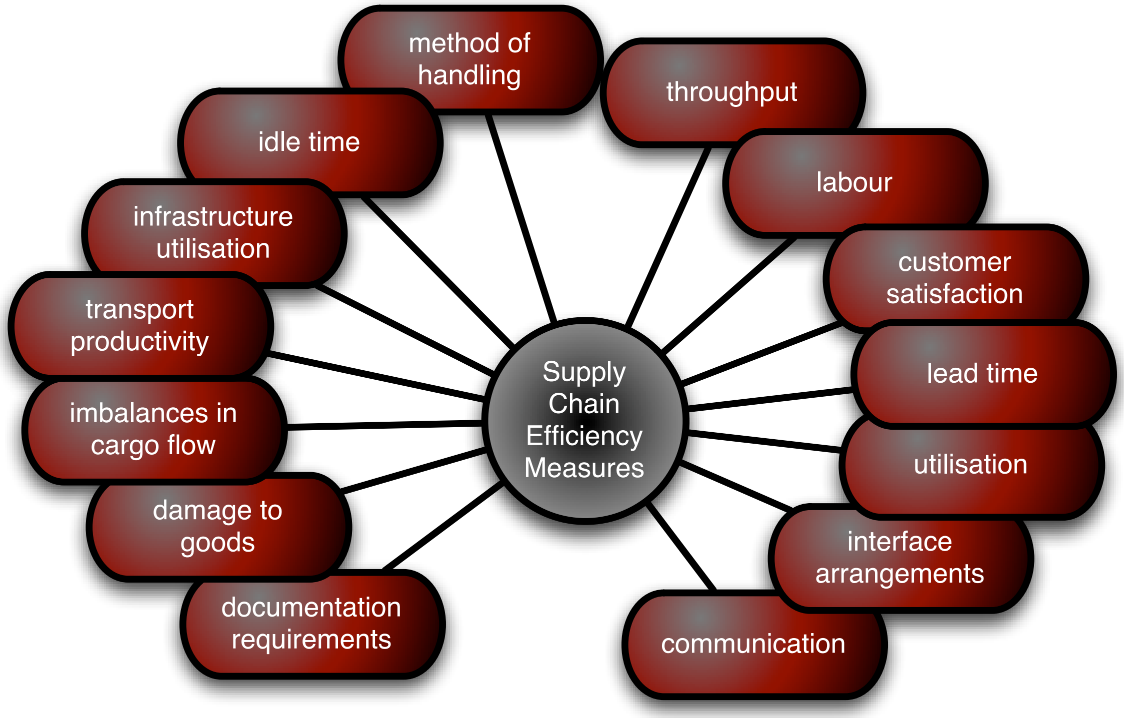
Because the movement of cargo across borders requires extensive documentation, the flow of documents virtually constitutes a supply chain separate from that of the physical flow of cargo (Fourie, 2002). Each country has different import regulations, and, therefore, the exporter must know the specific requirements for the destination country and ensure that the proper documentation is provided. Inadequate documentation might cause cargo to be delayed, which can raise the costs of transport and result in customers switching to different suppliers. Because of the unpredictability of documentation errors, it is difficult to determine the effect that they will have on the speed of a supply chain. Therefore, documentation errors are measured in terms of reliability efficiency. The formula for calculating documentation errors is given below.

$$Documentation\ errors\ (\%) = \frac{Number\ of\ documents\ with\ errors}{Total\ number\ of\ documents\ used} \times \frac{100}{1} \tag{5.24}$$

## 5.14 Factors that Influence Supply Chain Efficiency in South Africa

Figure 5.1 shows a graphic representation of the different factors that influence supply chain efficiency in South Africa.

**Figure 5.1:** Factors that Influence Supply Chain Efficiency in South Africa[6].



## 5.15 A Consideration of Supply Chain Parameters that cannot be measured

Chow, Heaver & Henriksson (1994) identified various parameters or measures for efficiency and classified them as either "hard" or "soft". Hard measures are the numerical results obtained from business practices, for example, financial figures or actual statistics on loading rates or average ship turnaround time. Soft measures are those of a qualitative nature, where scales can be used to give numerical weight to opinions of managers or customer satisfaction ratings. The hard measures tend to exclude any personal experience built up by the senior managers over the years and the soft measures are more subjective views on the overall performance. Therefore, it is important to include both hard and soft measures when trying to determine the true overall efficiency of a supply chain.

In addition to hard and soft measures, there are sometimes parameters that influence the overall efficiency of a supply chain, but are very difficult or impossible to measure. In cases such as these, it is important to make note of the parameter and how it affects the overall efficiency of the supply

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[6] Source: Developed by author for the purpose of this study.

chain and state clearly that although it influences the overall efficiency there is no way of including it in the calculation. An alternative would be to state the point, but include it as a soft measure.

## 5.16 Factors that Affect Efficiency Measurement of a South African Supply Chain (examples pointed out during research process)

Throughout the research that was conducted for this dissertation, certain factors were highlighted that restrict the measurement of efficiency along South African supply chains. It is important to identify these factors in order to make it easier to achieve the necessary improvements.

Firstly, a major problem with measuring the efficiency of a South African supply chain is the fact that South African firms seldom keep records of various variables that are needed to conduct reliable efficiency measurement. Although firms acknowledge the importance of conducting efficiency measurements and seemed very interested in the research that was being conducted, when the author approached them for data to test the model with, a large percentage of the firms did not have the necessary data available.

Kemp-van der Werf (2007) is of the opinion that one of the biggest obstacles to improving the efficiency of supply chains in the clothing industry is the lack of information collected by the various firms along the supply chain, because South African firms do not realise the importance of being able to measure their overall performance. Although firms and overall supply chains could benefit from measuring efficiency along supply chains, it would require a change in business practices from the unskilled workers to top-level management before the real benefits will be achieved.

Secondly, some firms tend to focus on improving their own efficiency without taking the overall efficiency of the entire supply chain into account. For example, Ramchand (2007), Research and Development Planner from Transnet National Ports Authority in Saldanha feels that there is a lack of information sharing between supply chain role-players. This makes it difficult to identify problem areas and make the necessary corrections needed to improve the efficiency in supply chains. It also makes measuring efficiency along supply chains impossible.

Thirdly, cost constraints affect efficiency measures along South African supply chains. Klem (2007), Merchandise Director of Pepstores says that costs must be kept low for smaller or low-cost supply chains to be able to implement the measurement. If the costs involved in measuring the efficiency of a supply chain are too high many smaller and low-cost supply chains will avoid the measurement. It is therefore essential that a measurement be developed that is accessible to all supply chains.

Fourth, it is important to ensure that the measurement can provide reliable feedback. Hayward (2007) of Barloworld Logistics says that there are differences between theory and practice and in order for the measurement to be reliable it has to be able to adjust to the individual requirements of the supply chain.

Fifth, it is important that the employees trusted with the job of implementing the measurement have the necessary level of skills needed to draw the benefits. Louw (2007), (Department of Logistics, Stellenbosch University) a supply chain specialist says that a problem facing many firms in South Africa is a lack of training required to implement and manage performance measurement systems properly. It can often be a costly exercise to send employees to the different courses needed to apply the measurement properly and therefore in order to cut costs employees simply are not properly trained. Unfortunately this prevents firms from benefiting from monitoring and review.

Finally, many South African supply chains comprise firms from both the private and public sectors. This means that the objectives of the firms may differ, which will lead to different strategies. Floor (2007) says that there is a combination of social and economic ideals in many South African supply chains. This results in firms striving to achieve different goals and can lead to problems when trying to measure and improve efficiency across an entire supply chain.

## 5.17 Data Collection and Comparison

In order for the model to be beneficial for firms, it is important that they have access to reliable benchmarking information. Thus the data collection process must be properly planned and carried out. Firms must have access to a database of information, made up of custom peer comparisons as well as standard industry comparisons, with which to compare their performance.

The generic nature of the model developed allows the firms to select those variables that are most representative of their own requirements and therefore it is able to provide realistic results. Once the results of the model have been obtained, it is important to implement the results properly, so that the firm can obtain maximum benefit from the exercise.

## 5.18 Conclusion

Supply chains are made up of a number of functions that ensure that the products move from point A to point B. There are a number of different factors that could influence the overall functioning of a supply chain. This chapter introduces the factors that are taken into account for the purpose of this study and it provides formulae for measuring the effect of the different factors on the overall efficiency of a supply chain.

# CHAPTER 6

# Links and Nodes: A Model-Oriented View

## 6.1 Introduction

A supply chain can be divided into various links and nodes and all links and nodes in the supply chain add value to the product being transported. According to Langley et al. (2008), the nodes are established spatial points where the movement of goods stop for storage or processing and the links represent the transportation network connecting the nodes in the logistics system. The transport section of international supply chains can often be divided into two sections, namely, the ocean freight leg and the (two) inland transport leg(s). It has been found that the ocean freight portion of the South African supply chains account for 83% of the travel time and 60-68% of the transport cost (Department of Transport, 1998). This is mainly due to an average distance of over 11 000km from South Africa that must be covered to reach the main international markets. In comparison, inland transport comprises only 11% of the total time and 19-27% of the transport costs (Moving South Africa, 1998). From this it is clear that it is important to keep the inland leg of the transport system as short as possible. Thus, South Africa has maintained a complementary system of ports that, with the exception of the Port of Durban, focuses mainly on serving their own natural hinterland.

The inland transport section in South Africa is provided by either road or rail transport (with the exception of certain liquids and gases that are transported by pipelines). The national road network currently covers 7 200km. The roads include 1 400km of dual carriageway freeway, 440km of single carriageway freeway and 5 300km of single-carriage main road with unlimited access. Approximately 1 900km are toll roads, serviced by 27 mainline toll plazas (Transport, 2004). South Africa's national road network forms the primary link in South Africa's road network and serves mainly economic development. One of its main functions is to provide interregional access to major freight terminals, including the ports.

South Africa's rail network covers a total of 20 041 route kilometres and 30 400 track kilometres. The route kilometres represent the total distance of railway lines between all stations in the country. The track kilometres include the distance of tracks (route kilometres) taking into account double and triple lines in metropolitan areas, and also marshalling yards, sidings and loops. Transnet Freight Rail, which is a division of the State-owned Transnet Limited, provides all rail transport. Thus the efficiency with which any commodities are transported by rail is subject to Transnet Freight Rail's performance.

Even though the railways constitute an inherently good quality system complete with infrastructure to handle commodities by rail over long distances to the ports, service delivery is still not meeting the necessary levels of efficiency. According to research done by Merit (Pty) Ltd (2002), rail transport in South Africa is in principle less costly than road transport when the distance of haul is 700km or greater. However, this is not the present experience. That is borne out by the fact that freight is moving over long distances from the hinterlands to the ports by road. Transnet Freight Rail has lost market share to road transport since the deregulation of road transportation and as a result of its inability to compete effectively because of inefficiencies. Consequently it has fallen behind in necessary capital investments, and the renewal of equipment and the quality of its service to its customers is poor.

South Africa is increasingly being required to compete in a global market and exporters need to reduce costs and increase service levels as a matter of urgency in order to maintain and raise its share in world markets (Barloworld Logistics, 2005). With the globalisation of industries there is also pressure on liner shipping to provide efficient logistics chains. That necessitates vertical and horizontal integration of firms or alliances that can achieve economies of scale. According to a survey among South Africa's major industry bodies conducted by Barloworld Logistics (2005), 80% of respondents indicated that their key objective was to improve supply chain efficiency through collaboration. In fact, substantive economies of scale can be realised through horizontal alliances between shipping and railways, provided that an integrated and efficient logistics system can be created.

Another significant barrier to a more efficient land freight transportation system in South Africa is the lack of modal collaboration. To date there is very little discernable evidence that the rail industry and the leading trucking companies combine their efforts to provide a dependable, competitive land transport service. Rail infrastructure has degenerated and its effects are being felt at a time when efficient and cost effective transport is essential to maintain South Africa's competitive international market position (Railroad Association of South Africa, 2002). Advantages from modal co-operation in the form of increased trade are being lost due to this limitation.

Given the relatively long distance involved in the transport of cargo between the South African ports and their hinterlands, the railways should have a competitive advantage over road transport which provides opportunities for co-operation with private undertakings to ensure competitive logistics chains. However, with the current problem of unemployment in South Africa, it is important to ensure that the redundancy of jobs that could result from such cooperation is taken into account in order to avoid reaction by the labour unions. Other issues that also need to be factored into developing responsiveness and flexibility in the supply chain are increased trade into Africa and Black Economic Empowerment (Barloworld Logistics, 2005).

This chapter identifies the main categories of links or nodes in a South African maritime supply chain. It breaks supply chains down into five generic core functions. It also expands on the main group of functions that form the core of a maritime supply chain and in so doing highlights all the factors that are going to be used in the model (see Chapter 7) to measure supply chain efficiency across South African maritime supply chains.

## 6.2 Sources/Suppliers and Markets/Customers

A source is defined as "a facility where something is available" (WordReference.com, 2009), while a supplier is defined as "Individuals, companies or other organisations which provide goods or services to a recognisable customer or consumer" (Beech & Chadwick, 2009). Thus the sources/suppliers are the origin of the supply chain. The markets are defined as "the customers for a particular product or service" (WordNet, 2007), while customers are defined as "a person, firm or company who purchases goods from the firm" (clipdisplay.com, 2006). Thus markets/customers are the destination of the supply chain.

Competition may oblige the purchaser (markets/customer) of the supplies to seek cheaper sources, but not necessarily change all the supply chain arrangements. Supply chain managers thus need to understand the business of their customers and co-operate to ensure that, although purchasers may change the source of supplies, the supply chain should be capable of adapting to accommodate new sources/suppliers. That might not always be feasible, but the existence of the supply chain should constitute such a benefit for the trade that procurement arrangements will not readily be changed if the consequences will be a less efficient supply chain. To a large extent, supply chains may thus link sources/suppliers and markets/customers in a more enduring manner than occurs in general distribution.

Sources or suppliers have an important role to fulfil in a supply chain. At the origin of a supply chain, it is important that the supplier be able to adapt to the requirements for a seamless functioning supply chain. Customers can conduct a series of tests or measures in order to ensure that they make the correct choice. In addition, once the suppliers have been selected, the customers must continue to evaluate their performance in order to ensure that they receive the service required.

Sources/suppliers and markets/customers form two of the five categories of links or nodes of a generic South African maritime supply chain as described by this research. They are both classified as nodes. For the purpose of the model (refer to Chapter 7) the sources or suppliers will be evaluated to determine their influence on the overall level of efficiency of the supply chain, while the opinions of the markets or customers will be as an additional measure of efficiency, namely, customer service efficiency.

## 6.3 Points of Production

Points of production include three broad categories, namely, mines, manufacturing plants and agriculture. Points of production are the physical nodes in a supply chain at which goods are sourced, whether in raw material, semi-manufactured or manufactured form, to pass along the supply chain. They are the starting point for the various products being traded.

Points of production are the second set of nodes in the five categories of links or nodes of a generic South African maritime supply chain, as described in this research. Like sources/suppliers and markets/customers they are also considered nodes and are evaluated in order to determine their influence on the overall level of efficiency of the supply chain (see the model in Chapter 7 of this research).

### 6.3.1 Mines

Mines are the nodes of production in bulk supply chains conveying ores and minerals. The South African economy depends substantially upon the export of ores and minerals, mined long distances from the country's ports to earn foreign currency. Mining is South Africa's largest industry in the primary economic sector, followed by agriculture (Department of Minerals and Energy, 2006). South Africa contributes significantly to the world's mineral (both raw and processed) requirements as shown in Table 6.1.

**Table 6.1:** South Africa's Role in World Mineral Reserves, Production and Exports, 2005[1].

| Commodity | Reserve Base | | | | Production | | | | Exports | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Unit | Mass | % | Rank | Unit | Mass | % | Rank | Unit | Mass | % | Rank |
| Aluminium$^{*}$ | | ∗ | ∗ | ∗ | kt | 846 | 2.7 | 9 | kt | 671 | 4.2 | 7 |
| Alumino-silicates | Mt | 51 | ∗ | ∗ | kt | 228 | 36.4 | 1 | kt | 134 | 34.4 | 1 |
| Antimony | kt | 200 | 6.4 | 4 | t | 5 979 | 3.2 | 7 | t | 5 744 | ∗ | ∗ |
| Chrome Ore | Mt | 5 500 | 72.4 | 1 | kt | 7 494 | 38.7 | 1 | kt | 657 | 15.1 | 4 |
| Coal | Mt | 31 022 | 3.5 | 8 | Mt | 245 | 4.93 | 5 | Mt | 71.4 | 9.3 | 4 |
| Copper | Mt | 13 | 1.4 | 14 | kt | 97 | 0.7 | 16 | kt | 30 | ∗ | ∗ |
| Ferro-chromium | | ∗ | ∗ | ∗ | kt | 2 812 | 40.5 | 1 | kt | 2 460 | 50.9 | 1 |
| Fe-Mn/Fe-Si-Mn | | ∗ | ∗ | ∗ | kt | 634 | 6.0 | 4 | kt | 724 | 16.4 | 2 |
| Ferro-silicon | | ∗ | ∗ | ∗ | kt | 127 | 3.1 | 6 | kt | 41.3 | 2.1 | 7 |
| Fluorspar | Mt | 80 | 16.7 | 2 | | ∗ | ∗ | ∗ | | ∗ | ∗ | ∗ |
| Gold | t | 36 000 | 40.1 | 1 | t | 295 | 11.7 | 1 | t | 265 | ∗ | ∗ |
| Iron Ore | Mt | 1 500 | 0.9 | 9 | Mt | 40 | 3.0 | 7 | Mt | 27 | 3.8 | 6 |
| Lead | kt | 3 000 | 2.0 | 7 | kt | 42.4 | 1.2 | 13 | kt | 47 | ∗ | ∗ |
| Manganese Ore | Mt | 4 000 | 80.0 | 1 | kt | 4 612 | 13.3 | 2 | kt | 2 119 | 19.7 | 2 |
| Nickel | Mt | 12 | 8.4 | 5 | kt | 42.4 | 3.1 | 9 | kt | 22.2 | ∗ | ∗ |
| PGMs | t | 70 000 | 87.7 | 1 | t | 303 | 56.7 | 1 | t | 259 | ∗ | ∗ |
| Phosphate Rock | Mt | 2 500 | 5.0 | 4 | kt | 2 577 | 1.7 | 10 | kt | 91 | ∗ | ∗ |
| Silicon Metal | | ∗ | ∗ | ∗ | kt | 53.5 | 3.2 | 8 | kt | 48.2 | 3.7 | 7 |
| Silver | | ∗ | ∗ | ∗ | t | 88 | 0.4 | 17 | t | 98 | ∗ | ∗ |
| Ti Minerals | Mt | 220 | 18.3 | 2 | kt | 952 | 19.8 | 2 | | ∗ | ∗ | ∗ |
| Uranium | kt | 341 | 7.2 | 5 | t | 795 | 1.6 | 11 | | ∗ | ∗ | ∗ |
| Vanadium | kt | 12 000 | 31.0 | 1 | kt | 23 | 48.0 | 1 | | ∗ | ∗ | ∗ |
| Vermiculite | Mt | 80 | 40.0 | 2 | kt | 210 | 39.6 | 1 | kt | 164 | ∗ | ∗ |
| Zinc | Mt | 15 | 3.3 | 8 | kt | 32.1 | 0.3 | 22 | kt | 1.7 | ∗ | ∗ |
| Zirconium | Mt | 14 | 19.4 | 2 | | ∗ | ∗ | ∗ | | ∗ | ∗ | ∗ |

### 6.3.2 Manufacturing Plants

Value is added to products by taking raw materials in a form that cannot be used easily and converting it into a product for which there is a demand.

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[1] Source: Department of Minerals and Energy (2006).

South Africa has developed an established, diversified manufacturing base (South Africa, 2003). It contributes over 18.5% of the national gross domestic product (GDP); over half of all exports and is the second largest employer (*A National Advanced Manufacturing Technology Strategy for South Africa*, 2003).

### 6.3.3 Agriculture

Agriculture supply chains differ from other supply chains because production cannot be influenced in the same way as the production of manufactured products, such as motor vehicles, for example. There is no direct relationship between the demand and the amount of the agricultural product produced (van der Ham, Becker & Guis, 2002). In fact, agriculture production plays a significant role in determining what happens in the rest of the supply chain.

Among many uncertainties, one certainty is that the agricultural products grow according to their own tempo and it is very difficult to determine long in advance when the products are going to be ready for harvest. However, irrespective of this fact, the trend towards demand-driven chains is as visible in the agriculture industry as in other industries and therefore special care must be taken to ensure that the supply chain is as efficient as possible. South African agriculture production has almost doubled over the past 30 years and it continues to fulfil an important role in the economy. A true reflection of agriculture's contribution to the national economy is often obscured by its nominally low direct contribution to the Gross Domestic Product (GDP) (Agriculture currently contributes 4% to South Africa's GDP (SouthAfrica.info, 2007)). However, if the full impact of the "agro-industrial" partnership complete with forward and backward employment linkages and multiplier effects on the rest of the economy are included, agriculture contributes at least 15% to the GDP (Goedhals, 2003).

## 6.4 Points of Storage and Transhipment

The need for storage comes about because of differences in the temporal supply and demand for goods. If the demand for a firm's products could be determined precisely and products could be supplied on demand, then theoretically, there would be no need for storage as no inventory would be held. However, it is impossible to determine the exact demand for a product and no form of transport is able to provide a reliable service all the time (at least without incurring exorbitant costs). Therefore, storage helps to add time utility of products by ensuring that the products, whether they are raw materials or finished products, are available when required. In addition, firms use inventories to improve supply-demand coordination, reduce cycle times, and improve customer service and to lower overall cost (Ballou, 2004). The need for carrying inventories results in the need for a place to keep the inventories, which more often than not, is called a warehouse. However, there are numerous diferent forms of storage available. Examples include warehouses, stockpiles, yards and tank farms. Due to the case study covered in this dissertation a brief description of warehouses and stockpiles is given. In addition, there is a need to be able to handle the inventories in storage, which is called "materials handling".

The costs of storage and materials handling are justified because they can be traded-off with transportation and production-purchasing costs in a supply chain. That is, by storing inventory needed in the production process, a firm can often lower production costs through economical production lot sizing and sequencing. By doing this, the firm avoids the wide fluctuations in output levels due to uncertainties and variations in demand patterns. Also, the storage of inventories can lead to lower transportation costs through the shipment of larger, more economic quantities. The objective is to use just enough storage so that a good economical balance can be realized among storage, production and transportation costs in a supply chain (Ballou, 2004).

In research conducted by Schoeman (2007), it was found that the duplication of distribution centres and/or the underutilization of warehouse capacity are a problem in certain South African supply chains. This is mainly due to the variability in the levels of supply and demand for fast moving consumer goods. Another problem that was highlighted is a shortage of skills, i.e. lack of understanding of common supply chain principles, which results in inventory lying idle and product aging (Schoeman, 2007).

Transhipment is defined as "the process of unloading cargo at an intermediary port and then reloading it for shipment to its final destination. When the cargo is reloaded, it is possible it can be placed on another mode (i.e. from ocean vessel to truck)" (TradeCard, 2007). There are points along a supply chain that assist with the overall throughput of the chain and without them it is not possible for a supply chain to perform efficiently.

Points of storage or points of transhipment are the fourth set of nodes out of the five categories of links or nodes of a generic South African maritime supply chain as described in this research. They fulfil an important role in determining the overall efficiency of a supply chain and are included in the model (see Chapter 7).

### 6.4.1 Warehouses

A warehouse is defined by Edmonds & Kyle (1998) as "a building for the storage of goods". Warehouses are used by manufacturers, importers, exporters, wholesalers, transport businesses, customs, etc. They are usually equipped with loading docks to load and unload road vehicles; and sometimes are served directly by railways, airports, or seaports. They are also usually equipped with cranes and forklifts for moving goods (Hansen & Gibson, 2009).

### 6.4.2 Stockpiles

Stockpiles are defined by BHP Billiton (2008) as "an accumulation of ore or mineral built up when demand slackens or when the treatment plant or beneficiation equipment is incomplete or temporarily unequal to handling the mine output; any heap of material formed to create a reserve for loading or other purposes or material dug and piled for future use". They serve the same purpose as a warehouse in a semi-manufactured or manufactured goods supply chain and therefore fulfil an important role in balancing supply and demand for the bulk materials. Stockpiles are located at different points, such as at a mine, port, refinery, or manufacturing facility.

### 6.4.3 Ports

The most important role of a port is to facilitate trade, not only internationally, but also locally via coastal shipping. Ports are the transhipment points for the import and export of goods. The cost of goods movement through the ports has two main effects. Firstly, the lower the costs, the lower the landed cost of imported goods and, the lower the cost of exporting goods.

The function of ports has changed during recent years, as a result of the globalisation of world trade. Globalisation or the participation in the so-called global village has required products to compete on a worldwide basis for which the supplier needs to achieve or maintain a competitive advantage. One of the consequences of the intensification of competition has been that markets traditionally served directly by shipping services became incorporated in the networks of shipping alliances that supply services often necessitating the transhipment of cargo through hub-ports to feeder services. Not only has that logistical arrangement changed the hinterlands of many historical seaports, but also the roles they are required to fulfil. Ports are required to offer efficient and reliable services which provide transport, transhipment, storage, warehousing, processing, documentation, customs procedures and communication systems for electronic data processing and interchange specifically to ensure an effective flow of goods. In fact, ports have become part of the production chain and a functional element in the logistics of supply.

Ports form a vital link in the overall trading chain and consequently their level of efficiency and performance determines to a large extent a country's international competitiveness. However, in order to achieve and maintain a competitive edge in the international markets port authorities need to understand the underlying factors of port competitiveness and continually assess its performance relative to ports elsewhere so that appropriate business strategies can be devised (Tongzon, 1995).

The technological and organisational innovation in the movement of cargo in order to reduce the costs of shipment, including inventory costs for goods-in-transit, has become increasingly necessary to sustain the comparative cost advantages of exporting countries.

Improvements in transport technology and investments in transport infrastructures have become increasingly necessary to meet the demands of technological change as well as customer needs. Ports, therefore, need to adapt to these changes and develop ways of creating and maintaining competitive advantages. All these changes demand improvements in logistics and supply chain management.

Port operations involve an intricate combination of many different functions that need to be effectively carried out in order to achieve efficient throughput. An efficient port is a port through which goods move quickly – rapid throughput is all important. Their ability to help balance the supply and demand for goods along a supply chain and in so doing contribute to the value of the goods is the reason that they are classified as points of transhipment for the purpose of this dissertation.

### 6.4.4 Container Depots and Inland Terminals

A container depot is "a place for the storage, detention, packing, unpacking, or customs examination of containers or their contents" (Guide to Importing into South Africa, 1999). They are usually located near major industrial centres. Both depots and terminals are located in or around major ports and many rail and highway hubs throughout the world (Interport Maintenance Co., 2008). In South Africa, all depots are run by South African Container Depots (SACD) and terminals are operated by Transnet (Guide to Importing into South Africa, 1999).

Inland terminals provide the essential intermodal link between road and rail freight systems. These terminals act as inland ports for container traffic, transferring imported containers from trains onto road vehicles near their inland destinations, and export containers from road vehicles onto trains destined for the port. Container depots provide a storage role for cargo before it is loaded onto vessels or after being discharged from vessels. In addition, they include facilities for the maintenance and repair of containers and provide a critical link in the tracking function for liner shipping.

Container depots also provide for the stuffing and unstuffing of containers for consignments comprising less than full container loads (LCL). Cargo made up of parcel sizes that are not large enough to fill a container are sent to container depots where consolidation into full container loads (FCL) takes place, after which the containers are forwarded to container terminals in the ports for loading onto ships. Generally, the cost of shipping FCL cargo is cheaper than LCL cargo and thus container depots can help reduce ocean freight rates. Once containers arrive in the destination country, they are transported from the port to a container depot. Here the LCL is divided up into individual consignments before being transported to the various markets/customers. Customs clearance usually takes place at container depots.

Whilst there are numerous container depots and inland terminals in South Africa, the well-known one is at City Deep, located just south of Johannesburg. The City Deep terminal is the largest in Africa and the fifth largest in the world. According to Transnet (2002), City Deep was planned specifically as a transit terminal for containerisation. In the past, City Deep only handled import and export containerised freight, but now it also handles domestic cargo. City Deep fulfils an important role in the economy of Gauteng and more than 30% of all South Africa's exports move through this inland port.

Container depots and inland terminals fulfil a vital role in ensuring the smooth flow of goods along a container supply chain. The important part that they fulfil in ensuring a balance in supply and demand is the reason that they are classified as points of transhipment in this dissertation.

## 6.5 Transport Links

Transport links the producers and consumers. Without transport no supply of goods could take place. Thus transport adds value to a product by providing place and time utility. Transport usually accounts for a large portion of the overall supply chain costs if the cost of the production of the goods is excluded. Therefore an efficient and inexpensive transportation system contributes to greater competition in the market place, greater economies of scale in production, and reduced prices for goods (Ballou, 2004).

Research conducted by Botes, Jacobs & Pienaar (2007), indicates that that has been a significant increase in the contribution of transport costs to total logistics costs (from 62.5% in 2003 to 63.1% in 2005). This increase in the transport sector's contribution can be attributed to the fact that this sector is more susceptible to "administered" prices (cost elements outside the control of logisticians) and due to the poor configuration and management of South Africa's freight network, this trend seems likely to continue in the near future (Botes, Jacobs & Pienaar, 2007). The total land transport in the South African economy increased by 8% (to 1.4 billion tonnes) from 2003 to 2005. This growth was captured by the road transport sector – the rail transport tonnages have now remained more or less stagnant for the past decade. Considering the predicted growth in the economy, it is clear that revolutionary change is required in the long-haul road/rail relationship in order to avoid road gridlock (Botes, Jacobs & Pienaar, 2007). The split between road and rail, and changes since 2004, are depicted in Figure 6.1.

Transport links are the fifth set of links of the five categories of links or nodes of a generic South African maritime supply chain as described in this research. These link the nodes and are vitally important in determining the overall efficiency of a supply chain. Their impact on the overall efficiency will be measured and included in the model (see Chapter 7).

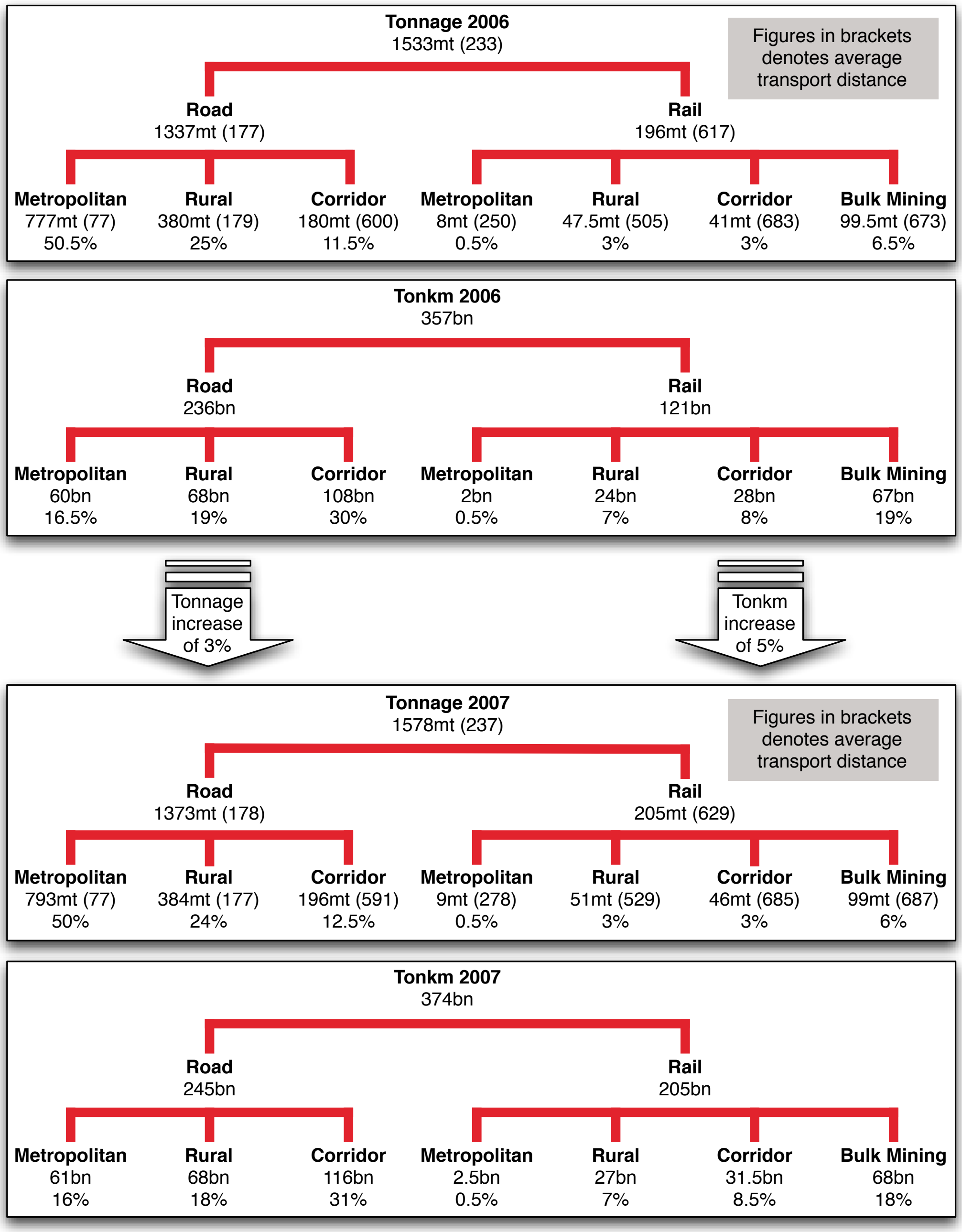
### 6.5.1 Road Transport

Since deregulation of freight transport, road transport in South Africa has become a highly competitive industry. The road transport industry can be divided into local, intra-regional carriers and carriers who operate inter-provinces (Erero & van Heerden, 2005). The freight forwarders have effectively created an oligopoly in the latter sector, so that even though there are many owners/drivers operating between the major cities, they are generally either attached to one of the large forwarding companies, or at least obtain most of their loads from the latter's depots (Erero & van Heerden, 2005).

In South Africa private hauliers were only given full access to Transnet container terminals in 1999 (provided they could meet certain criteria). Prior to this, only Transnet's own hauliers and appointed hauliers could have access to container terminals (Qukula, 2000).

For road hauliers to be able to sell their services, they must adapt to customer needs and meet these in an efficient manner while remaining in constant communication with users of their services (Fourie,

**Figure 6.1:** Land Freight Transport in South Africa[2].



2002). Road is usually the preferred mode of transport due to the flexibility of service. It does not have a fixed timetable and can change routes according to the requirements and convenience of the users. Well-maintained fleets and vehicles equipped for security (with satellite tracking) are essential in order to provide those services. Figure 6.1 shows a breakdown of the land freight transport in South Africa.

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[2] Source: de Waal, Hobbs & van Eeden (2007) (Percentages denote share of total ton and ton.km respectively).

Road transport also has the advantage that it provides a door-to-door service. It is the only mode of transport that can collect goods at the origin and deliver them right at the destination. It is also a highly accessible mode of transport as it is not limited to a fixed route (there is usually more than one route from origin to destination). Road transport is the fastest mode of transport over short distances and the carrying unit (truck) protects the commodities while they are being transported.

However, there are a few disadvantages for users. Road transport has a limited carrying capacity and therefore finds it difficult to compete with the economies of scale that are achieved by rail transport. Road transport has a high energy consumption, which can be negatively affected by an increase in the petrol or diesel price. The high energy consumption also results in road transport having a greater impact on the environment and as governments focus more of their attention on preventing pollution, they are also striving to shift freight transport away from the roads. Road transport takes place on a shared right of way and is therefore subject to high levels of congestion, which may disrupt schedules. Road vehicles are also vulnerable to high-jacking, while breakdowns and accidents also occur. Road transport is exceptionally suitable for the conveyance of manufactured high-value goods over relatively short distances.

Figure 6.2 shows a graphic representation of South Africa's road corridors to the national ports as well as to the Port of Maputo.

### 6.5.2 Rail Transport

In South Africa, the rail transport is provided by Transnet Freight Rail, a division of the government owned Transnet Ltd. Transnet Freight Rail is the largest division of Transnet. It comprises a general freight business ("GFB" Commercial), a heavy haul coal line ("COALlink"), a dedicated heavy haul iron ore line ("OREX"), an inter-city passenger service operation ("Shosholoza Meyl"), and the Blue Train luxury train service ("Luxrail"). In addition, Transnet Freight Rail has a division, Freight Rail International Joint Ventures, through which Transnet Freight Rail hopes to become a significant global player in the provision of freight logistics solutions to its customers on the African continent and beyond (Transnet, 2007). It is operated as a rail monopoly, but encounters stiff competition from road hauliers. That gives rise to the problem that many of the lines are not profitable and that rolling stock and other assets are under-utilised (Fourie, 2002).

Since the deregulation of road transport, rail transport in South Africa has experienced a serious

**Figure 6.2:** The Road Corridors to South Africa's National Ports[3].

decline in its market share. Rail transport has an inherent advantage over road transport over longer distances if economies of scale are realised. However, as a result of the rigidity of its movement and double transhipments, rail transport has lost client preference to the door-to-door service of road transport. In international settings, long-haul rail costs generally average below 70% of those of road, whereas currently in South Africa rail and road freight have similar costs. Both these factors reduce the level of competition between road and rail transport in South Africa.

According to the African Economic Outlook report (OECD, 2006), rail infrastructure suffers from 15 years of deferred investment: 45% of trains are late and 25% do not show up; freight loads per wagon are at only half the international best-practice level; and the average age of locomotives is 25 years, compared with the international average of 16 years. Frequent derailments and other efficiency problems result in customers using rail for goods that are least time-sensitive, limiting Transnet Freight Rail's scope to increase container traffic.

Another major hurdle for Transnet Freight Rail to overcome is the perception that companies have of the rail transport service in South Africa. According to a survey among South Africa's major industry bodies conducted by Barloworld Logistics (2005), almost every respondent felt that the state-run rail

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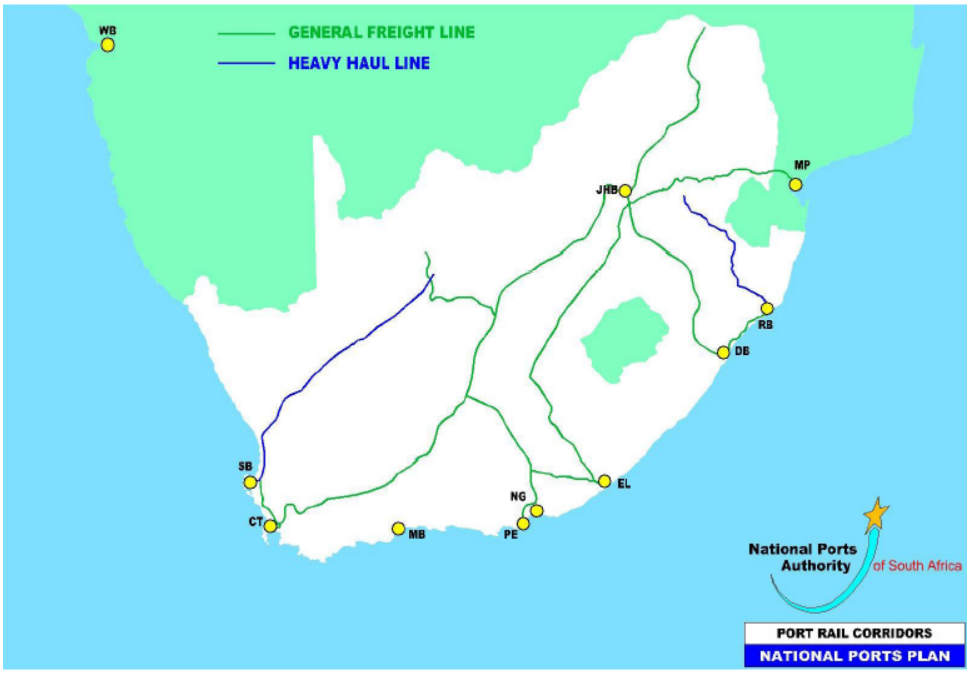
[3] Source: National Ports Authority of South Africa.

network is either below average or poor and that their experience of the road transport network is generally positive. This illustrates the need for Transnet Freight Rail to improve their service if they want to increase their market share.

Despite its shortcomings, there are initiatives to increase the share in rail transport worldwide. This is because rail transport can carry large, high-density commodities and bulk consignments over long distances at low cost. Thus rail transport has a potential advantage over road transport in that the disparity between the capacity of ships and trains is less than that between ships and road vehicles. Containers offloaded from ships can therefore be removed far more quickly from port terminals by rail than by road, resulting in fewer delays or dwell-time for containers (Stopford, 2009). Rail transport also consumes much less space and energy than road transport and is therefore more environmentally sustainable than road transport. Transnet Freight Rail currently has an initiative in place to improve container trains between Gauteng and Durban and Gauteng and Cape Town. Figure 6.3 shows a graphic representation of South Africa's rail corridors to the national ports as well as the Port of Maputo.

**Figure 6.3:** Rail Corridors to South Africa's National Ports[4].



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[4] Source: National Ports Authority of South Africa.

### 6.5.3 Shipping Lines - Ocean Freight

Liner services play a central part in the global trading network. They provide fast, frequent and reliable transport for almost any cargo to almost any foreign destination at a predictable charge (Stopford, 2009). These services are often the primary link in global supply chains. Although the transit time of seafreight is often long in comparison with air transport, sea freight is considerably cheaper and it has the added advantage that it can carry large consignments of cargo.

Over the last few decades, the international liner shipping industry has been characterised by a relatively rapid change in its composition, scope and scale. With the advent of containerisation in the late 1960s and, more recently, modern information technology, shipping companies are evolving from small companies, offering port-to-port services, to large international transportation companies offering world-wide door-to-door services (Department of Treasury, 1999). Shipping operators have also evolved from specialising in single trade routes into specialising in global operations, and containers may shift between different trades (Department of Treasury, 1999). This has resulted in shipping lines having greater power when negotiating with ports and terminal operators for better service and lower charges. Thus ports have less scope to monopolize and are increasingly being penalized for their inefficiency.

As with any other mode of transport, shipping also has its disadvantages. Perhaps its main disadvantage is that it can provide only a terminal-to-terminal service. Thus shipping can be supplied only to and from a suitable port. Another disadvantage of shipping is that it is vulnerable to inclement weather. Weather has a major influence on shipping and can affect the duration of the voyage, disrupting schedules and even causing ports to be bypassed (Fourie, 2002). Ships caught in storms, either at sea or in the port, can lose their cargo or in some cases can result in ship wrecks. Storms, mist and winds can also prevent the loading/unloading of cargo in ports, which can result in a back-log in the throughput of a supply chain. The Port of Cape Town is an example of a port that experiences the effects of strong winds. The longest delays occur in the months of December through to February. These are the months when the port handles deciduous fruit (stone fruit and grapes) for export. These fruits have a short shelf life as well as a relatively short marketing (sales) period. Therefore delays during this time period have major consequences for the exporters (Goedhals, 2003).

In addition to the flexibility of the service, the most important value-adding aspect of the service provided by liner shipping to shippers is service reliability. The more control liner shipping has over the elements of the transport logistics supply chain, the easier it is for liner shipping to provide a more reliable service. Integration of land transport services with the sea leg of shipping is therefore a key strategic consideration for service differentiation and competitive advantage in liner shipping (Qukula, 2000). Not only does such integration give the liner companies virtual control over the movement of the cargo from origin to destination, enabling the reduction of costs, but it enables ship operators to earn higher profits through investing in the entire supply chain service, instead of only in the highly competitive liner service (Fourie, 2002).

The development of containers has made it easier to determine where commodities are at any stage in the supply chain. Many liner companies have introduced satellite tracking for each container. This allows the customer to track the goods from the origin to the destination on a real-time basis. It provides the customer with information as to where consignments are in the supply chain and enables unexpected delays to be perceived. Thus, both shippers and cargo owners can plan timeously for cargo arrival.

Containerisation and other technological improvements have led to vessel size emerging as an important factor in reducing operating costs. Larger ships can achieve lower unit costs and tend to be faster, reducing service times on each leg and allowing a faster turnaround (Department of Treasury, 1999). Vessels which at one time carried between one hundred and six hundred Twenty-foot Equivalent Unit (TEU) containers have been replaced by 5 000, 6000, 8000 and 11 000 TEU container vessels and there are already plans for a new generation of vessels that will carry approximately 18 000 TEU containers. Table 6.2 shows the international characteristics of large container vessels and Figure 6.4 shows a picture of an 11000 TEU vessel that is currently in operation.

**Table 6.2:** International Characteristics of Large Container Vessels[5].

| **Category** | **Capacity TEUs** | **Dimensions (ft)** | | | **Typical Arrangement** | | |
|---|---|---|---|---|---|---|---|
| | | **Length** | **Beam** | **Draught** | **Below** | **Above** | **Across** |
| Panamax | 4000 - 4 500 | 930-970 | 106 | 40 | 8 | 5 | 13 |
| Post Panamax I | 4500 - 6 000 | 930-970 | 130-135 | 42-46 | 8 | 5 | 15 |
| Post Panamax II | 6000 - 9 000 | 980-1 200 | 140-150 | 45-47 | 9 | 6 | 17 |
| Post Panamax III | 9000 - 12 500 | 1150-1 300 | 150-180 | 46-48 | 10 | 6 | 22 |

Post Panamax I = First Generation Containership
Post Panamax = Containership unable to fit into the Panama Canal Locks due to width

However, although the unit costs of carrying containers decreases substantially as the number of containers carried per ship increases, there are constraints on the length, breadth and draught of ships

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[5] Source: National Ports Authority (2005).

**Figure 6.4:** Emma Maersk - the World's Biggest Container Vessel[6]

that can enter ports (Fourie, 2002). In addition, the economic benefits can only be achieved when the capacity utilisation of the ship is high.

The size of a ship can also be a disadvantage if it is too large as it may not be able to pass through the Panama Canal or enter certain ports. Container ships wider than 32.25m are called post-Panamax container ships because they are not able to cross the Panama Canal locks. This means longer sailing distances, higher costs and lower flexibility. Furthermore, the breadth of the post-Panamax container ship requires quay cranes to have sufficient outreach to service the outboard container on the ship's deck. Because of the large depth, cranes must be higher, which means that the movements of the spreader will be longer. Thus ports that handle post-Panamax vessels require specialized equipment in order to do so. This can be very costly and can prevent poorer countries from having the means necessary to handle larger vessels.

Due to their additional size, post-Panamax container ships have to load and unload more containers in each port. This means a longer port-time and additional port costs, unless the loading speed can be increased. Thus speedy working at the terminals is a priority to meet exact schedules. In order

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[6] Source: Ramchand (2007).

for ports to be able to service post-Panamax ships successfully, they require a high number of cranes to work on the ship as well as the necessary infrastructure to store and to feed the containers to and from ship side.

Certain ports and indeed whole areas, e.g. the east coast of the USA, have limited water depth that requires deadweight restrictions on some of the deeper draught Panamax ships. The high costs of building new deepwater terminals in many locations could consequently put the larger ships at an economic disadvantage. The draughts permissible along the South African coastline range from 6.5m in the Port of Mossel Bay to 21.5m (under certain circumstances) in the Port of Saldanha. The draughts at the container terminals are as follows:

- Port of Durban: from 11.1m to 12.3m
- Port of Port Elizabeth: a maximum permissible draught of 11.2m
- Port of Cape Town: from 9.4m to 14m

The draught at the new container terminal planned in the Port of Ngqura is 14m. This will allow container ships of up to 6500 TEU to be handled in the port. Table 6.3 shows the sizes of existing container ships calling at South African ports and the sizes of ships likely to be employed in the future.

**Table 6.3:** Container Ship Sizes[7].

| **Container ships** | **TEU capacity** |
|---|---|
| Mainly feeder/coastal size | 200 - 499 TEU |
| Mainly feeder/coastal size | 500 - 999 TEU |
| Mainly feeder/coastal size | 1000 - 1999 TEU |
| Panamax (in current use) | 2000 - 3500 TEU |
| Post-Panamax (planned use) | 3500 - 4500 TEU |
| Post-Panamax (planned use) | 4500 - 6000 TEU |

The bulk shipping industry provides transport for cargoes that are traded in the market in shiploads. Large companies shipping substantial quantities of bulk materials often operate their own shipping fleets to handle a proportion of their transport requirements (Stopford, 2009). If a shipper has a long-term requirement for bulk transport, but does not want to become actively involved as a shipowner, he may charter tonnage on a long-term basis from a shipowner. In order to achieve scale economies

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[7] Source: (Fourie, 2002)

in the conveyance by sea of vast quantities of raw materials, very large ships are employed. However, the economies of scale that such ships enable can be achieved only if the unproductive time of the ships, which is largely the time required in ports for loading and unloading, can be reduced (Fourie, 2002). Table 6.4 shows the sizes of existing bulk ships calling at South African ports.

**Table 6.4:** Sizes of the Ships used in Carrying Bulk Commodities to and from SA Ports[8].

| **Dry-bulk ships** | |
|---|---|
| **Capacity** | **Comments** |
| 10 - 49999 dwt | Handysize |
| 50 - 69999 dwt | Panamax |
| 340000 dwt | Capesize |
| **Tankers** | |
| **Capacity** | **Comments** |
| 10 - 49999 dwt | Handy |
| 50 - 69999 dwt | Panamax |
| 70 - 99999 dwt | Aframax |
| 100 - 199999 dwt | Suezmax |
| 200 - 299999 dwt | VLCC |
| 300000 + dwt | ULCC |
| **Chemical carrier** | |
| **Capacity** | **Comments** |
| 4000 - 6000 dwt | Chemical tanker |
| 6000 - 10000 dwt | Chemical tanker |
| 10000 - 20000 dwt | Chemical tanker |
| 20000 dwt< | Products tanker |

### 6.5.4 Shipping Lines - Feeder and Coastal Services

A feeder service provides regional services by collecting cargo from international carriers and “feeding” it to various smaller South African ports where, due to size constraints, larger vessels cannot dock. Similarly, it collects cargo from small ports and feeds it to international carriers at the larger ports (Manoim, 2002). A coastal service carries out the shipping of regional commercial cargo from South African ports along the west and east coasts of Africa (Manoim, 2002).

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[8] Source: (Fourie, 2002)

The most important operator of coastal and feeder services to and from South African ports is Ocean Africa Container Lines (a joint venture between Safmarine N.V. and Grindrod Ltd, previously known as Unifeeder). Ocean Africa Container Lines employ seven vessels to service all ports on a weekly basis between Luanda on the West Coast of Africa and Mombassa on the East Coast of Africa (Ocean Africa Container Lines, 2006).

The cargo that is collected through feeder or coastal services is then integrated into supply chains either through agreements between the shipowners or through the acquisition of coastal feeder services by the large liner companies (Fourie, 2002). The transhipment of containers for feeding between ports lengthens the transit time and is not readily accepted by cargo owners. As a result, much of the South African coastal cargo has been lost to road transport and it is doubtful whether that could be regained. Many initiatives to revive such traffic through the years have failed.

## 6.6 Conclusion

In order for South African supply chains to compete on an international level they have to be efficient in terms of speed and reliability as well as competitive in terms of cost. In order for this to be achievable they have to be able to identify and overcome bottlenecks. One way of doing this is through an efficiency measurement.

In an attempt to develop a model that can be used to measure supply chain efficiency throughout South African supply chains irrespective of the type of commodity moved, this chapter divides supply chains into five categories, namely, sources or suppliers (who are the origin of the supply chain), markets or customers (who are the final destination in a supply chain), points of production, points of storage or point of transhipment and transport nodes. By breaking supply chains down into these five basic categories it becomes easier to measure and in so doing identify and improve areas of weakness.

# CHAPTER 7

# Model and Analyses

## 7.1 Introduction

The purpose of this chapter is to propose a model that can measure efficiency across an entire supply chain.

Supply chains are fundamental in international globalised trade and therefore the level of efficiency of a supply chain directly affects a country's competitiveness. Supply chain efficiency is a determinant of lower import and export costs. In order to maintain a competitive position in international markets, countries must understand the variables that lie behind supply chain efficiency.

The performance of supply chains should be evaluated through the use of techniques designed to measure efficiency so that executives are able to identify the bottlenecks in a supply chain and how competitors use their resources. The model developed in this chapter can be used to benchmark the overall efficiency of a supply chain by comparing it to other similar supply chains. In addition, it has the ability to compare the efficiency of each activity in the supply chain with other similar activities from other supply chains and in so doing can pinpoint the activities that are causing the problems in attaining overall efficiency. An advantage of the model is that it has been constructed as a generic model and can therefore be adapted to measure the efficiency of practically all types of supply chains by making a few adjustments.

As noted in Chapter 4, the author acknowledges that the input factors used in the development of the model below to measure the efficiency of a supply chain may differ from supply chain to supply chain. However, due to the generic formulation of the model and the guidelines provided in this chapter, it is possible for the firms using the model to make the necessary adaptations with minimal effort.

## 7.2 Model Framework and Parameters

The model was developed to measure efficiency across an entire supply chain. In an attempt to keep the mathematical equations simple, the supply chain has been broken down into five categories of links or nodes, namely, sources/suppliers, points of production, points of storage and/or transhipment, transport links and markets/customers.

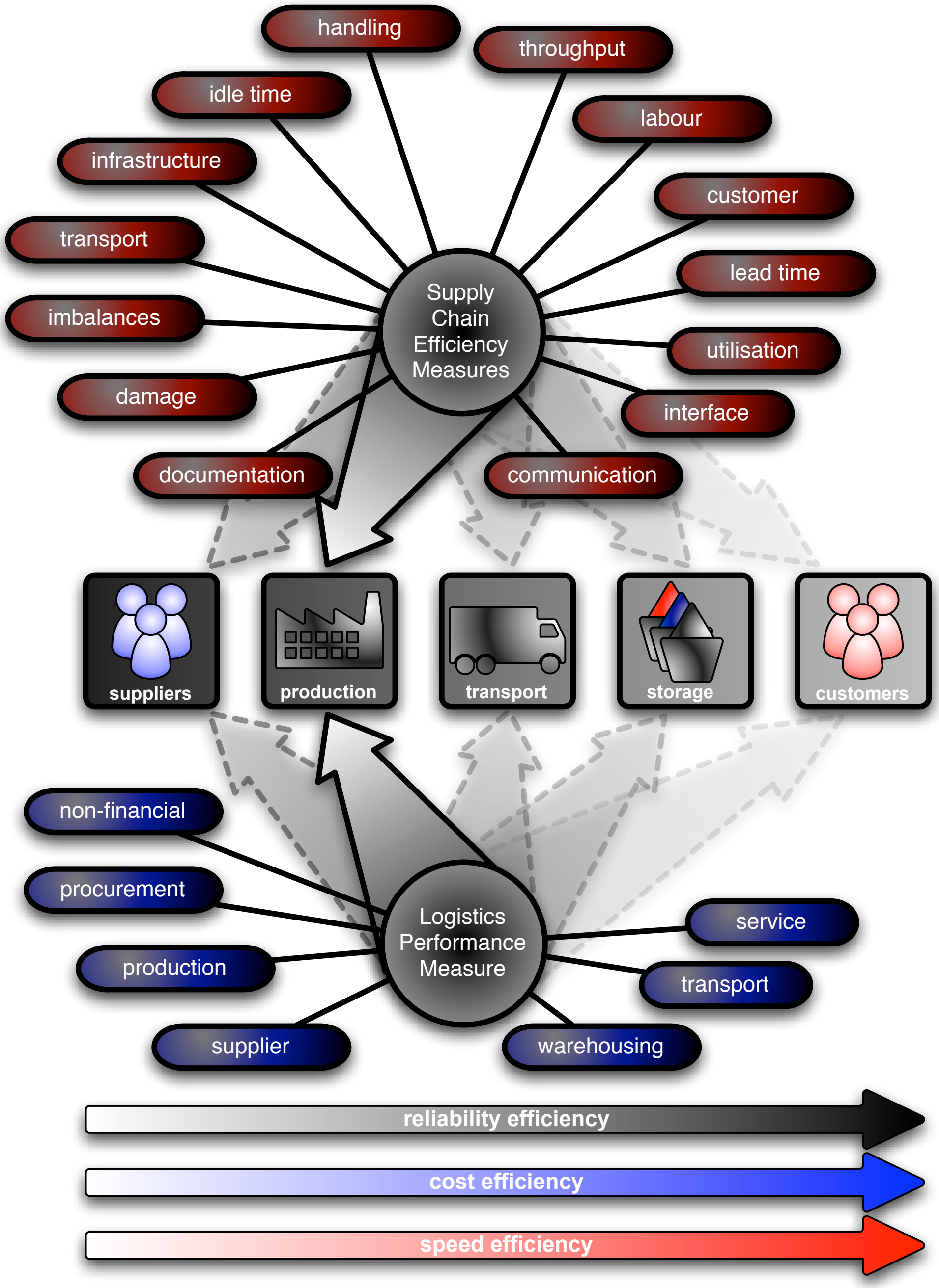
Parameters were chosen according to those factors that were considered as important in determining efficiency across a supply chain. These decisions were made after researching previous studies as well as conducting interviews. Firstly, the parameters were broken down into three broad categories, namely, speed, reliability and cost. Each parameter plays an important role in determining whether or not a supply chain is efficient. Secondly, further information was collected about different performance measures (see Chapter 4) 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 in Chapter 5 have on the overall efficiency of a supply chain. Figure 7.1 shows a graphic representation of how the model was developed.

## 7.3 Model Development

The model for this dissertation was developed in three stages:

1. Definition of model inputs and outputs. This involved determining the factors that influence the overall level of efficiency in a South African supply chain. It was achieved by conducting a review of the literature already available on the subject or topics relevant to the study. The

**Figure 7.1:** Graphic representation of the composite supply chain efficiency model[1].



output of the model is a measure of efficiency for an entire supply chain.

2. Interviews with experts in the field. The second stage of the process involved speaking to business executives who work with supply chains on a daily basis and who are concerned with their inefficiencies. That made it possible to compare the variables identified in literature with those considered as the most important by the experts.

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[1] Developed by the author for the purpose of this study.

3. Structure of the model: The first step in the model involves the use of equations to measure the efficiency within each link or node in the supply chain in terms of reliability efficiency, speed efficiency, and cost efficiency. Reliability efficiency and speed efficiency will be given in terms of a percentage, while cost efficiency will be measured as a monetary value. These calculations will give a good indication of how the individual firms along the supply chain are performing. The information gathered in step one is then carried forward to step two 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 then be compared with the frontier in order to determine how efficient it is and where the bottlenecks occur.

If a firm finds that it wants to make changes to the input factors selected below, by either including additional factors or removing some of the factors included, it could do so by simply following the steps given above. It is also important to note that even though it may not be possible to compare supply chains that are exactly the same (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 key points (in terms of this dissertation, 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.

An additional advantage of the method chosen for 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 other 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.

## 7.4 Model

The first step in the model involves calculating the efficiency within each link or node along a supply chain. This can be achieved by using the formulas given below. The formulas grouped under each link or node (*i.e.* points of production or transport links) are used to calculate the efficiency of the link or node in terms of reliability efficiency, cost efficiency and speed efficiency. (It is important to remember that the purpose of the dissertation is to develop a generic model for measuring supply chain efficiency and therefore if there are measurements included that are meaningless to a specific supply chain, they can simply be left out of the measurement - as long as they are excluded from all the supply chains used to develop the frontier.)

### 7.4.1 Sources/Suppliers

**Reliability**

$$Delivery\ reliability\ (\%) = \frac{Maximum\ delivery\ time - Minimum\ delivery\ time\ (hours)}{Average\ delivery\ time\ (hours)} \times \frac{100}{1} \tag{4.17}$$

$$Complete\ shipments\ (\%) = \frac{Number\ of\ orders\ delivered\ in\ full}{Total\ number\ of\ orders} \times \frac{100}{1} \tag{4.18}$$

$$Percentage\ good\ parts = \frac{Total\ quantity\ supplied - Number\ of\ defectives}{Total\ quantity\ supplied} \times \frac{100}{1} \tag{4.19}$$

$$Idle\ time\ (\%) = \begin{array}{l} the\ percentage\ of\ time\ employees\ and\ equipment\ are\ available \\ for\ work\ but\ are\ not\ required\ to\ work \end{array} \tag{5.1}$$

$$Throughput\ efficiency\ (\%) = \frac{Acutual\ throughput}{Best\ Practice\ throughput} \times \frac{100}{1} \tag{5.12}$$

$$Communication = Number\ of\ key\ processes\ integrated\ through\ the\ entire\ supply\ chain \tag{5.18}$$

$$Documentation\ errors\ (\%) = \frac{Number\ of\ documents\ with\ errors}{Total\ number\ of\ documents\ used} \times \frac{100}{1} \tag{5.24}$$

**Cost**

$$Cost\ of\ suppliers\ (Rands) = Rate\ charged\ by\ suppliers\ for\ their\ goods\ and/or\ services \tag{4.20}$$

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ cost\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ costs\ (Rands)}{Actual\ goods\ handling\ i.t.o.\ costs\ (Rands)} \times \frac{100}{1} \tag{5.10}$$

$$\begin{array}{l} Throughput\ efficiency\ i.t.o.\ cost \\ (Rands\ per\ throughput\ units) \end{array} = \frac{BP\ throughput\ (Rands/unit)}{Actual\ throughput\ (Rands/unit)} \tag{5.13}$$

$$\begin{array}{l} Labour \\ \left.\begin{array}{l} \bullet\ Number\ of\ employees \\ \bullet\ Skills\ of\ the\ workforce \\ \bullet\ Average\ hours\ worked\ per\ week \\ \bullet\ Average\ age\ of\ the\ total\ workforce \end{array}\right\} Remuneration\ paid\ (Rands) \end{array}$$

$$Communication = Communication\ cost\ as\ a\ \%\ of\ revenue \tag{5.19}$$

**Speed**

$$Total\ cycle\ time\ (hours) = \begin{array}{l} maximum\ of\ (order\ processing\ time + \\ manufacturing\ lead\ time + transportation\ time)\ and \\ (order\ processing\ time + delivery\ time\ from\ warehouse) \end{array} \tag{4.2}$$

$$Idle\ time\ (\%) = \begin{array}{l} the\ percentage\ of\ time\ employees\ and\ equipment\ are\ available \\ for\ work\ but\ are\ not\ required\ to\ work \end{array} \tag{5.1}$$

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ time\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)}{Actual\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)} \times \frac{100}{1} \tag{5.11}$$

$$Throughput\ efficiency\ (\%) = \frac{Actual\ throughput}{BP\ throughput} \times \frac{100}{1} \tag{5.12}$$

### 7.4.2 Points of production

**Reliability**

$$System\ uptime\ (\%) = \frac{Hours\ that\ a\ system\ is\ available\ in\ a\ period}{Total\ hours\ in\ that\ period} \times \frac{100}{1} \tag{4.3}$$

$$\begin{array}{l} Percent\ defective \\ i.t.o.\ reliability\ (\%) \end{array} = \frac{Total\ number\ of\ defectives\ shipped\ from\ production\ plant}{Total\ number\ of\ items\ shipped\ from\ production\ plant} \times \frac{100}{1} \tag{4.4}$$

$$Idle\ time\ (\%) = \begin{array}{l} The\ percentage\ of\ employees\ and\ equipment\ that \\ are\ available\ for\ work\ but\ are\ not\ required\ to\ work \end{array} \tag{5.1}$$

$$\begin{array}{l} Reduction\ in\ production\ due\ to \\ lack\ of\ necessary\ infrastructure\ (\%) \end{array} = \frac{Decrease\ in\ prod.\ from\ lack\ of\ infrastructure}{Total\ produced\ if\ there\ was\ no\ shortage} \times \frac{100}{1} \tag{5.2}$$

$$Throughput\ efficiency\ (\%) = \frac{Actual\ throughput}{BP\ throughput} \times \frac{100}{1} \tag{5.12}$$

$$Communication = Number\ of\ key\ processes\ integrated\ through\ the\ entire\ supply\ chain \tag{5.18}$$

$$Documentation\ errors\ (\%) = \frac{Number\ of\ documents\ with\ errors}{Total\ number\ of\ documents\ used} \times \frac{100}{1} \tag{5.24}$$

**Cost**

$$Production\ cost\ per\ unit\ (Rands/unit) = \frac{Total\ cost\ of\ goods\ produced}{Total\ number\ of\ goods\ produced} \tag{4.14}$$

or

$$Extraction\ cost\ per\ ton\ (Rand/ton) = \frac{Total\ cost\ of\ product\ mined}{Total\ tons\ of\ product\ mined} \tag{4.15}$$

$$\begin{array}{l} Cost\ to\ balance\ production\ resources \\ with\ production\ requirements \end{array} = \begin{array}{l} Sum\ of\ costs\ associated\ with\ the\ balance\ of \\ production\ resources\ with\ production\ requirements \end{array} \tag{5.5}$$

$$Cost\ per\ ton\ of\ goods\ transported\ (Rands/ton) = \frac{Total\ transport\ cost\ (Rands)}{Number\ of\ tons\ of\ goods\ transported\ (tons)} \tag{4.30}$$

$$\begin{matrix} Throughput\ efficiency\ in\ terms\ of\ cost \\ (Rands\ per\ throughput\ unit) \end{matrix} = \frac{BP\ throughput\ (Rands/unit)}{Actual\ throughput\ (Rands/unit)} \tag{5.13}$$

*Labour*

$$\left.\begin{matrix} \bullet\ Number\ of\ employees \\ \bullet\ Skills\ of\ the\ workforce \\ \bullet\ Average\ hours\ worked\ per\ week \\ \bullet\ Average\ age\ of\ the\ total\ workforce \end{matrix}\right\} Remuneration\ paid\ (Rands)$$

$$Communication\ efficiency = Communication\ cost\ as\ a\ \%\ of\ revenue \tag{5.19}$$

$$\begin{matrix} Percentage\ defective \\ i.t.o.\ cost\ (\%) \end{matrix} = \frac{Total\ cost\ of\ defectives\ shipped\ from\ production\ plant\ (Rands)}{Total\ cost\ of\ items\ shipped\ from\ production\ plant\ (Rands)} \times \frac{100}{1} \tag{4.4}$$

**Speed**

$$Total\ production\ time\ (hours) = Actual\ operating\ time + downtime \tag{4.16}$$

$$Idle\ time\ (\%) = \begin{matrix} The\ percentage\ of\ time\ employees\ and\ equipment \\ are\ available\ for\ work\ but\ are\ not\ required\ to\ work \end{matrix} \tag{5.1}$$

$$\begin{matrix} Goods\ handing\ efficiency \\ i.t.o.\ time\ (\%) \end{matrix} = \frac{BP\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)}{Actual\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)} \times \frac{100}{1} \tag{5.11}$$

$$Throughput\ efficiency\ (\%) = \frac{Actual\ throughput}{BP\ throughput} \times \frac{100}{1} \tag{5.12}$$

### 7.4.3 Points of storage / transhipment

**Reliability**

$$Warehouse\ operating\ cost\ per\ unit\ (Rands/unit) = \frac{Total\ operating\ cost\ in\ warehouse}{Number\ of\ units\ handled} \tag{4.26}$$

$$Percentage\ damaged = \frac{Number\ of\ goods\ damaged\ in\ storage}{Total\ number\ of\ goods\ stored} \times \frac{100}{1} \tag{4.24}$$

$$Utilisation\ of\ warehouse\ equipment\ (\%) = \frac{Delays\ incurred}{Total\ time\ warehouse\ equipment\ was\ employed} \times \frac{100}{1} \tag{4.25}$$

$$Idle\ time\ (\%) = \begin{array}{l} The\ percentage\ of\ time\ employees\ and\ equipment \\ are\ available\ for\ work\ but\ are\ not\ required\ to\ work \end{array} \tag{5.1}$$

$$\begin{array}{l} Reduction\ in\ storage\ due\ to\ lack \\ of\ available\ infrastructure\ (\%) \end{array} = \frac{Decrease\ in\ storage\ due\ to\ lack\ of\ infrastructure}{Total\ stored\ if\ there\ was\ no\ shortage} \times \frac{100}{1} \tag{5.3}$$

$$Throughput\ efficiency\ (\%) = \frac{Actual\ throughput}{BP\ throughput} \times \frac{100}{1} \tag{5.12}$$

$$Communication = Number\ of\ key\ processes\ integrated\ through\ the\ entire\ supply\ chain \tag{5.18}$$

$$Documentation\ errors\ (\%) = \frac{Number\ of\ documents\ with\ errors}{Total\ number\ of\ documents\ used} \times \frac{100}{1} \tag{5.24}$$

### Cost

$$Warehouse\ operating\ cost\ per\ unit\ (Rands/unit) = \frac{Total\ operating\ cost\ in\ warehouse}{Number\ of\ units\ handled} \tag{4.26}$$

$$\begin{array}{l} Cost\ to\ balance\ storage\ resources \\ with\ storage\ requirements \end{array} = \begin{array}{c} Sum\ of\ costs\ associated\ with\ the\ balance \\ of\ storage\ resources\ with\ storage\ requirements \end{array} \tag{5.6}$$

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ cost\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ costs\ (Rands)}{Actual\ goods\ handling\ i.t.o.\ costs\ (Rands)} \times \frac{100}{1} \tag{5.10}$$

$$Throughput\ efficiency\ i.t.o.\ cost\ (Rands\ per\ throughput\ unit) = \frac{BP\ throughput\ (Rands/unit)}{Actual\ throughput\ (Rands/unit)} \tag{5.13}$$

*Labour*

$$\left.\begin{array}{l} \bullet\ Number\ of\ employees \\ \bullet\ Skills\ of\ the\ workforce \\ \bullet\ Average\ hours\ worked\ per\ week \\ \bullet\ Average\ age\ of\ the\ total\ workforce \end{array}\right\} Remuneration\ paid\ (Rands)$$

$$Communication = Communication\ cost\ as\ a\ \%\ of\ revenue \tag{5.19}$$

$$Percentage\ damages\ i.t.o.\ cost\ (\%) = \frac{Total\ cost\ of\ damages\ in\ storage\ (Rands)}{Total\ cost\ of\ goods\ stored\ (Rands)} \times \frac{100}{1} \tag{5.21}$$

**Speed**

$$Order\ picking\ time\ (hours) = \begin{array}{l} order\ processing\ time + travel\ time\ to\ first\ location\ + \\ inter - location\ travel\ time + travel\ from\ last\ location\ + \\ pick - up\ time + interference\ time \end{array} \tag{4.22}$$

$$Warehouse\ throughput\ (loads/hour) = \frac{Number\ of\ loads\ received,\ stored\ and\ retrieved}{Number\ of\ hours} \tag{4.23}$$

$$Idle\ time\ (\%) = \begin{array}{l} The\ percentage\ of\ time\ employees\ and\ equipment \\ are\ available\ for\ work\ but\ are\ not\ required\ to\ work \end{array} \tag{5.1}$$

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ time\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)}{Actual\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)} \times \frac{100}{1} \tag{5.11}$$

$$Throughput\ efficiency\ (\%) = \frac{Actual\ throughput}{BP\ throughput} \times \frac{100}{1} \tag{5.12}$$

### 7.4.4 Transport links

**Reliability**

$$\begin{array}{l} Variability\ as\ a\ \% \\ of\ transit\ time \end{array} = \frac{Max\ transit\ time\ (hours) - Min\ transit\ time\ (hours)}{Average\ transit\ time\ (hours)} \times \frac{100}{1} \tag{4.28}$$

$$Perfect\ shipments\ (\%) = \frac{Number\ of\ perfect\ shipments}{Total\ number\ of\ shipments} \times \frac{100}{1} \tag{4.29}$$

$$\begin{array}{l} Utilisation\ of \\ transport\ means\ (\%) \end{array} = \frac{Delays\ incurred\ (hours)}{Time\ transport\ means\ were\ employed\ (hours)} \times \frac{100}{1} \tag{4.31}$$

$$Idle\ time\ (\%) = \begin{array}{l} The\ percentage\ of\ time\ employees\ and\ equipment \\ are\ available\ for\ work\ but\ are\ not\ required\ to\ work \end{array} \tag{5.1}$$

$$\begin{array}{l} Reduction\ in\ transportation\ due\ to \\ lack\ of\ necessary\ infrastructure\ (\%) \end{array} = \frac{Decrease\ due\ to\ lack\ of\ infrastructure}{Total\ transported\ if\ there\ was\ no\ shortage} \times \frac{100}{1} \tag{5.4}$$

$$Throughput\ efficiency\ (\%) = \frac{Actual\ throughput}{BP\ throughput} \times \frac{100}{1} \tag{5.12}$$

$$Communication = Number\ of\ key\ processes\ integrated\ through\ theentire\ supply\ chain \tag{5.18}$$

$$Documentation\ errors\ (\%) = \frac{Number\ of\ documents\ with\ errors}{Total\ number\ of\ documents\ used} \times \frac{100}{1} \tag{5.24}$$

**Cost**

$$Cost\ per\ ton\ of\ goods\ transported (Rands/ton) = \frac{Total\ transport\ cost\ (Rand)}{Number\ of\ tons\ of\ goods\ transported\ (tons)} \tag{4.30}$$

$$\begin{array}{l} Cost\ to\ balance\ transportation\ resources \\ with\ transportation\ requirements \end{array} = \begin{array}{c} \sum of\ costs\ to\ balance\ transportation \\ resources\ with\ transportation\ requirements \end{array} \tag{5.7}$$

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ cost\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ cost\ (Rands)}{Actual\ goods\ handling\ i.t.o.\ cost\ (Rands)} \times \frac{100}{1} \tag{5.10}$$

$$Throughput\ efficiency\ i.t.o.\ cost\ (Rands/unit) = \frac{BP\ throughput\ (Rands/unit)}{Actual\ throughput\ (Rands/unit)} \times \frac{100}{1} \tag{5.13}$$

*Labour*

$$\left.\begin{array}{l} \bullet\ Number\ of\ employees \\ \bullet\ Skills\ of\ the\ workforce \\ \bullet\ Average\ hours\ worked\ per\ week \\ \bullet\ Average\ age\ of\ the\ total\ workforce \end{array}\right\} Remuneration\ paid\ (Rands)$$

$$Communication = Communication\ cost\ as\ \%\ of\ revenue \tag{5.19}$$

$$Damaged\ shipments\ i.t.o.\ cost\ (\%) = \frac{Cost\ of\ goods\ damaged\ during\ shipment\ (Rands)}{Total\ cost\ of\ goods\ shipped\ (Rands)} \times \frac{100}{1} \tag{5.22}$$

$$Imbalance\ in\ goods\ flows\ (\%) = \frac{ton.kilometre\ utilised}{ton.kilometre\ available} \times \frac{100}{1} \tag{5.23}$$

**Speed**

$$Total\ transit\ time\ (hours) = \begin{array}{c} Travel\ time + Waiting\ time\ at\ terminals/docks\ + \\ Transfer\ time + Handling\ time \end{array} \tag{4.27}$$

$$Idle\ time\ (\%) = \begin{array}{l} The\ percentage\ of\ time\ employees\ and\ equipment \\ are\ available\ for\ work\ but\ are\ not\ required\ to\ work \end{array} \tag{5.1}$$

$$\begin{array}{l} Goods\ handling\ efficiency \\ i.t.o.\ time\ (\%) \end{array} = \frac{BP\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)}{Actual\ goods\ handling\ i.t.o.\ turnaround\ times\ (t)} \times \frac{100}{1} \tag{5.11}$$

$$Throughput\ efficiency\ (\%) = \frac{Actual\ throughput}{BP\ throughput} \times \frac{100}{1} \tag{5.12}$$

### 7.4.5 Markets/Customers

**Reliability**

$$Service\ reliability\ (\%) = \frac{Number\ of\ shipments\ within\ \text{``}x\text{''}\ hours\ of\ promised\ delivery\ time}{Total\ number\ of\ shipments} \times \frac{100}{1} \tag{4.32}$$

**Cost**

$$\begin{array}{l} Information\ must\ be\ collected\ as\ to\ whether\ the\ customers\ are\ satisfied\ with \\ the\ prices\ that\ are\ being\ charged \end{array}$$

**Speed**

$$Line\ count\ fill\ rate\ (\%) = \frac{Number\ of\ order\ lines\ shipped\ on\ initial\ order}{Total\ number\ of\ order\ lines\ ordered} \times \frac{100}{1} \tag{4.33}$$

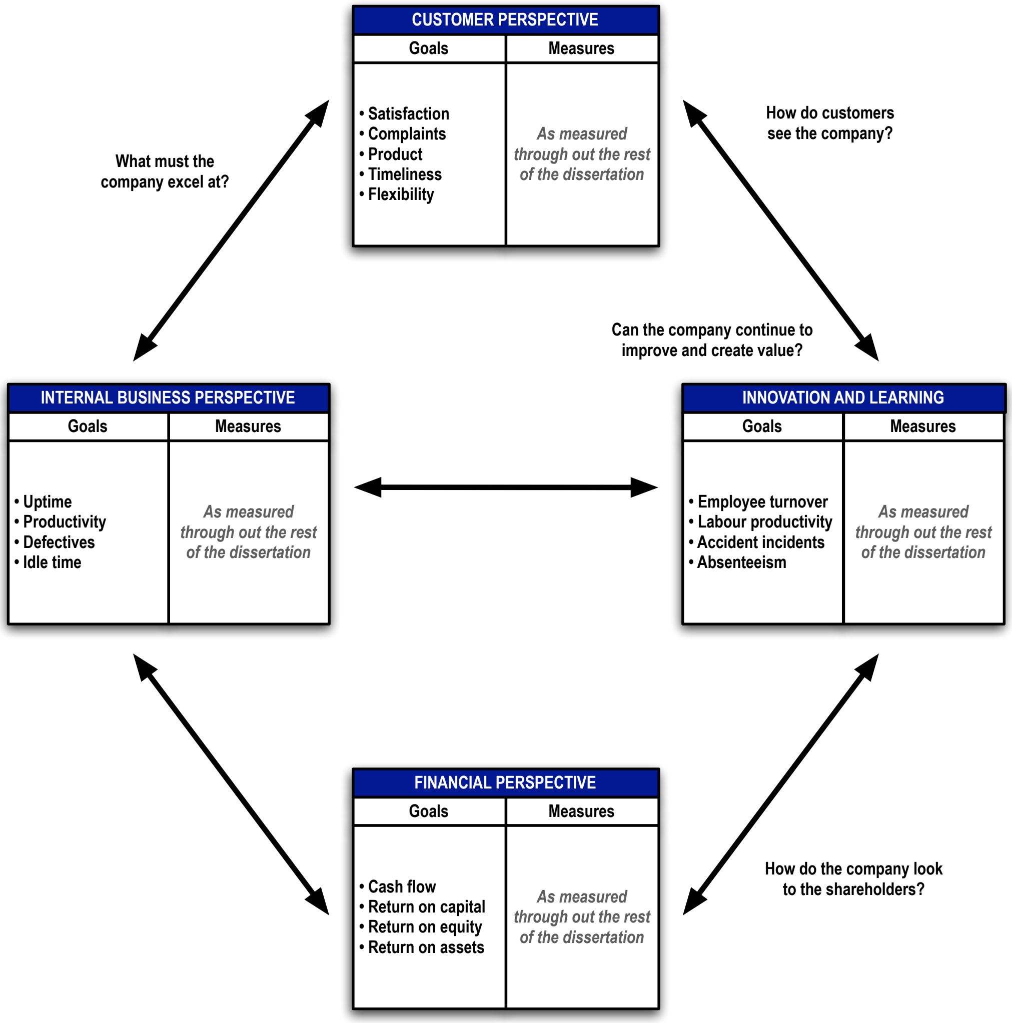
$$SKU\ fill\ rate\ (\%) = \frac{Number\ of\ SKUs\ shipped\ on\ initial\ order}{Total\ number\ of\ SKUs\ ordered} \times \frac{100}{1} \tag{4.34}$$

$$Lead\ time\ (time\ period\ (t)) = \frac{Time\ it\ takes\ for\ goods\ to\ arrive\ at\ the\ customer}{in\ the\ correct\ condition\ after\ the\ order\ has\ been\ placed} \tag{5.17}$$

The information gathered from step one in the model can then be carried forward to step two in the model. Step two involves incorporating DEA and determining the most efficient supply chain (the most efficient supply chain can be made up of a combination of links and nodes from various supply chains).

## 7.5 Comparison with the Balanced Scorecard Method

**Figure 7.2:** The BSC framework[2]



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[2] Source: Davis & Spekman (2004).

The Balanced Sorecard Method is a method that has been identified as a possible alternative for the first step of the model. It is a multi-step process which firstly converts the mission and vision statement of the firm into key areas before setting objectives under each key area and finally develops plans to achieve all the objectives. The typical key areas used by the Balanced Scorecard Method as illustrated in 7.2 are:

- Customer Perspective
- Internal Business Perspective
- Innovation and Learning
- Financial Perspective

Simply identifying key areas within a firm does not lead to improved performance levels. The firm also has to set specific objectives that must be met under each key area. The goals highlight what the firm wants to be able to achieve under each area. Finally, the Balanced Scorecard method measures the performance under each objective. Selecting the right performance measures is key to obtaining worthwhile results.

The Balanced Sorecard method is a well-known method for measuring supply chain performance. Although it can be used as an alternative for the first step in the model it has its shortfalls. The firm selects its own goals and then establishes the measurements used to determine the performance of the firm. This can lead to a biased view of how the firm is performing. With the method provided in this dissertation, all firms use the same criteria for measuring supply chain efficiency and therefore excludes the possibility of obtaining biased results.

In the later steps of the model developed, DEA is used to measure efficiency across the entire supply chain. A strength of DEA is that assigns weights to the variables automatically, so the model determines the importance of the measurement. With respect to the Balanced Scorecard method the firm decides what goals are important and determines which measurements are included. After which the method handles each measurement as equally important.

## 7.6 Input-Oriented Models

Input-oriented models are configured with the aim of minimizing the inputs in order to achieve a certain level of output. According to Pascoe et al. (2003) with input-oriented DEA, the linear programming model is developed in order to determine how much input usage could decrease if used efficiently to achieve the same level of output.

For firms who base their performance on optimizing the management of available resources, the improvement targets used will be input oriented because the aim is to evaluate the technical efficiency of all the DMUs in the supply chain based on a given set of inputs, while ensuring that the current output levels for the DMUs are not decreased. In addition, managers also have more control over the inputs compared to the outputs, which makes any possible areas of improvement that are identified through the evaluation process easier to implement.

## 7.7 Output-Oriented Models

Output-oriented models are developed in order to maximize the level of output given the levels of inputs. According to Pascoe et al. (2003) with output-oriented DEA, the linear programming model is configured to determine a firm's potential output given its inputs if it operated as efficiently as firms along the best practice frontier. Output-oriented models are "... very much in the spirit of neo-classical production functions defined as the maximum achievable output given input quantities" (Färe, Grosskopf & Lovell, 1994).

For firms who base their performance on maximizing their output by utilising available inputs as efficiently as possible, the improvement targets will be output oriented. Managers who benefit from higher output levels should set up their evaluation process accordingly.

## 7.8 Constant Returns to Scale

The constant returns to scale (CRS) model is also referred to as the Charnes, Cooper, Rhodes (CCR) model. According to Pascoe et al. (2003) CRS "reflects the fact that output will change by the same proportion as inputs are changed". Anderson (1996) states that CRS can only be assumed when the producers are able to linearly scale the inputs and outputs without increasing or decreasing efficiency.

This is a significant assumption to be made (Anderson, 1996). According to Anderson (1996) the assumption of CRS may be valid over limited ranges but its use must be justified.

## 7.9 Variable Returns to Scale

Returns to scale refers to increasing or decreasing efficiency based on size (Anderson, 1996). The variable returns to scale (VRS) model is also known as the Banker, Charnes, Cooper (BCC) model. VRS "reflects the fact that production technology may exhibit increasing, constant and decreasing returns to scale" (Pascoe et al., 2003).

For example, a vehicle manufacturer can achieve certain economies of scale by manufacturing a hundred motor vehicles at a time rather than manufacturing each one separately, however, it might be only ten times as hard as producing one at a time. This is an example of increasing returns to scale (IRS).

Conversely, the vehicle manufacturer might find it more than a thousand times as difficult to manufacture a thousand vehicles at a time because of equipment limitations and restrictions on the hours worked by the work force. This scenario is an example of decreasing returns to scale (DRS). Combining both the increasing and decreasing returns to scale would necessitate building a model that incorporates variable returns to scale (VRS).

CRS tends to lower the efficiency scores while VRS tends to raise efficiency scores (Anderson, 1996).

## 7.10 Notation Used in the Second Step of the Model

**DMU** (Decision Making Unit) - the term refers to any entity that is to be evaluated by the model in terms of its abilities to convert inputs into outputs.

$n$ - the number of DMUs that are to be evaluated for a supply chain.

$u_r$ - the weight for the output $r$

$v_i$ - the weight for the input $i$

$y_{rj}$ - the amount of output $r$ for $\mathrm{DMU}_j$

$x_{ij}$ - the amount of input $i$ for $\mathrm{DMU}_j$

$s$ - the number of outputs

$m$ - the number of inputs

$\epsilon$ - a small positive number (smaller than any positive real number)

$\theta$ - the technical efficiency score

$\lambda_j$ - a dual variable

$s_i^-$ - input slack (indicates amount of surpluses in the inputs)

$s_i^+$ - output slack (indicates how many units short in the outputs)

$c_{ij_o}$ - the unit cost of input i of DMU$_{j_o}$ which may vary from one DMU to another

## 7.11 Model Construction

The model developed below, is done so in order to measure the efficiency of a supply chain. The mathematical technique chosen for 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 & Wong, 2007). DEA has been proven in various forms of academic literature as a suitable mathematical method for measuring efficiency. 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 & Wong, 2007).

The first step in the mathematical model is to write DEA in ratio form. This form was first introduced by Charnes, Cooper and Rhodes in 1978 and is used to measure the efficiency of the DMU$_{j_o}$ relative to ratios of all the DMUs $j = 1, 2, \ldots, n$. For a particular DMU the ratio of the single virtual output to single virtual input provides a measure of efficiency that is a function of the multipliers (Cooper, Seiford & Zhu, 2004). The ratio form of DEA can be written as follows:

$$
\begin{aligned}
&\text{Maximise } z = \frac{\sum_{r=1}^{s} u_r y_{rj_o}}{\sum_{i=1}^{m} v_i x_{ij_o}} \\
&\text{Subject to:} \\
&\qquad \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \qquad\qquad j = 1, 2, \ldots, n \\
&\qquad u_r \geq \epsilon, r = 1, 2, \ldots, s \quad v_i \geq \epsilon, i = 1, 2, \ldots, m
\end{aligned}
\tag{7.1}
$$

The objective function of equation (7.1) strives to maximise the efficiency score of DMU$_{j_o}$ by selecting a set of weights for all inputs and outputs. The first constraint set for equation (7.1) limits the ratio of the weighted sum of outputs and weighted sum of inputs to be less than or equal to 1. The second and third constraint sets for equation (7.1) ensure that none of the weights are equal to 0. This ensures that all inputs and outputs are considered towards the overall efficiency of DMU$_{j_o}$. A DMU$_{j_o}$ is considered efficient if the objective function provided above (in equation (7.1)) results in an efficiency score of 1, otherwise it is considered inefficient (Wong & 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. The above equations can be rewritten in canonical form by moving the denominator in the first constraint set in equation (7.1) to the right-hand side of the equation and setting the denominator in the objective function (in equation (7.1)) to 1. Equation (7.1) can then be rewritten as follows:

$$
\begin{aligned}
&\text{Maximise } z = \sum_{r=1}^{s} u_r y_{rj_o} \\
&\text{Subject to:} \\
&\qquad \sum_{i=1}^{m} v_i x_{ij_o} = 1 \\
&\qquad \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \qquad\qquad j = 1, 2, \ldots, n \\
&\qquad u_r \geq \epsilon, r = 1, 2, \ldots, s \quad v_i \geq \epsilon, i = 1, 2, \ldots, m
\end{aligned}
\tag{7.2}
$$

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 $m + s$ constraints. As $n$, the number of units, is usually considerably larger than $ts + m$, 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 (7.2) can be given as follows:

$$\begin{aligned} & \theta^* = \text{Minimise } \theta \\ \text{Subject to:} & \\ & \sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ij_o} \quad && i = 1, 2, \ldots, m \\ & \sum_{j=1}^{n} \lambda_r y_{rj} \geq y_{rj_o} \quad && r = 1, 2, \ldots, s \\ & \lambda_j \geq 0, && j = 1, 2, \ldots, n \end{aligned} \tag{7.3}$$

By virtue of the dual theorem of linear programming $z^* = \theta^*$. Therefore either equation (7.2) or equation (7.3) can be used to calculate the solution. The optimal solution, $\theta^*$, yields an efficiency score for a particular DMU. The process can be repeated for each $\text{DMU}_{j_o}$. 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. However, this problem can be avoided by rewriting equation (7.3) to include the slacks which are taken to their maximal values. This equation can be written as follows:

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

Subject to:

$$\begin{aligned} &\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta^* x_{ij_o} && i = 1, 2, \ldots, m \\ &\sum_{j=1}^{n} \lambda_r y_{rj} - s_r^+ = y_{rj_o} && r = 1, 2, \ldots, s \\ &\lambda_j, s_i^-, s_r^+ \geq 0, && \forall\ i, j, r \end{aligned} \tag{7.4}$$

where the choices of $s_i^-$ and $s_r^+$ do not affect the optimal $\theta^*$ which is determined from equation (7.3).

These developments now lead to the following definition based upon the relative efficiency definition which was given in section 4.13.

The definition for DEA efficiency states that the performance of DMU$_{j_o}$ is only fully (100%) efficient if and only if both (i) $\theta^* = 1$ and (ii) all slacks $s_i^- = s_r^+ = 0$ (Cooper, Seiford & Zhu, 2004).

The definition for weakly DEA efficient states that the performance of DMU$_{j_o}$ 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 & Zhu, 2004).

The variable $\theta$ 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. The input slacks indicate the surplus number of inputs that are being utilised by DMU$_{j_o}$ and the output slacks represent the shortfalls in the outputs of DMU$_{j_o}$. The slacks are indirectly correlated to the level of efficiency that is achieved (large values for the slack variables results in lower levels of efficiency) and therefore form an important relationship. Based on the two definitions above, it is clear when DMU$_{j_o}$ is either strongly DEA efficient or weakly DEA efficient and if either case is proven then no further calculations are required. However, when DMU$_{j_o}$ is inefficient appropriate adjustments can be applied to the inputs and outputs in order to make DMU$_{j_o}$ more efficient. The following input/output adjustments would render it efficient to other DMUs:

$$x_{ij_o}^{'} = \theta^* x_{ij_o} - s_i^{-*}, \quad i = 1, 2, \ldots, m \tag{7.5}$$

$$y'_{rj_o} = y_{rj_o} + s_r^{+^*}, \quad r = 1, 2, \ldots, s \tag{7.6}$$

From the duality theory in Linear Programming (LP), for an inefficient DMU$_{j_o}$, $\lambda^* > 0$ in the optimal dual solution also implies that DMU$_i$ is a unit of the peer group (Wong & Wong, 2007). A peer group of an inefficient DMU$_{j_o}$ is defined as the set of DMUs that reach the efficiency score of 1 using the same set of weights that result in the efficiency score of DMU$_{j_o}$ (Wong & Wong, 2007). The improvement targets given in equations (7.5) and (7.6) are obtained directly from the dual solutions. This is because the constraints in equation (7.4) relate the levels of outputs and scaled inputs of DMU$_{j_o}$ to the levels of the outputs and inputs of a composite DMU formed by the peer group (Wong & Wong, 2007). The goals that are set in order for DMU$_{j_o}$ to become more efficient are classified as "input orientated" because the main focus is on improving efficiency through the reduction of inputs utilized. However, if the focus shifts towards the improvement of efficiency through the increase of outputs, the input-orientated improvement targets can be replaced with output-oriented adjustments.

The dual model of the above formulation is also known as the envelopment model. It has the ability to solve the LP problem more efficiently than the primal model when the number of DMUs is larger than the total number of inputs and outputs, which is normally the case in applying DEA (Wong & Wong, 2007). More importantly, the dual variables provide alternative solutions which would result in an inefficient DMU becoming more efficient when compared to the efficient DMUs and in so doing highlight 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 (7.4) 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 (7.4)) 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 look at the costs along the supply chain. In this case the aim will be to minimize costs without reducing the level of outputs achieved. The cost efficiency model is shown below:

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

Subject to:

$$\begin{aligned} x_i &\geq \sum_{j=1}^{n} \lambda_j x_{ij} && i = 1, 2, \ldots, m \\ y_{rj_o} &\leq \sum_{j=1}^{n} \lambda_r y_{rj} && r = 1, 2, \ldots, s \\ \lambda_j &\geq 0 \end{aligned} \tag{7.7}$$

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

$$CE = \frac{c'_{ij_o} x'_{ij_o}}{c'_{ij_o} x_{ij_o}} \tag{7.8}$$

Equation 7.8 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 7.9 below (Allocative Efficiency is defined as "the situation that occurs when no resources are wasted – when no one can be made better off without making someone else worse off" (McAleese, 2007)). The TE value is obtained from the technical efficiency model (equation 7.4) and substituted into equation 7.9 (Wong & Wong, 2007):

$$AE = \frac{CE}{TE} \tag{7.9}$$

The AE measure includes slacks which reflect an inappropriate input mix (Ferrier & 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.

Both the TE and CE models were derived carefully from a literature review (most of which came from the works of Wong & Wong (2007) as well as Cooper, Seiford & Zhu (2004)).

## 7.12 Nondiscretionary Inputs and Outputs

DEA models usually assume that all inputs and outputs are discretionary, *i.e.* can be controlled by the management of each DMU and varied at its discretion (Cooper, Seiford & Zhu, 2004). They therefore calculate efficiency based purely on the relationship between inputs and outputs, with the failure of a DMU to produce maximum output levels while utilising the lowest possible number of inputs resulting in a lower efficiency score. However, circumstances may exist when the inputs and outputs are outside the control of management and are therefore classified as exogenously fixed or nondiscretionary inputs or outputs.

Possible examples of inputs and outputs which are outside management's control are:

1. Lower throughput through the port due to bad weather conditions
2. Number of transport operators providing a similar service, *i.e.* competitors
3. Geographical constraints, *i.e.* the distance between mines or the industrial centre of Johannesburg and the ports
4. The impact of the exchange rate on trade

According to Cooper, Seiford & Zhu (2004) the key to the proper mathematical treatment of a nondiscretionary variable lies in the observation that information about the extent to which a nondiscretionary input variable may be reduced is beyond the discretion of the individual DMU managers and thus cannot be used by them.

To evaluate performance accurately it may be necessary to distinguish between discretionary and nondiscretionary inputs. In such a situation the input-oriented CCR model can be adjusted as follows:

$$\text{Minimise } \theta - \epsilon\left(\sum_{i\in I_D} s_i^- + \sum_{r=1}^{s} s_r^+\right)$$

Subject to:

$$\begin{aligned}
&\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta x_{ij_o} && i \in I_D \\
&\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{ij_o} && i \in I_N \\
&\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{rj_o} && r = 1,2,\ldots,s \\
&\lambda_j \geq 0 && j = 1,2,\ldots,n.
\end{aligned} \tag{7.10}$$

Where $I_D$, $O_D$ and $I_N$, $O_N$ refer to discretionary (D) and nondiscretionary (N) input, I, and output, O, variables, respectively.

It is important to note that the $\theta$ to be minimized appears only in the constraints for which $i \in I_D$, whereas the constraints for which $i \in I_N$ operate only indirectly because the input levels $x_{io}$ for $i \in I_N$ are not subject to managerial control. It is also to be noted that the slack variables associated with $I_N$, the nondiscretionary inputs, are not included in the objective and hence the non-zero slacks for these inputs do not enter directly into the efficiency scores to which the objective is oriented (Cooper, Seiford & Zhu, 2004).

The necessary modifications to incorporate nondiscretionary variables for the output-oriented CCR model are given by:

$$\text{Maximise } \phi + \epsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r\in O_D} s_r^+\right)$$

Subject to:

$$\begin{aligned}
&\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{ij_o} && i = 1,2,\ldots,m \\
&\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = \phi y_{rj_o} && r \in O_D \\
&\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{rj_o} && r \in O_N \\
&\lambda_j \geq 0 && j = 1,2,\ldots,n.
\end{aligned} \tag{7.11}$$

It is important to note that there can be subtle issues associated with the concept of controllable outputs that may be obscured by the symmetry of the input/output model formulations (Cooper, Seiford & Zhu, 2004). Specifically, switching from an input to an output orientation is not always as straightforward as it may appear. Interpretational difficulties for outputs not directly controllable may be involved as in the case of outputs influenced through associated input factors (Cooper, Seiford & Zhu, 2004).

## 7.13 Incorporating Judgement or A Priori Knowledge

One of the most important proposed extensions to DEA is restricting the possible range for the multipliers. In the CCR model, the only restriction for the multipliers is positivity, *i.e.* $\epsilon > 0$. This characteristic of DEA analysis is often seen as an advantage of the method, since a priori specification of the multipliers is not required (Cooper, Seiford & Zhu, 2004), and it is still possible for each DMU to be evaluated comprehensively.

Although this feature is usually a strength of DEA analysis, there are occasions when it can lead to undesirable consequences, since it can point towards a DMU being efficient in ways that cannot be backed up. According to Cooper, Seiford & Zhu (2004) the model can assign unreasonably low or excessively high values to multipliers in an attempt to drive the efficiency rating for a particular DMU as high as possible.

There are three circumstances for which it has been proven beneficial to have various levels of control. These are as follows (Cooper, Seiford & Zhu, 2004)):

1. the analysis would otherwise ignore additional information that cannot be directly incorporated into the model that is used, e.g., the envelopment model;
2. management has strong preferences about the relative importance of different factors and what determines best practice; and
3. for a small sample of DMUs, the method fails to discriminate, and all are efficient.

There is more than one way of enforcing additional restrictions on multipliers. The general approach used is shown below.

$$\alpha_i \leq \frac{\nu_i}{\nu_{i_o}} \leq \beta_i, \quad i = 1, 2, \ldots, m$$
$$\delta_r \leq \frac{\mu_r}{u_{r_o}} \leq \gamma_r, \quad , r = 1, 2, \ldots, s$$

Here $\nu_{i_o}$ and $\mu_{r_o}$ represent multipliers which serve as "numeraires" (the base unit in which quantities are measured) in establishing the upper and lower limits represented here by $\alpha_i, \beta_i$ and $\delta_r, \gamma_r$ for the multipliers associated with inputs $i = 1, \ldots, m$ and outputs $r = 1, \ldots, s$ where $\alpha_{i_o} = \beta_{i_o} = \delta_{r_o} = \gamma_{r_o} = 1$. The above constraints are called Assurance Region (AR) constraints as developed by Thompson et al. (1986) and defined more precisely in Thompson et al. (1990) cited in (Cooper, Seiford & Zhu, 2004).

The generality of the AR constraints means that they can be used in various circumstances. In addition, they can also be used to examine provisional solutions and then adjust the upper and lower bounds until one or more solutions are achieved that appears to be reasonably satisfactory to the decision makers who cannot state the values for their preferences in advance. The assurance region approach also greatly relaxes the conditions and widens the scope for use of a priori conditions (Cooper, Seiford & Zhu, 2004).

In the core formulations of DEA the Decision Making Units freely assign weights to inputs and outputs in order to maximise efficiency subject to the system of weights being feasible for all other DMUs (Thanassoulis, Portela & Allen, 2004). This approach to assigning weights can be seen as an advantage of DEA since it allows all inputs and outputs to be treated as equal and it shows the DMU in the best possible light, which is very important when determining inefficiency. If a DMU is free to choose its own value system and some other DMU uses the same value system to show that the first DMU is not efficient, then a stronger statement is being made (Thanassoulis, Portela & Allen, 2004). Although it is an advantage when determining inefficiency, it can sometimes be a disadvantage when calculating efficiency. This is because a DMU might be shown as efficient due to a zero weight being assigned to the inputs and/or outputs which performed badly. This might not be acceptable to managers and decision makers as they spend a lot of time deciding which factors should be included in the evaluation process and would therefore not like any inputs or outputs to be excluded from the assessment.

There are often situations when decision makers have insight and expertise that they want to include in the efficiency assessment. These value judgments can include known information about how the factors used by the DMUs behave, and/or accepted beliefs or preferences on the relative worth of inputs, outputs or even DMUs (Thanassoulis, Portela & Allen, 2004).

The number of variables and DMUs used in a DEA assessment is directly related to the discerning strength of DEA models and also with the potential number of zero weights. As the number of variables in the model increase the probability of a DMU finding at least one aspect at which it performs well also increases and the possibility exists that the DMU can ignore the aspects that are performing badly and still rate the DMU as efficient. In contrast, if the number of DMUs being evaluated is very small it is likely that each one specialises on a specific input/output mix not directly compared with the mix of other DMUs (Thanassoulis, Portela & Allen, 2004). This might lead to DMUs being considered efficient simply because there are not a sufficient number of referents with which to compare.

### 7.13.1 Reasons for including Value Judgements

Empirical applications have justified the inclusion of value judgments for a number of reasons, such as (Thanassoulis, Portela & Allen, 2004):

1. To capture prior views on the marginal rates of substitution and/or transformation of the factors of production.
2. To capture special interdependencies between the inputs and outputs of the production process being modelled.
3. To arrive at some notion of overall efficiency.
4. To improve discrimination between efficient DMUs.
5. To ensure that widely differing weights are not assigned to the same factor.
6. To establish preferences of the decision maker over the potential adjustments of inputs and outputs.

## 7.14 Window Analysis

Another advantage of DEA analysis is its ability to not only compare numerous similar DMUs with one another, but it also has the ability of comparing a single DMU with itself in order to determine changes in efficiency over time. In such situations DEA uses a moving average analogue, where the DMU in each different time period is treated as a different DMU.

## 7.15 Virtual Inputs and Outputs

A virtual output is the product of the output level and the corresponding DEA weight (Fried, Lovell & Schimdt, 2008). Virtual inputs are defined in an analogous manner. The main advantage of using restrictions on virtual inputs and outputs is that the latter do not depend on the units of measurements of inputs and outputs (Thanassoulis, Portela & Allen, 2004). Depending on orientation, either the sum of virtual inputs or that of virtual outputs is normalised and the nonnormalized sum of virtual values at the optimal solution to the DEA model reflects the efficiency rating of the unit. Thus, virtual inputs or outputs can be readily compared as to their significance for the efficiency rating of a DMU (Fried, Lovell & Schimdt, 2008). A virtual input or output can be seen as "normalised weights reflecting the extent to which the efficiency rating of a DMU is underscored by a given input or output variable" (Thanassoulis, Portela & Allen, 2004).

The first study to use restrictions on virtual inputs and outputs was that of Wong & Beasley (1990). Such restrictions assume the form, where the proportion of the total virtual output of DMU$_j$ accounted for by output $r$ is restricted to lie in the range $[\phi, \psi]$. A similar restriction can be set on the virtual inputs (Thanassoulis, Portela & Allen, 2004).

$$\phi_r \leq \frac{u_r y_{rj}}{\sum\limits_{r=1}^{s} u_r y_{rj}} \leq \psi_r, \quad r = 1, 2, \ldots, s$$

The range is normally determined to reflect prior views on the relative importance of individual outputs (Fried, Lovell and Schimdt, 2008).

## 7.16 Basic DEA models

Table 7.1 shows the input-oriented CCR model as an envelopment and multiplier model, while Table 7.2 shows the notation for the linear programming variables. Table 7.3 shows the envelopment and multiplier model in linear programing form.

**Table 7.1:** Input-oriented CCR DEA Model.

| **Input-oriented**<br>**Envelopment Model** | **Multiplier Model** |
|---|---|
| $\text{Min } \theta - \epsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{t} s_r^+\right)$<br>Subject to:<br>$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{ij_o} \quad i = 1, 2, \ldots, m;$<br>$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{rj_o} \quad r = 1, 2, \ldots, s;$<br>$\lambda_j \geq 0, \quad j = 1, 2, \ldots, n.$ | $\text{Max } z = \sum_{r=1}^{s} u_r y_{rj_o}$<br>Subject to:<br>$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \quad i = 1, 2, \ldots, m;$<br>$\sum_{i=1}^{m} v_i x_{ij_o} = 1 \quad r = 1, 2, \ldots, s;$<br>$u_r, v_i \geq \epsilon > 0 \quad j = 1, 2, \ldots, n.$ |

**Table 7.2:** Linear programming notation.

| **DMU$_1$** | **DMU$_2$** | **Weights** | **Slacks** |
|---|---|---|---|
| $x_{11}$ | $x_{12}$ | $v_1$ | $s_1^-$ |
| $x_{21}$ | $x_{22}$ | $v_2$ | $s_2^-$ |
| $y_{11}$ | $y_{12}$ | $u_1$ | $s_1^+$ |
| $y_{21}$ | $y_{22}$ | $u_2$ | $s_2^+$ |
| $y_{31}$ | $y_{32}$ | $u_3$ | $s_3^+$ |

**Table 7.3:** Expanded version of an input-oriented CCR DEA model as LP.

| **Input-oriented**<br>**Envelopment Model** | **Multiplier Model** |
|---|---|
| $\text{Min } \theta - \epsilon(s_1^- + s_2^- + s_1^+ + s_2^+ + s_3^+)$<br>Subject to:<br>$x_{11}\lambda_1 + x_{12}\lambda_2 + s_1^- = \theta x_{11}$<br>$x_{21}\lambda_1 + x_{22}\lambda_2 + s_2^- = \theta x_{21}$<br>$y_{11}\lambda_1 + y_{12}\lambda_2 + s_1^+ = y_{11}$<br>$y_{21}\lambda_1 + y_{22}\lambda_2 + s_2^+ = y_{21}$<br>$y_{31}\lambda_1 + y_{32}\lambda_2 + s_3^+ = y_{31}$<br>$\lambda_j \geq 0, \quad j = 1, 2, \ldots, n.$ | $\text{Max } u_1 y_{11} + u_2 y_{21} + u_3 y_{31}$<br>Subject to:<br>$u_1 y_{11} + u_2 y_{21} + u_3 y_{31} - v_1 x_{11} - v_2 x_{21} \leq 0$<br>$u_1 y_{12} + u_2 y_{22} + u_3 y_{32} - v_1 x_{12} - v_2 x_{22} \leq 0$<br>$v_1 x_{11} + v_2 x_{21} = 1$<br>$u_r, v_i \geq \epsilon > 0 \quad j = 1, 2, \ldots, n.$ |

Table 7.4 shows the output-orientated CCR model as an envelopment and multiplier model, while Table 7.5 shows it in the form of a pair of dual linear programs.

If the constraint $\sum_{j=1}^{n} \lambda_j = 1$ is added to the above CCR (Charnes, Cooper & Rhodes, 1978) models,

**Table 7.4:** Output-oriented CCR DEA model.

| Output-oriented | |
|---|---|
| **Envelopment Model** | **Multiplier Model** |
| $\text{Max } \phi + \epsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{t} s_r^+\right)$<br>Subject to:<br>$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{ij_o} \qquad i = 1, 2, \ldots, m;$<br>$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = \phi y_{rj_o} \qquad r = 1, 2, \ldots, s;$<br>$\lambda_j \geq 0, \qquad j = 1, 2, \ldots, n.$ | $\text{Min } q = \sum_{i=1}^{m} v_i x_{ij_o}$<br>Subject to:<br>$\sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} \geq 0 \qquad i = 1, 2, \ldots, m;$<br>$\sum_{r=1}^{s} u_r y_{rj_o} = 1 \qquad r = 1, 2, \ldots, s;$<br>$u_r, v_i \geq \epsilon > 0 \qquad j = 1, 2, \ldots, n.$ |

**Table 7.5:** Expanded version of an output-oriented CCR model as LP.

| Input-oriented | |
|---|---|
| **Envelopment Model** | **Multiplier Model** |
| $\text{Max } \phi + \epsilon(s_1^- + s_2^- + s_1^+ + s_2^+ + s_3^+)$<br>Subject to:<br>$x_{11}\lambda_1 + x_{12}\lambda_2 + s_1^- = x_{11}$<br>$x_{21}\lambda_1 + x_{22}\lambda_2 + s_2^- = x_{21}$<br>$y_{11}\lambda_1 + y_{12}\lambda_2 + s_1^+ = \phi y_{11}$<br>$y_{21}\lambda_1 + y_{22}\lambda_2 + s_2^+ = \phi y_{21}$<br>$y_{31}\lambda_1 + y_{32}\lambda_2 + s_3^+ = \phi y_{31}$<br>$\lambda_j \geq 0, \quad j = 1, 2, \ldots, n.$ | $\text{Min } v_1 x_{11} + v_2 x_{21}$<br>Subject to:<br>$v_1 x_{11} + v_2 x_{21} - u_1 y_{11} - u_2 y_{21} - u_3 y_{31} \geq 0$<br>$v_1 x_{12} + v_2 x_{22} - u_1 y_{12} - u_2 y_{22} - u_3 y_{32} \geq 0$<br>$u_1 y_{11} + u_2 y_{21} + u_3 y_{31} = 1$<br>$u_r, v_i \geq \epsilon > 0 \quad j = 1, 2, \ldots, n.$ |

then they are known as BCC (Banker, Charnes & Cooper, 1984) models.

## 7.17 Simple example of DEA

To illustrate how DEA works a simple example has been taken from the works of Zhu (2000) and Cooper, Seiford & Zhu (2004). There are five DMUs representing five supply chain operations. Within each week, each DMU generates the same profit of \$2 000 with a different combination of supply chain cost and response time.

If the BCC model is applied Table 7.6 presents the five DMUs and the piecewise linear DEA frontier.

**Table 7.6:** Supply Chain operations within a week.

| | Inputs | | Output |
|---|---|---|---|
| **DMU** | **Cost ($100s)** | **Response time (days)** | **Profit ($1000s)** |
| 1 | 1 | 5 | 2 |
| 2 | 2 | 2 | 2 |
| 3 | 4 | 1 | 2 |
| 4 | 6 | 1 | 2 |
| 5 | 4 | 4 | 2 |

DMUs 1, 2, 3 and 4 are on the frontier. If the constraint $\sum_{j=1}^{n} \lambda_j = 1$ is included for DMU$_5$; the following formulation is achieved from the data in Table 7.6 by using equation 7.3.

$$
\begin{aligned}
&\text{Minimise } \theta \\
\text{Subject to:}& \\
&1\lambda_1 + 2\lambda_2 + 4\lambda_3 + 6\lambda_4 + 4\lambda_5 \leq 4\theta \\
&5\lambda_1 + 2\lambda_2 + 1\lambda_3 + 1\lambda_4 + 4\lambda_5 \leq 4\theta \\
&2\lambda_1 + 2\lambda_2 + 2\lambda_3 + 2\lambda_4 + 2\lambda_5 \geq 2 \\
&\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 = 1 \\
&\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \geq 0
\end{aligned}
\tag{7.12}
$$

This model has the unique optimal solution of $\theta^* = 0.5$, $\lambda_2^* = 1$ and $\lambda_j^* = 0$ $(j \neq 2)$ indicating that DMU$_5$ needs to reduce its costs and response time to the amounts used by DMU$_2$ if it is to be efficient. This example indicates that technical efficiency for DMU$_5$ is achieved at DMU$_2$ on the boundary.

Now if the model with $\sum_{j=1}^{n} \lambda_j = 1$ is implemented for DMU$_4$, the solutions $\theta^* = 1$, $\lambda_4^* = 1$ and $\lambda_j^* = 0$ $(j \neq 4)$ are obtained, indicating that DMU$_4$ is on the frontier and is a boundary point. However, DMU$_4$ can still reduce its response time by 2 days to achieve coincidence with DMU$_3$ on the efficiency frontier. This input reduction is the input slack and the constraint with which it is associated is satisfied as a strict inequality in this solution. Hence, DMU$_4$ is weakly efficient.

The nonzero slack can be found by using equation 7.4. With the constraint $\sum_{j=1}^{n} \lambda_j = 1$ adjoined and setting $\theta^* = 1$ yields the following model,

$$\text{Maximise } s_1^- + s_2^- + s_1^+$$

Subject to:

$$\begin{aligned}
&1\lambda_1 + 2\lambda_2 + 4\lambda_3 + 6\lambda_4 + 4\lambda_5 + s_1^- = 6\theta^* = 6\\
&5\lambda_1 + 2\lambda_2 + 1\lambda_3 + 1\lambda_4 + 4\lambda_5 + s_2^- = 1\theta^* = 1\\
&2\lambda_1 + 2\lambda_2 + 2\lambda_3 + 2\lambda_4 + 2\lambda_5 - s_1^+ = 2\\
&\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 = 1\\
&\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, s_1^-, s_2^-, s_1^+ \geq 0
\end{aligned} \tag{7.13}$$

The optimal slacks are ${s_1^-}^* = 2$, ${s_1^-}^* = {s_1^+}^* = 0$, with $\lambda_3^* = 1$ and all other $\lambda_j^* = 0$.

## 7.18 Additional Features of the Composite Supply Chain Efficiency Model

All the formulae included in the composite supply chain efficiency model are used to measure the reliability, cost and speed efficiency for each link and node along a supply chain. The basis of this model is to determine the best practice for each category at each link or node along a similar supply chain. The best practice measures need not all come from the same supply chain, thus, allowing the model to use an optimal measure as a benchmark for each stage of the supply chain. After the best practice measures have been collected they are then compared against the measures collected for the supply chain under review.

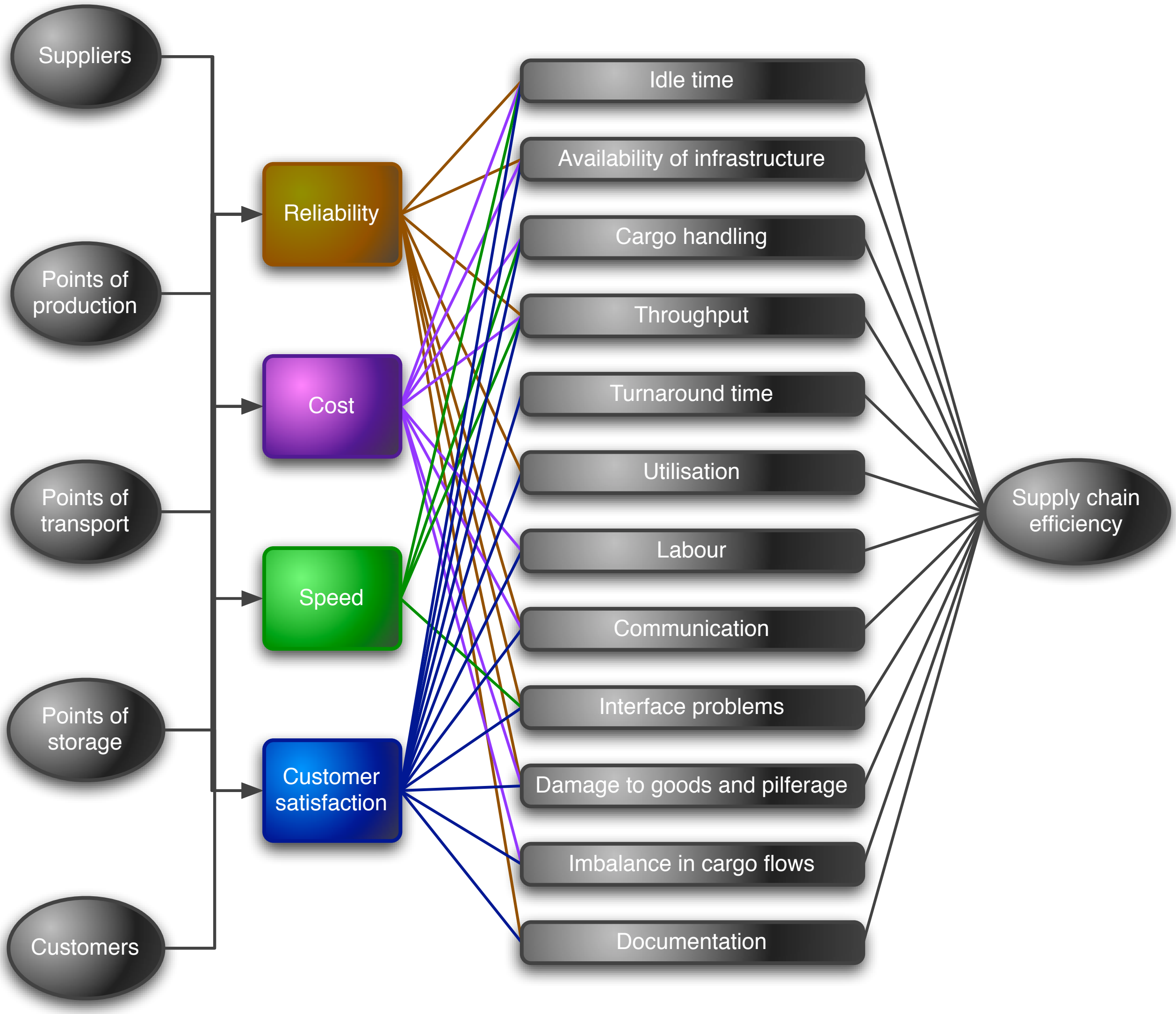
In addition to measuring the supply chain according to reliability, cost and speed efficiency, it is valuable to consider the level of customer satisfaction in the supply chain (this approach is supported by the literature given in Chapter 3). Thus as an added feature of the model it is worthwhile to measure customer satisfaction. The best way of achieving this measure is by approaching all the role-players and customers along each stage of the supply chain under review and asking them pertinent questions in the form of a survey.

*Customer satisfaction can be determined by a survey conducted with the main customers.*

The information gained from the survey can be used to determine the relative importance of reliability, cost and speed efficiency for the supply chain under review.

An additional aspect of the model is its ability to determine which factors are the bottlenecks in the supply chain. The model enables the role-player to calculate the effect that each node is having on the efficiency of the overall supply chain. By highlighting the problem areas in the supply chain, it makes it far easier for the role-players in the supply chain to make the necessary changes required to improve overall efficiency. Figure 7.3 shows a diagram of the composite supply chain efficiency model.

**Figure 7.3:** Flow diagram of the composite supply chain efficiency model[3].



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[3] Developed by the author for the purpose of the study.

## 7.19 Model Verification and Validation

This step can be combined with the development stage of the model, because without proper verification and validation, model development is not complete. Verification and validation entails making sure that the model adequately represents reality. It is also important to ensure that the model makes logical sense and that all the inputs are taken into consideration when generating the output.

The first step of this model is verified and validated by the fact that it 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 step of this model or the Balanced Scorecard method will give the same 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 & Wong, 2007). Various sources of literature substantiate the use of DEA in measuring efficiency (Collier & Storbeck (1993); Seiford (1994); Bell & Morey (1995); Talluri & 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 & 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. In this dissertation the data was transformed to a uniform scale, so that it could be compared with a uniform weight. A value of 100 represents optimal or close to optimal efficiency and any value lower than 100 indicates that the variable is not efficient. 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 the time.

## 7.20 Conclusion

The process of building a dynamic supply chain model provides valuable insights and understanding regarding the behaviour and characteristics of a supply chain. It highlights the core factors that influence the functioning of a supply chain and it identifies relationships that affect the overall efficiency of a supply chain.

The generic model developed in this chapter focuses on measuring the overall efficiency of a supply chain, with the aim of using the information gained as a tool for improving the efficiency levels in the future. The generic nature of the model allows it to be used on a variety of different supply chains. 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. The manner in which the model is set up makes it very easy for managers to select the variables that are important to their evaluation. In addition, the model calculates the efficiency of each factor in the supply chain and in so doing it can pinpoint the factors that are causing the biggest problems to the overall efficiency. This enables firms to focus their efforts on the right areas, which results in improved resource allocation and higher levels of integration.

# CHAPTER 8

# Application of the composite supply chain efficiency model

## 8.1 Introduction

The model in Chapter 7 of this research has been constructed with the aim of improving the overall efficiency of South Africa's supply chains. In an attempt to explain the actual operations of the model, this chapter will describe how the model is applied to an operational supply chain. It will explain to the reader the choices that are made under certain conditions (and why they are made). It will explain the impact of the choices and the improvements that are possible.

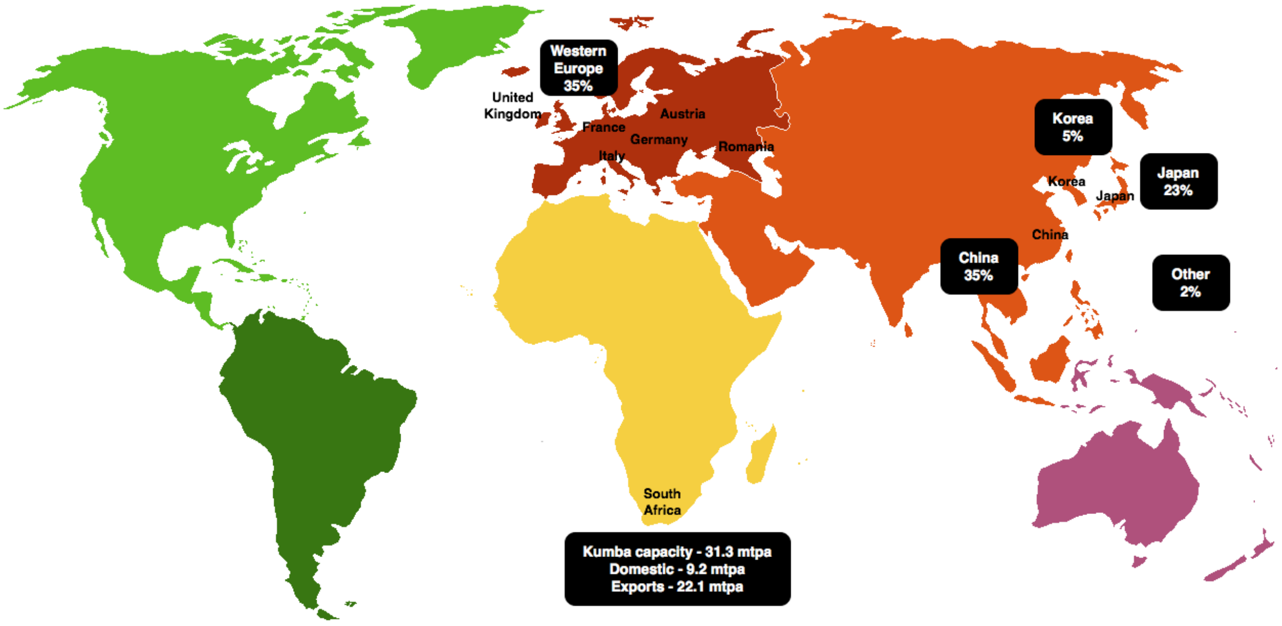
## 8.2 The Iron Ore Supply Chain from Sishen to Saldanha

Iron ore is the "mainstay metal for the infrastructure of modern civilization, from ships to bridges, railways, skyscrapers, cars, trucks, trains, engines, and machines of all kinds, down to everyday pins and paperclips" (Rio Tinto, 2006).

The origin of the iron ore supply chain dates back to 1953 when Iscor (Iron and Steel Corporation - now known as ArcelorMittal) started mining iron ore near Sishen in the Northern Cape. Due to the depletion of some of the country's gold reserves in the 1960s, mines were forced to look for alternative mineral resources. After the discovery of a 4 000 Mt deposit of high grade iron near Sishen, the feasibility of a new, large-scale iron-ore export project was investigated. These investigations led to Saldanha Bay being chosen as the best export harbour for the ore. The railway line connecting the ore-mines with the harbour was built as a result (Truter, 2004).

Construction on the railway line started on 1 June 1973 and the first ore train arrived at Saldanha on 14 May 1976. On 27 September of the same year the first ore carrier left Saldanha, bound for Europe (Truter, 2004). The supply chain was subsequently acquired and developed by Transnet Freight Rail and is now known as Orex. The main countries to which the ore is currently being exported are Western Europe, China, Japan and Korea as shown in Figure 8.1.

**Figure 8.1:** Percentage of iron ore exported to various countries[1].



The four major players in the iron ore industry are BHP Billiton, Rio Tinto, CVRD, and Kumba Resources (Bonga, 2005). Kumba, a South African company, is the fourth largest of the companies after the three aforementioned companies. Figure 8.2 shows the distribution of iron ore reserves throughout the world.

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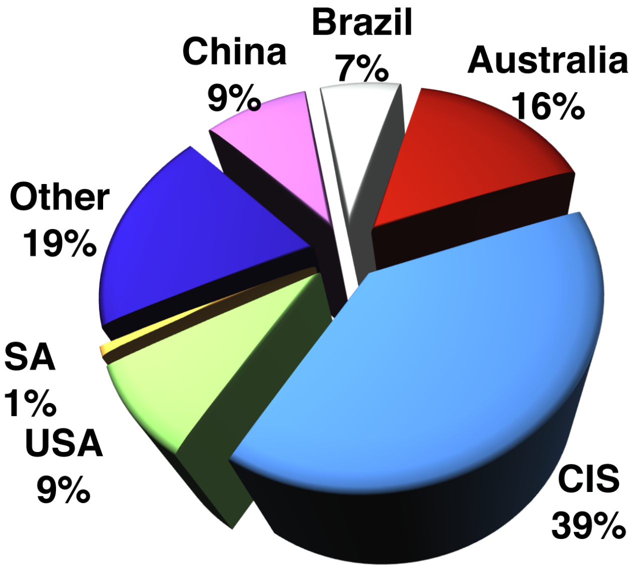
[1] Source: (Kumba Resources, 2006)

**Figure 8.2:** World Reserves of iron ore[2].



## 8.3 Critical Links in the Orex Supply Chain

The major links and nodes in the Orex supply chain are:

- the mines (Kumba Resources Ltd and Associated Manganese (ASSMANG) iron ore mine)
- vehicles carrying the products in the mine (often diesel-electric trucks or trains)
- loading apparatus to build stockpiles
- benefication plant at the mine (e.g. washing plant)
- the railway line (Orex)
- the storage and handling equipment
- the Port of Saldanha (Transnet National Ports Authority, Transnet Port Terminals and Kumba Port Operations Saldanha)

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[2] Source: Bonga (2005). CIS represents the Commonwealth of Independent States.

- the ship

Each element of the supply chain plays an important role in determining the overall efficiency of the supply chain. The supply chain is only as efficient as its weakest link and therefore steps must be taken to ensure maximum efficiency not only at each function, but also throughout the entire supply chain.

### 8.3.1 The Mines

South Africa is the largest iron ore producer on the African continent and the majority of its production is provided by Kumba Resources Ltd (Kumba Resources Ltd split from parent company Iscor (now known as ArcelorMittal) in 2001). Kumba Resources Ltd has reserves, which exceed two billion tons of high-quality iron ore at their two mines at Sishen in the Northern Cape and Thabazimbi in the Limpopo Province. A new mine at Sishen South, located 70 km south of the Sishen mine, has been developed to produce an additional 10 Mt per year from 2005 until 2032. Assmang is South Africa's second biggest iron ore producer. It has an iron ore mine at Beeshoek, which has recently been expanded onto a neighbouring property, Olynfontein (MBendi, 2004). In 2007 it opened the Khumani iron ore mine just south of Sishen, which yields approximately 8Mt of the world's highest grade iron ore. Currently, the production capacity is being expanded to yield 16Mt per year. This together with Kumba's increase in total output will increase the total delivery via Orex to appoximately 60Mt per year by 2012/2013.

A new jig plant at Beeshoek enables Beeshoek to recover ore from what was previously regarded as waste material. This helps to reduce costs, improve the quality of the ore and ultimately extend the life of the mine.

Mining at Sishen takes place in a single open pit, while the ore at Beeshoek is mined from various different pits. This is ideal for selective mining and in-pit blending to provide ore to meet customer needs (Assmang, 2004). The mining process operates in the following sequence: drilling, blasting, loading and hauling. The mined ore is then processed by crushing, washing and screening, heavy media separation, blending and loading onto stockpiles at the mine via conveyor belts. The ore is reclaimed from the stockpiles onto conveyor belts and loaded into the train wagons. The iron ore mines are responsible for loading the iron ore into rail wagons. Kumba Resources Ltd makes use of automated equipment to load the ore onto the rail wagons, while ASSMANG uses semi-automated equipment at their loading stations.

At the mine, a computerised geological database is used for planning, scheduling and grade control. The analytical results of all blast holes are continuously reconciled with the computer-generated grade models to ensure that the correct grade is blasted before being transported to the treatment plant. A continuous sampling process at various points in the treatment and loading plants ensures the production of a consistent grade of ore that meets customer requirements (Assmang, 2004).

Kumba produced over 30.1 Mt of lumpy and fine iron ore during the 2004 financial year from its two mining operations, of which 20.9 Mt was exported. Thabazimbi generally provides iron ore (2 389 000 tons in 2003) for ArcelorMittal's steelworks in Vanderbijlpark and Newcastle, while the bulk of Sishen's production is exported via the Port of Saldanha. ASSMANG currently produces approximately 5 Mt of iron ore per annum and is aiming to expand production to 10 Mt per annum by 2010 (Assmang, 2004). Recent expansion plans at the mine have added an additional life span of approximately fourteen years to Assmang's iron ore mining operations in the area.

### 8.3.2 The Railway Line

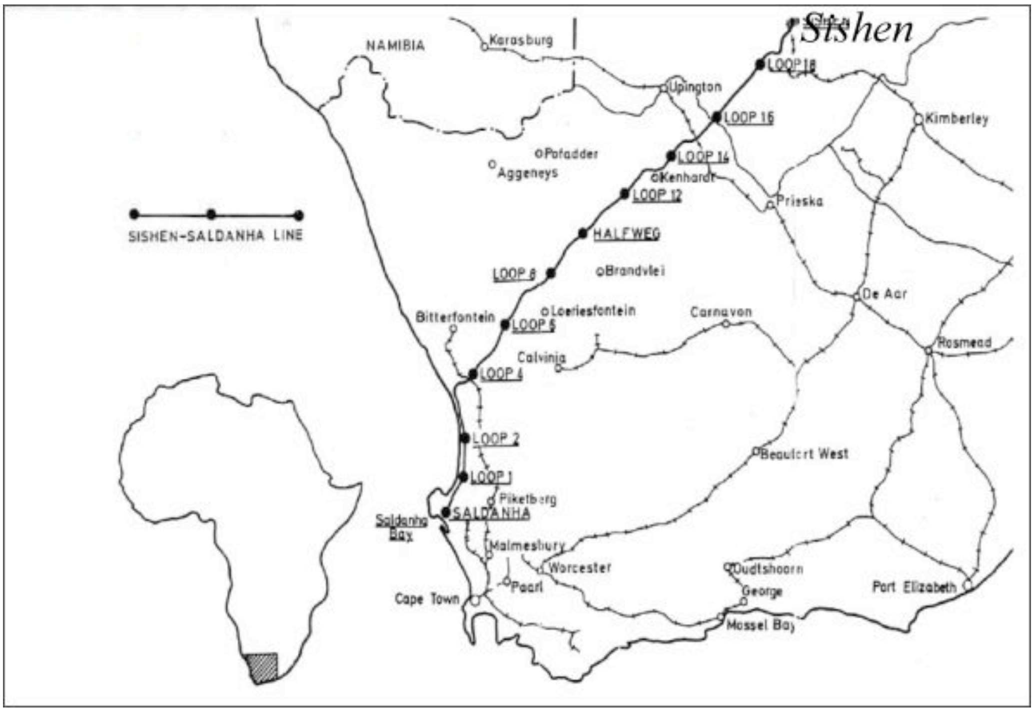
A highly sophisticated infrastructure exists to transport the iron ore from the mines in the Northern Cape to the deep-water port of Saldanha on the west coast of South Africa, via rail transport.

The railway line is approximately 861 km long and is operated by Orex, a Transnet Freight Rail specialist business unit. It was specially built to be able to handle the transportation of very heavy iron ore trains. There are no wooden or concrete sleepers to carry the rails, as they would give way under the weight of the iron ore trains and cause extensive maintenance and repair costs. Instead, the sleepers have been replaced by thick steel bars that are able to handle the weight of the train (Fourie, 2002). The railway line is a single line and therefore it has been fitted with 19 loops to allow trains travelling in opposite directions to pass one another. A schematic diagram of the loops along the rail line is shown in Figure 8.3 below.

The rail line is also equipped with signalling equipment at the Salkor control office in Saldanha. The signalling system is run by one computer on in-house developed software. This helps to ensure the safety of the freight and the train by using last vehicle detectors that can detect and signal when the last wagon of the train exits the section between two crossing loops.

All communication on the rail line is conducted by microwave technology, which supports three radio

**Figure 8.3:** Sishen rail line[3].



systems operated by traffic control personnel. The traffic control personnel use the radios to remain in constant communication with train drivers, maintenance staff and all personnel in charge of the traction power systems. Transformed traction power supplies the signalling, communication and control equipment with the power needed to operate. It is also backed up by diesel generators in case of power cuts. Switching between the two power supplies can be done manually, but normally takes place at Salkor. Control software for the rail line is run on a super mini-computer.

In addition to the highly integrated and well controlled electrical component of the Orex rail line, the line is also equipped with two monitoring systems, namely, Dragging Equipment Detectors (DED's) and the Olifants River Bridge Monitor (ORBM). DED's are automated defect detectors that are used to identify broken or damaged parts of the train's undercarriage dragging along the ground that could cause damage to the train or the freight. They have proven to be very successful and are situated once every five kilometers along the track. The ORBM continuously measures the parameters of rail force, air, rail and concrete temperature as well as expansion gaps on the bridge and then sends the recorded data to a computer at the Salkor control office, which warns the control officer when measures exceed safety levels.

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[3] Source: (Kumba Saldanha Port Operations, 2004a)

The Kumba and Assmang Khumani trains mainly consist of 3x108 units, which is the equivalent of 324 wagons per train (these account for the majority of trains to Saldanha). Assmang Beeshoek handles mainly 86-ton wagons and Assmang Khumani handles mainly 100-ton wagons. The trains are drawn by various combinations of 9E electric locomotives and Diesel-electric locomotives. An interface called a 'slim kabel' is used to integrate the different locomotives.

The railway line is operational seven days a week and every day loaded trains transport iron ore from Sishen and Beeshoek to the Port of Saldanha. Every journey takes approximately 18 hours (full or empty) from Sishen, which is fully electrified at 50kV AC from six supply points (Mining Review Africa, 2004). The average speed is thus 47.8km per hour.

Rolling stock maintenance is also performed by Saldanha, where the locomotives and wagons are inspected and maintained (if necessary) by the Rolling Stock Department at the end of each journey (Kumba Saldanha Port Operations, 2004b).

Iron ore produced at Beeshoek is transported 70 kilometres by rail to Sishen where the trucks are transferred to the Sishen-Saldanha railway line. The Beeshoek siding facilities are capable of handling 400 trucks of 85 tons each per 24-hour period and will be upgraded to cope with the envisioned increase in volumes of the future.

The Orex line currently has an available capacity of 32.5 mMt per annum, and Transet has plans to expand the capacity by a further 47 Mt per annum by 2009. This increase in capacity is required to cope with the new volume of supply available from both Kumba and Assmang.

### 8.3.3 Storage and Handling Equipment

The ore arriving from the mines are stored in lots of approximately one week's production. Chemical variations in the quality of the ore exist, because of the different ground chemicals at the various mines from which the port is supplied. In order to ensure consistency in the quality of the ore supplied to customers, the stockpiling is regulated by stockpile diagrams that control the stacking procedure.

When a train arrives at the Port of Saldanha, it is separated into two equal parts. This is because the railway that is connected to the positioner and the tippler can only carry the weight of half a train. A tandem tippler offloads the ore from the rail trucks. Two trucks, coupled together, enter the tippler, which contains a revolving drum. A positioner is then used to position the two trucks in the tippler. Four hydraulic clamps are applied to each truck and the tippler revolves, turning the trucks upside down and emptying the contents onto the band feeders and then onto a conveyer belt which deposits the ore onto stockpiles via a Stacker/Reclaimer (as shown in Figure 8.4). A maximum of 110 trucks are offloaded at a time and the duration of the process (from the start of the positioning to the end of the tippling) takes 72 seconds. The capacity of a tippler is 8 000 t/h.

**Figure 8.4:** A Stacker/Reclaimer depositing ore onto a stockpile in the Port of Saldanha[4].

Once on the stockpiles (there are fourteen in total), the ore is reclaimed for loading using the stacker reclaimers. Currently the iron ore terminal implements 2 Stacker/Reclaimers and both have a stacking capacity of 8 000 t/h and an average reclaiming capacity of 8000 t/h. The ore is then transported via a single 7 km conveyer belt at a speed of 4 m/s through a sampling plant (where the moisture content of the ore must be tested) before being fed to the shiploaders. The processes in the sampling plant are conducted while the consignment is being loaded onto the ship. The samples taken in the plant are used to determine:

- the moisture content, and
- the size grading per consignment

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[4] Source: (National Ports Authority of South Africa, 2005)

The plant contains a primary cutter, a riffler, three jaw crushers and a roller crusher. These decomposing machines are used to cut, crush or roll the ore sample into the desired sizes or level of pulverised ore needed for the physical, chemical and moisture sampling. Samples are mostly conveyed between the various analysing areas via a separate conveyor system. The fitting of a riffler at the head of the skip hoist allows for samples to be split in two, which enables physical and chemical samples to be processed concurrently.

Physical sampling entails the size grading per consignment. For lump ore the sample is segregated to oversize (bigger than 25mm), nominal (bigger than 8mm) and undersized (smaller than 8mm) scales. Weights per grouping are measured and then recorded and then the sample is released back onto the main conveyor and transported to the shiploaders. For fine ore the sample undergoes much the same procedure except the sizes are now classified as oversize for bigger than 2mm, nominal for sizes from 2mm to 0.2mm and undersized for ore smaller than 0.2mm. The sample weights are also recorded and then the samples are discharged similarly as lump ore.

The second part of the main sample, which was originally separated by the riffler, undergoes crushing from two jaw crushers before it is subjected to chemical and moisture sampling. The ore sample is again divided into two equal portions, after which the half used in the chemical sampling is crushed once more before being roller crushed. This ore sample is then passed on to a chemical sample station and kept for processing until the vessels have been fully loaded. Once this is completed the sample is mixed by passing through a riffler. A 1.2kg portion is taken from this and dried in an oven. It is then exposed to more pulverisation until two bags are filled with between 100 and 120 grams of ore, one of which is sent to Corporations headquarters in Pretoria for analysis, and the other is stored at Saldanha. The remainder of the sample is riffled until 3kg of ore remains on each side of the riffler. These portions are stored in two pots, one of which is sent to Sishen mine for analysis and one that is stored at Saldanha.

A chute to the moisture sampling station carries the part of the original sample destined for moisture sampling. The sample is divided into containers of approximately 6kg each. These containers are then emptied and spread out on a tray by hand. The tray is placed on an electronic scale that measures and records the weight of the sample. After the scale, the tray is placed in an oven at a temperature of $105^oC$, where it is dried for one hour in the case of lump ore and two and a half hours in the case of fine ore. After the sample has been dried the weight is measured again and recorded by computer. The ore is then dispatched to the shiploaders via the main conveyor system. The computer uses the recorded weights to calculate the average moisture for the shipment complete with standard deviation.

This information is printed and presentable upon completion of the ship loading.

There are two operational shiploaders available for use at the port. The two shiploaders have a capacity of 7 200 t/h and 8 000 t/h respectively, the current performance of the shiploaders in cross ship loading only amounts to an average of 2250 tons per hour (National Ports Authority, 2005). Finally the shiploaders feed the ore onto another belt on a boom that carries the ore to a shoot, and feeds the ore into a ship's hold. The average loading time of a ship is 27.8 hours.

Figure 8.5 shows a shiploader in the Port of Saldanha.

**Figure 8.5:** A Shiploader in the Port of Saldanha[5].

The Port of Saldanha is currently undergoing expansion. Phase one of the expansion includes acquiring a second tippler, a third Stacker/Reclaimer, a second conveyor system and additional stockpile capacity. Once the new equipment is operational, the terminal will be able to handle 41 Mt of iron ore per year.

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[5] Source: (National Ports Authority of South Africa, 2005)

### 8.3.4 Port of Saldanha

The Port of Saldanha is the deepest and largest natural port in Southern Africa and is partly protected by an artificial breakwater (NPA website, 2006). The Port of Saldanha is the only iron ore handling port in South Africa. The terminal has been purpose built for the export of iron ore through the Port.

The existing port facilities consist of a 990-metre long jetty with two iron ore berths (and one crude oil berth) joined at the northern shore of the Bay by a 3 100-metre causeway. The ore handling capacity is currently being upgraded from 22 to 41 Mt per annum. Table 8.1 shows the existing iron ore handling capacity in the Port of Saldanha.

**Table 8.1:** Existing Iron ore handling capacity[6].

| Item | Currently Available |
|---|---|
| Quay length | 1260m either side of 630m long ore jetty |
| No. of berths | 2 |
| Berth depths | 101: -23 chart datum (cd)<br>102: -23 chart datum (cd) |
| Quayside equipment | 2 Ship loaders |
| Open Stockpile Facilities | 2 Stockyards of 4 Beds of 24 Mt capacity |
| Stacking Equipment | 1 Single rotary tandem tippler<br>2 Stacker reclaimer |
| Transfer Equipment | +- 7 km of single overload conveyor system and dual jetty conveyor system feeding either of two ship loaders |

NOTES:

- “The ship loaders operate on the same rail system on the iron ore jetty and can therefore not work independently of each other. This implies that only one vessel can be loaded at a time. The width of the jetty does not allow for the ship loaders to pass one another via a dual rail system. There is also insufficient space alongside a vessel for both ship loaders to simultaneously load one vessel”.
- “The equipment and infrastructure indicated in Table 8.1 does not take into consideration the terminal expansion and refurbishment project presently in progress”.
- “Due to the specialized nature of the infrastructure and equipment in the Terminal, and the high volumes handled, the inland transport capacity serving the terminal is critical in ensuring

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[6] Source: (National Ports Authority of South Africa, 2005)

> the required throughputs are met. All iron ore is transported to the Port via rail from Sishen where the iron ore is mined". Source: (National Ports Authority, 2005)

The port operates 24 hours a day, 365 days a year on a common user basis (there is no discrimination in the access to the port). It can accommodate vessels with a maximum draught of 20.5m and with the Harbour Master's permission it can handle vessels with a draught requirement of 21.5m. Vessels with a draught exceeding fourteen metres are berthed during daylight hours. Although the jetty can accommodate two vessels (with a maximum deadweight of 300 000 tons), it can only load one at a time and loading stops during the night time. Ships with beams of less than 30 metres are not allowed because of the reach of the loading appliances. The average consignment size is 150 000 tons per vessel. The terminal loads on average 2 250 tons an hour onto vessels, which will increase to about 7 000 tons an hour once the expansion has been completed.

The total time spent by ships in the port, measured from arrival to departure and including piloting, berthing, loading, draft survey and de-berthing takes approximately 24 hours for an Ore Vessel of 120 000 tons; 36 hours for an Ore Vessel of 180 000 tons and 48 hours for an Ore Vessel of 240 000 tons (Kumba Saldanha Port Operations, 2004b).

### 8.3.5 Ships

The ships used to carry the ore are usually large (Cape size) ore carriers of between 150 000 and 180 000 dwt[7], as it would be uneconomical to use smaller ships regularly for the ore exports (Floor, 2007). An average of 215 vessels leaves from the Port of Saldanha in a year (National Ports Authority of South Africa, 2004).

## 8.4 Application of Model

The composite supply chain efficiency model is applied to the iron ore supply chain from Sishen to Saldanha to validate the robustness of the model. For the purpose of the model the supply chain was broken up into a mine, a rail transport leg, a port and a shipping leg (see Figure 8.6 below). In

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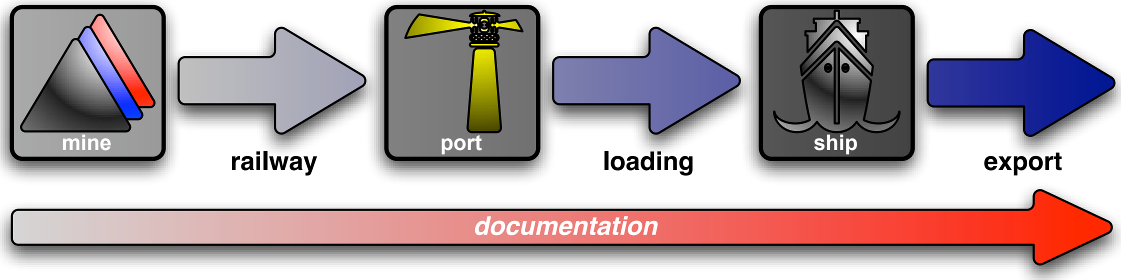
[7] dead weight tonnage - the dwt of a ship is the difference in the amount of water in tons replaced when the ship is empty and the amount of water in tons replaced when it is loaded to the load line. It represents the tons that a ship can carry in terms of cargo, ballast, bunkers and supplies (van Niekerk, 2004).

addition to the main links or nodes described above there are points of storage (mainly in the form of stockpiles) that help balance the supply and demand of the product being transported. Due to the fact that the sea leg of the supply chain is operated by a foreign shipping line, and therefore outside the control of a South African firm, it is excluded from the evaluation process.

**Figure 8.6:** An example of a bulk export supply chain[8].



The example used in the dissertation 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.

## 8.5 Data used in the model

The data used in this model was based on data collected from real firms along the Sishen-Saldanha supply chain through the application of questionnaires and personal interviews. The author was only able to obtain between six and nine years of historical data from each link or node along the iron ore supply chain. With reference to the composite supply chain efficiency model a DMU refers to one year of data for each link or node along the supply chain.

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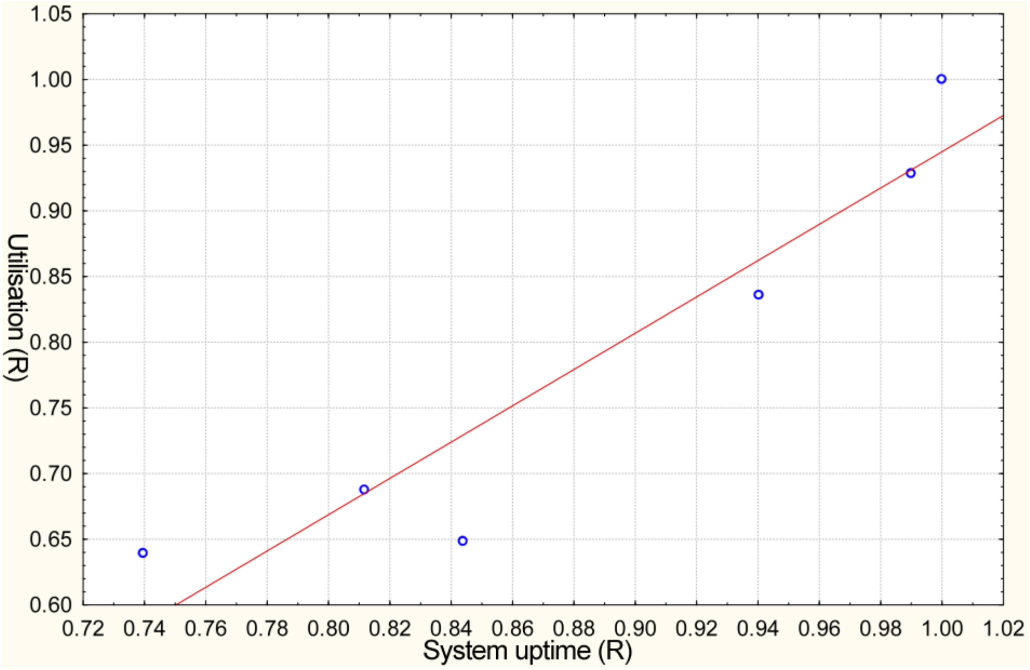
[8] Source: Developed by the author for the purpose of the study.

This was insufficient data for the purpose of the study. According to Tan & Sheps (1998) the number of input and output variables should be less than half the number of DMUs and therefore provides an upper limit on the number of input and output variables used in the model. Thus in order for the model to provide meaningful results it was important to have sufficient data with which to work. Due to the fact that the example used in this dissertation is for explanatory purposes only, data was generated from the original, real data sets using a recognised statistical method.

According to Johnson & Wichern (2007), data that is proven to be both univariate normal and bivariate normal can be assumed to follow an approximate multivariate normal distribution. The data was therefore tested for univariate and bivariate normality using the Statistica (2008) statistical analysis program. Firstly, all the data was tested for univariate normality using Q-Q plots. The plots are a representation of the sample quantile versus the quantile one would expect to observe if the observations actually are normally distributed. When the points lie close to the straight line, it is possible to assume normality (Johnson & Wichern, 2007). All the data met the requirements for bivariate normality. Figure 8.7 shows a graphic representation of the Q-Q plots for utilisation measurement of the mine node.

**Figure 8.7:** Q-Q Plot for the utilisation measurement of the mine node



Secondly, the data was tested for bivariate normality. For data to meet the requirements of bivariate normality the contours of constant density would be ellipses, i.e. scatterplots drawn of the data should exhibit an overall pattern that is nearly elliptical (Johnson & Wichern, 2007). The statistical analysis of the data highlighted problems with a few variables that were originally included in the composite supply chain efficiency model for measuring the efficiency of the iron ore supply chain. These variables were imbalances in cargo flows in the rail leg, and the percentage of defective goods and the percentage of damages to goods for all three links or nodes. Careful consideration of the variables in question identified the reasons behind the problems. The Sishen-Saldanha railway line is a dedicated railway line that transports iron ore from Sishen to the Port of Saldanha. It is not required to carry any goods on its return leg and therefore imbalances in cargo can be left out of the evaluation of the rail leg. Due to the nature of iron ore, there is very little chance that the commodity can be damaged or defective, so both measurements were left out of the evaluations of all three links or nodes. Once the three variables were removed from the evaluation, all the remaining variables met the requirements of both the univariate normal distribution as well as the bivariate normal distribution and could therefore be considered multivariate normal. Figure 8.8 shows a graphic representation of the scatterplots drawn for the mine node.

**Figure 8.8:** Scatter plot for mine node

Once it was proven that the data met the requirements for univariate normality and bivariate normality, it could be assumed that the data followed a multivariate normal distribution. Therefore, for the second method used to generate data, the assumption was made that each individual data set for the mine node, rail operator and port node is approximately multinormally distributed. Let $Q = \{X_1, \cdots X_i, Y_1, \cdots, Y_j\}$ be a matrix of the data, with mean $\mu = \{\mu_1, \cdots, \mu_{(i+j)}\}$. Let $\sum$ be the covariance matrix

$$\sum = \begin{pmatrix} \sigma_{11} & \cdots & \cdots & \sigma_{1n} \\ \sigma_{21} & \sigma_{22} & & \vdots \\ \vdots & & \ddots & \vdots \\ \sigma_{n1} & \cdots & \cdots & \sigma_{nn} \end{pmatrix}$$

From the matrix above, it is evident that $\sigma_{ij}$ is the covariance of $X_i$ and $X_j$ , and $\sigma_{ii}$ is the covariance between $X_i$ and itself, and consequently $\sigma_i^2$. The diagonal elements of the covariance matrix are therefore the variances of the $X_i$'s. The statistical software, R 2.9.2 (2009), was used to calculate the mean $\mu$ of each attribute, as well as the covariance matrix $\sum$ of the data set. Given the $\mu$ and $\sum$, R 2.9.2 (2009) was used to statistically generate more data following the same multivariate normal distribution. The $\mu$ of each attribute was needed to ensure that the newly generated data had similar means, and $\sum$ ensured that the correlation between attributes was taken into consideration in the generation of new data. After the data was generated, it was tested to ensure that it had a similar distribution to the original data.

Although this is not the ideal situation, the purpose of the research is to develop a generic guideline for measuring supply chain efficiency and not to present a case study of an actual supply chain. Thus, because the data was generated using a recognised statistical method, it can be assumed that the data meets the necessary requirements for testing the authenticity of the model.

The first step in the process of measuring supply chain efficiency is to measure the efficiency of the sources or suppliers. The idea is that if the supplier(s) are shown to be inefficient, then the overall supply chain efficiency can be improved by changing suppliers (selecting more efficient suppliers) or if there are no alternative suppliers available then the fact that the suppliers have been shown to be inefficient should encourage them to make changes. In the supply chain that has been chosen as an example, the origin starts at the mine itself (which is a point of production). Thus, there are no suppliers to evaluate.

The second step in the process is to evaluate the efficiency of the mine. Since mines extract ores and minerals and are therefore dependent on geology of deposits and economies of their recovery, output might be of more concern to their owners than competition when the world price for the commodity is above the production costs. Nevertheless, profitability will be determined by the efficiency with which the product is delivered to customers and supply chain efficiency remains of cardinal importance to the success of mining. The data representing the mines was obtained from an actual mine in South Africa.

The third step in the model is to evaluate the transport leg(s). The transport leg(s) are an important part of a supply chain. There is often more than one transport leg in a supply chain and each must be evaluated separately to determine its impact on the efficiency of the overall supply chain. It is also possible for there to be more than one mode of transport used in a supply chain, which would result in different regulations and policies governing the modes. In South Africa, all commercial freight rail transport is provided by Transnet Freight Rail, which is a subsidiary of the government owned Transnet. Thus, there is no intra-modal competition in rail transport. However, road freight transport is deregulated and offers high levels of inter-modal competition. This results in the two modes having different objectives and can lead to variations in the interpretation of what is an efficient mode of transport. South Africa does not currently have ships on their register and therefore relies on foreign ships to provide the sea transport leg. This gives the foreign shipowners control over the terms of ocean transport and places South Africa at a disadvantage in terms of bringing foreign exchange into the country. Due to the fact that South Africa has little control over the deep-sea leg, only a rail transport leg was evaluated in the supply chain used in the example below. The data representing the rail leg was obtained from one of Transnet Freight Rail's operations.

The fourth step in the model is to evaluate the nodes of storage and/or transhipment. Storage plays an important role in a supply chain as it helps buffer the goods and prevents delays due to goods shortages. Points of transhipment are where goods are transferred from one mode of transport to another. Any delays at either of these points can cause inefficiencies along a supply chain. For the example presented below, the port was included as a point of transhipment. All data used in the example was obtained from one of South Africa's commercial ports.

The final step in the model is to evaluate the markets/customers. This step involves determining whether the markets/customers are satisfied with both the physical product and service they received. It serves as an additional form of evaluation and can be used either as part of the overall evaluation or as a comparison with the results obtained from the other links and nodes. Due to the fact that all the markets/customers of the supply chain used are based overseas and therefore difficult to obtain information from, the markets/customers were left out of the example.

Once the sets of data (based on the original sets) obtained from the mine was generated per measurement, all the data was categorised in terms of a particular year. Next, DEA was used to evaluate the data and determine how efficient each set was. The results obtained from the model indicate what the optimal operations of the mine would be as well as how the mine is operating on an annual basis and where the bottlenecks occur. The same procedure is followed for the rail leg and port node.

## 8.6 Virtual Values

In DEA, multiple inputs and outputs are linearly aggregated using weights. This enables the weight restrictions to be uniform. Thus a *virtual input* of a link or node is obtained as the linear weighted sum of all its inputs.

$$Virtual\ Input \ = \sum_{i=1}^{m} v_i x_{ij}$$

where $v_i$ is the weight assigned to its corresponding to input $x_{ij}$ during the aggregation and $v_i \geq 0$.

Similarly, *virtual output* of a firm is obtained as the linear weighted sum of all its outputs.

$$Virtual\ Output \ = \sum_{r=1}^{s} u_r y_{rj}$$

where $u_r$ is the weight assigned to its corresponding to output $y_{rj}$ during the aggregation. Also $u_r \geq 0$.

Given these virtual inputs and outputs, efficiency of the DMU in converting the inputs to outputs can be defined as the ratio of outputs to inputs.

$$Efficiency \ = \frac{Virtual\ Output}{Virtual\ Input} = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}}$$

In this dissertation the data was all scaled to a value between 0 and 100, so that it could be compared with a uniform weight.

## 8.7 Classification of Data Used in the Model

An important step in the model is the classification of the DMU measurement variables used in the model. They can either be classified as input or output variables. This decision must be taken after careful consideration as it could affect the outcome of the model. Table 8.2 shows the classification of the variables as used in this dissertation. It is important to note that due to the fact that the iron ore supply chain is more affected by reliability efficiency than speed efficiency (the commodity does not benefit from a faster delivery time), the variable idle time will be used to measure reliability efficiency.

**Table 8.2:** Classification of data used in the model

| **Mines** | | **Railways** | | **Ports** | |
|---|---|---|---|---|---|
| **Reliability** | **Class** | **Reliability** | **Class** | **Reliability** | **Class** |
| System uptime | Input | Variability | Input | Idle time | Input |
| Idle time | Input | Perfect shipments | Output | Utilisation | Input |
| Utilisation | Input | Idle time | Input | Communication | Input |
| Throughput efficiency | Output | Utilisation | Input | Document errors | Input |
| Communication | Input | Throughput efficiency | Output | | |
| Document errors | Input | Communication | Input | | |
| **Cost** | **Class** | **Cost** | **Class** | **Cost** | **Class** |
| Extraction cost/ton | Input | Cost per ton | Input | Cost per ton | Input |
| Infrastructure cost | Input | Infrastructure cost | Input | Inv carr const | Input |
| Labour | Input | Labour | Input | Infrastructure cost | Input |
| Communication | Input | | | Communication | Input |
| **Speed** | **Class** | **Speed** | **Class** | **Speed** | **Class** |
| Extraction time | Output | Transit time | Output | Port throughput | Output |
| Goods handling efficiency | Output | Goods handling efficiency | Output | Goods handling efficiency | Output |

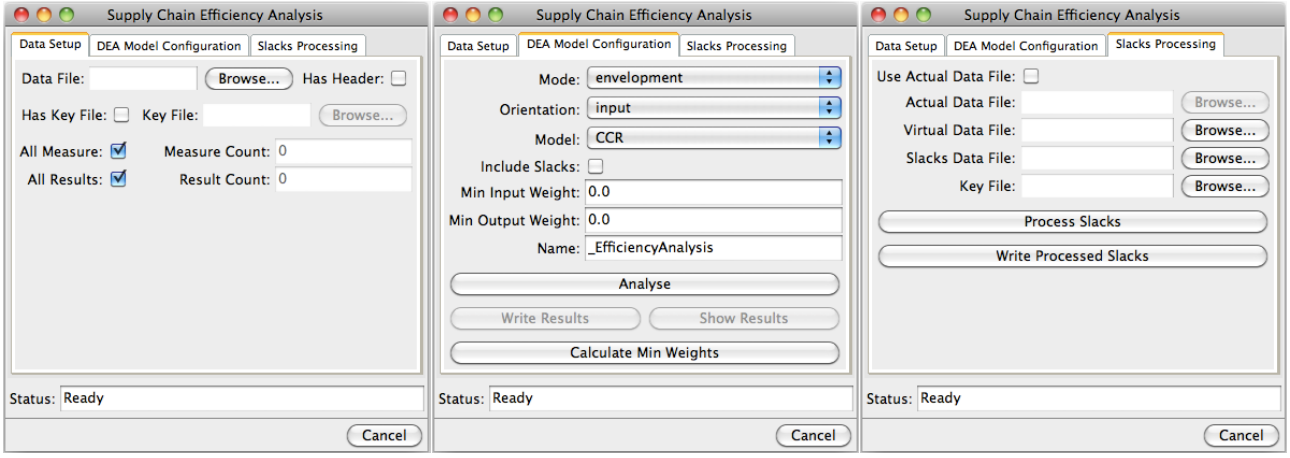
A variable in the model is classified as an input if it is a ratio used to measure resources placed into the link or node or used in its operation to achieve an output or a result. A variable in the model is classified as an output if it is a ratio used to measure the work done by the link or node. The 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. Therefore, all variables related to cost efficiency were determined to be inputs for all links and nodes. All variables related to speed efficiency were classified as outputs for all links and nodes and all variables related to reliability efficiency, with the exception of the two that measure throughput efficiency in terms of time and the number of perfect shipments, were classified as input variables for all links and nodes.

## 8.8 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 software can handle the DEA Multiplier and Envelopment mode, support both the CCR and BCC models and input and output oriented models. 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. Figure 8.9 shows a screen shot of the supply chain efficiency program. An user manual for the supply chain efficiency program is provided in Appendix F.

**Figure 8.9:** The supply chain efficiency program.



Has Header: ☐
Has Key File: ☐
All Measure: ☑
Measure Count: 0
All Results: ☑
Result Count: 0
Status: Ready

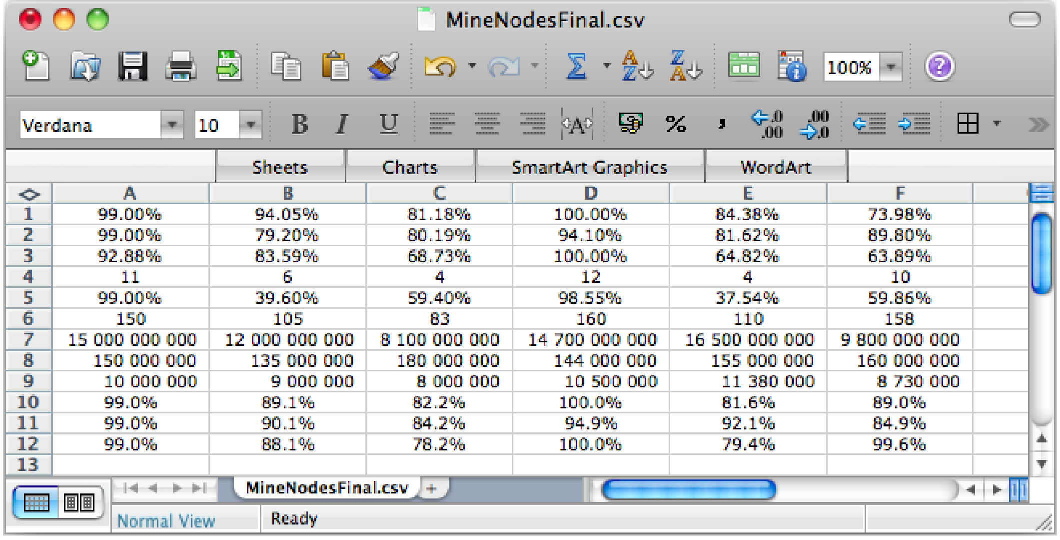
Mode: envelopment
Orientation: input
Model: CCR
Include Slacks: ☐
Min Input Weight: 0.0
Min Output Weight: 0.0
Name: _EfficiencyAnalysis
Status: Ready

Use Actual Data File: ☐
Status: Ready

## 8.9 Data and preparation for efficiency analysis

The data that was collected by the questionnaires was entered into Excel. Each column represents the data collected for one year of the link or node being evaluated, which is equivalent to one DMU. Figure 8.10 shows the format of the original input data of the mine as captured in Microsoft Excel. The original data was used to generate additional data with a multivariate normal distribution using R 2.9.2 (2009). The original data along with the generated data was then used in the analysis of the Sishen-Saldanha iron ore supply chain. Figure 8.11 shows the key that is used by the analysis program to determine the efficiency of the rail leg. The key defines the variable names that are assigned to each measurement during the DEA analysis. Variables V101-V109 represent the input variables used to measure the efficiency of the mine, while variables U101-U103 represent the output variables. The last column of the key data provides a description of the measurement.

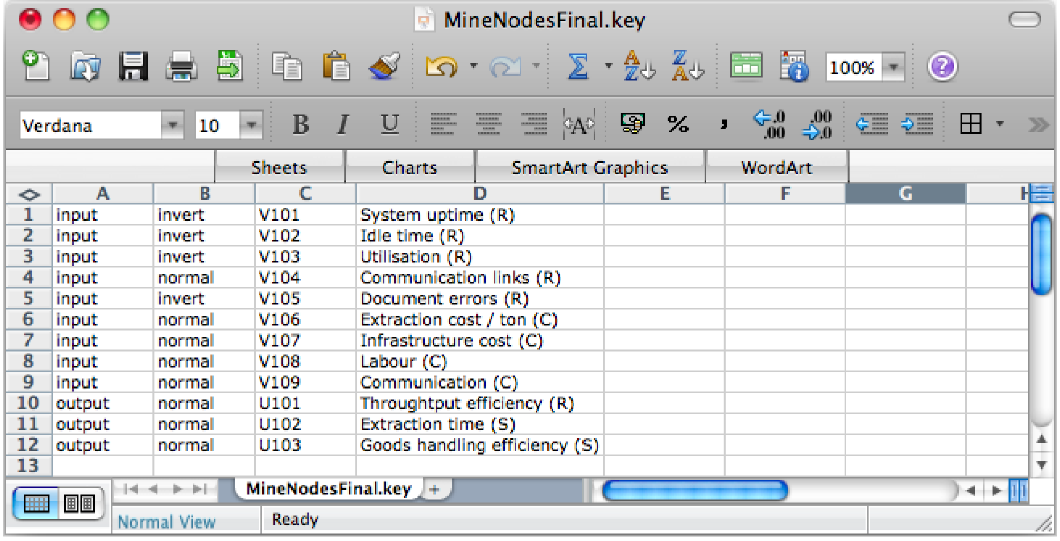
**Figure 8.10:** Original data as captured by questionnaire for the mine



|  | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | 99.00% | 94.05% | 81.18% | 100.00% | 84.38% | 73.98% |
| 2 | 99.00% | 79.20% | 80.19% | 94.10% | 81.62% | 89.80% |
| 3 | 92.88% | 83.59% | 68.73% | 100.00% | 64.82% | 63.89% |
| 4 | 11 | 6 | 4 | 12 | 4 | 10 |
| 5 | 99.00% | 39.60% | 59.40% | 98.55% | 37.54% | 59.86% |
| 6 | 150 | 105 | 83 | 160 | 110 | 158 |
| 7 | 15 000 000 000 | 12 000 000 000 | 8 100 000 000 | 14 700 000 000 | 16 500 000 000 | 9 800 000 000 |
| 8 | 150 000 000 | 135 000 000 | 180 000 000 | 144 000 000 | 155 000 000 | 160 000 000 |
| 9 | 10 000 000 | 9 000 000 | 8 000 000 | 10 500 000 | 11 380 000 | 8 730 000 |
| 10 | 99.0% | 89.1% | 82.2% | 100.0% | 81.6% | 89.0% |
| 11 | 99.0% | 90.1% | 84.2% | 94.9% | 92.1% | 84.9% |
| 12 | 99.0% | 88.1% | 78.2% | 100.0% | 79.4% | 99.6% |
| 13 |  |  |  |  |  |  |

The data was then transformed into virtual values that were scaled to a value between 0 and 100 so that it could be compared with a uniform weight. This was also done to compensate for the vast disparity in the scale of the data that was used. The uniform scale makes it easier for a firm to identify which variables are causing the bottlenecks in the supply chain, as the slack variables that identify these bottlenecks will be of uniform scale making it easier for companies to implement the changes that are necessary to improve the efficiency of the supply chain. The uniform scale also makes it possible to apply uniform weight restrictions so that value judgements or priori knowledge can be incorporated

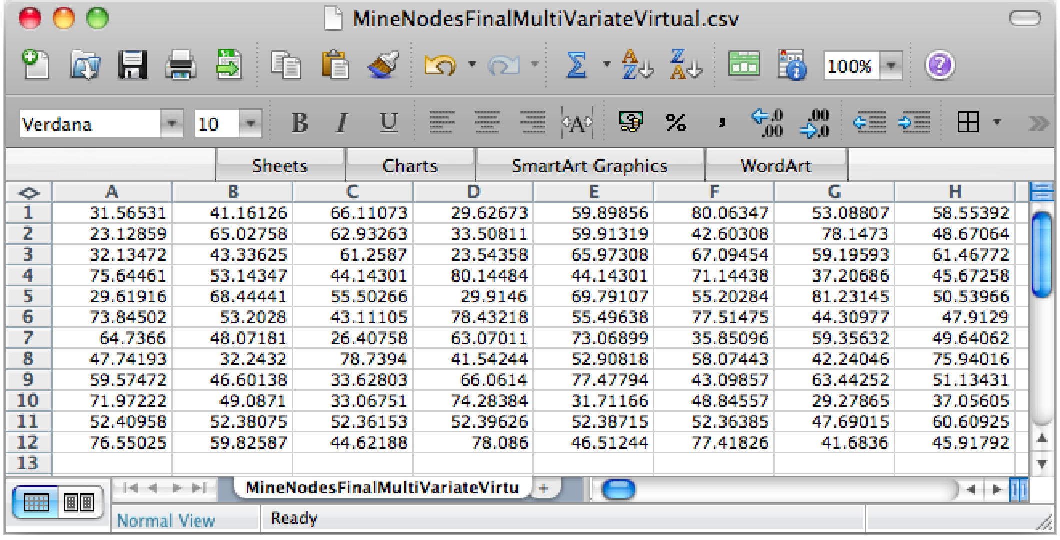
**Figure 8.11:** Key for data captured by questionnaire for the mine



| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | input | invert | V101 | System uptime (R) | | | |
| 2 | input | invert | V102 | Idle time (R) | | | |
| 3 | input | invert | V103 | Utilisation (R) | | | |
| 4 | input | normal | V104 | Communication links (R) | | | |
| 5 | input | invert | V105 | Document errors (R) | | | |
| 6 | input | normal | V106 | Extraction cost / ton (C) | | | |
| 7 | input | normal | V107 | Infrastructure cost (C) | | | |
| 8 | input | normal | V108 | Labour (C) | | | |
| 9 | input | normal | V109 | Communication (C) | | | |
| 10 | output | normal | U101 | Throughtput efficiency (R) | | | |
| 11 | output | normal | U102 | Extraction time (S) | | | |
| 12 | output | normal | U103 | Goods handling efficiency (S) | | | |
| 13 | | | | | | | |

into the model more easily (Cooper, Seiford & Zhu, 2004). Figure 8.12 shows the transformed data as used by the program to determine the efficiency of the mine. The complete set of the transformed data used to determine the efficiency of the mine can be found in Appendix C.

**Figure 8.12:** Transformed input data of the mine for efficiency analysis program

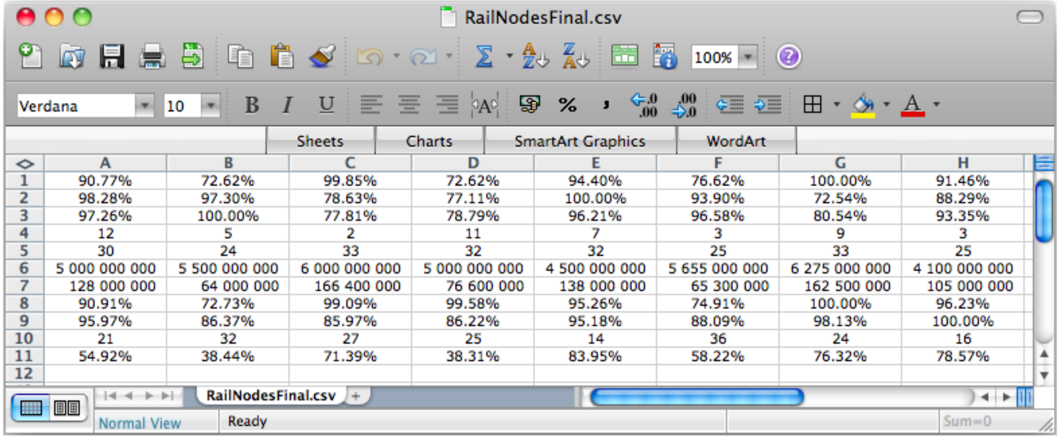


| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | 31.56531 | 41.16126 | 66.11073 | 29.62673 | 59.89856 | 80.06347 | 53.08807 | 58.55392 |
| 2 | 23.12859 | 65.02758 | 62.93263 | 33.50811 | 59.91319 | 42.60308 | 78.1473 | 48.67064 |
| 3 | 32.13472 | 43.33625 | 61.2587 | 23.54358 | 65.97308 | 67.09454 | 59.19593 | 61.46772 |
| 4 | 75.64461 | 53.14347 | 44.14301 | 80.14484 | 44.14301 | 71.14438 | 37.20686 | 45.67258 |
| 5 | 29.61916 | 68.44441 | 55.50266 | 29.9146 | 69.79107 | 55.20284 | 81.23145 | 50.53966 |
| 6 | 73.84502 | 53.2028 | 43.11105 | 78.43218 | 55.49638 | 77.51475 | 44.30977 | 47.9129 |
| 7 | 64.7366 | 48.07181 | 26.40758 | 63.07011 | 73.06899 | 35.85096 | 59.35632 | 49.64062 |
| 8 | 47.74193 | 32.2432 | 78.7394 | 41.54244 | 52.90818 | 58.07443 | 42.24046 | 75.94016 |
| 9 | 59.57472 | 46.60138 | 33.62803 | 66.0614 | 77.47794 | 43.09857 | 63.44252 | 51.13431 |
| 10 | 71.97222 | 49.0871 | 33.06751 | 74.28384 | 31.71166 | 48.84557 | 29.27865 | 37.05605 |
| 11 | 52.40958 | 52.38075 | 52.36153 | 52.39626 | 52.38715 | 52.36385 | 47.69015 | 60.60925 |
| 12 | 76.55025 | 59.82587 | 44.62188 | 78.086 | 46.51244 | 77.41826 | 41.6836 | 45.91792 |
| 13 | | | | | | | | |

Figure 8.13 shows the format of the original input data of the rail leg as captured in Microsoft Excel. Figure 8.14 shows the key that is used by the analysis program to determine the efficiency of the rail leg. Variables V201-V207 represent the input variables used to measure the efficiency of the rail leg,

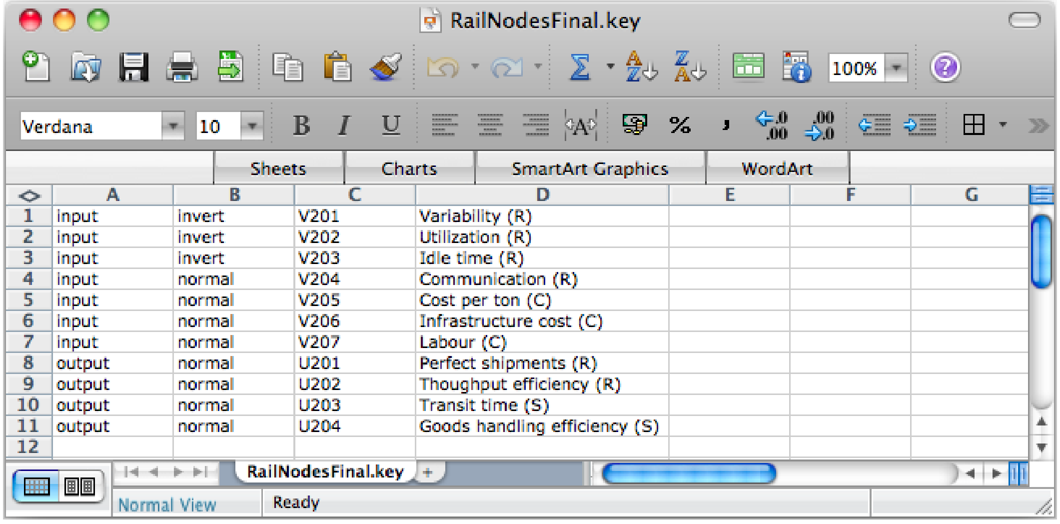
while variables U201-U204 represent the output variables used to measure the efficiency of the rail leg.

**Figure 8.13:** Original data as captured by questionnaire for the rail leg



| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | 90.77% | 72.62% | 99.85% | 72.62% | 94.40% | 76.62% | 100.00% | 91.46% |
| 2 | 98.28% | 97.30% | 78.63% | 77.11% | 100.00% | 93.90% | 72.54% | 88.29% |
| 3 | 97.26% | 100.00% | 77.81% | 78.79% | 96.21% | 96.58% | 80.54% | 93.35% |
| 4 | 12 | 5 | 2 | 11 | 7 | 3 | 9 | 3 |
| 5 | 30 | 24 | 33 | 32 | 32 | 25 | 33 | 25 |
| 6 | 5 000 000 000 | 5 500 000 000 | 6 000 000 000 | 5 000 000 000 | 4 500 000 000 | 5 655 000 000 | 6 275 000 000 | 4 100 000 000 |
| 7 | 128 000 000 | 64 000 000 | 166 400 000 | 76 600 000 | 138 000 000 | 65 300 000 | 162 500 000 | 105 000 000 |
| 8 | 90.91% | 72.73% | 99.09% | 99.58% | 95.26% | 74.91% | 100.00% | 96.23% |
| 9 | 95.97% | 86.37% | 85.97% | 86.22% | 95.18% | 88.09% | 98.13% | 100.00% |
| 10 | 21 | 32 | 27 | 25 | 14 | 36 | 24 | 16 |
| 11 | 54.92% | 38.44% | 71.39% | 38.31% | 83.95% | 58.22% | 76.32% | 78.57% |
| 12 | | | | | | | | |

**Figure 8.14:** Key for data captured by questionnaire for the rail

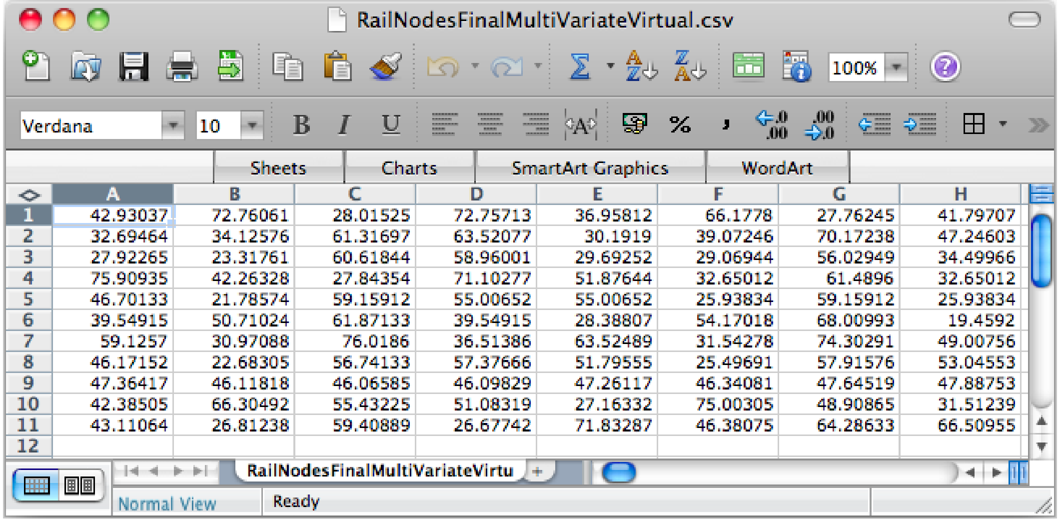


| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | input | invert | V201 | Variability (R) | | | |
| 2 | input | invert | V202 | Utilization (R) | | | |
| 3 | input | invert | V203 | Idle time (R) | | | |
| 4 | input | normal | V204 | Communication (R) | | | |
| 5 | input | normal | V205 | Cost per ton (C) | | | |
| 6 | input | normal | V206 | Infrastructure cost (C) | | | |
| 7 | input | normal | V207 | Labour (C) | | | |
| 8 | output | normal | U201 | Perfect shipments (R) | | | |
| 9 | output | normal | U202 | Thoughput efficiency (R) | | | |
| 10 | output | normal | U203 | Transit time (S) | | | |
| 11 | output | normal | U204 | Goods handling efficiency (S) | | | |
| 12 | | | | | | | |

Figure 8.15 shows the transformed data as used by the program to determine the efficiency for the rail leg. The complete set of the transformed data used to determine the efficiency of the rail operator can be found in Appendix D.

Figure 8.16 shows the format of the original input data of the port node as captured in Microsoft Excel. Figure 8.17 shows the key that is used by the analysis program to determine the efficiency of the port node. Variables V301-V309 represent the input variables used to measure the efficiency of

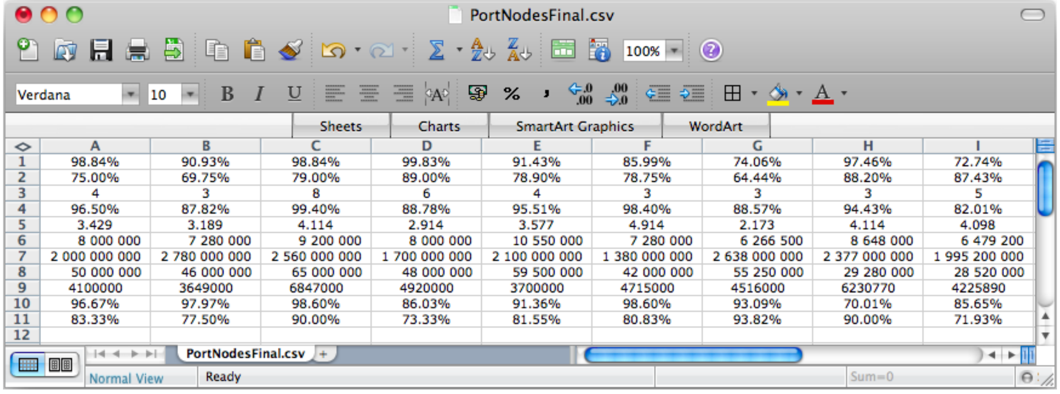
**Figure 8.15:** Transformed input data of the rail leg for efficiency analysis program



| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | 42.93037 | 72.76061 | 28.01525 | 72.75713 | 36.95812 | 66.1778 | 27.76245 | 41.79707 |
| 2 | 32.69464 | 34.12576 | 61.31697 | 63.52077 | 30.1919 | 39.07246 | 70.17238 | 47.24603 |
| 3 | 27.92265 | 23.31761 | 60.61844 | 58.96001 | 29.69252 | 29.06944 | 56.02949 | 34.49966 |
| 4 | 75.90935 | 42.26328 | 27.84354 | 71.10277 | 51.87644 | 32.65012 | 61.4896 | 32.65012 |
| 5 | 46.70133 | 21.78574 | 59.15912 | 55.00652 | 55.00652 | 25.93834 | 59.15912 | 25.93834 |
| 6 | 39.54915 | 50.71024 | 61.87133 | 39.54915 | 28.38807 | 54.17018 | 68.00993 | 19.4592 |
| 7 | 59.1257 | 30.97088 | 76.0186 | 36.51386 | 63.52489 | 31.54278 | 74.30291 | 49.00756 |
| 8 | 46.17152 | 22.68305 | 56.74133 | 57.37666 | 51.79555 | 25.49691 | 57.91576 | 53.04553 |
| 9 | 47.36417 | 46.11818 | 46.06585 | 46.09829 | 47.26117 | 46.34081 | 47.64519 | 47.88753 |
| 10 | 42.38505 | 66.30492 | 55.43225 | 51.08319 | 27.16332 | 75.00305 | 48.90865 | 31.51239 |
| 11 | 43.11064 | 26.81238 | 59.40889 | 26.67742 | 71.83287 | 46.38075 | 64.28633 | 66.50955 |
| 12 | | | | | | | | |

the port, while variables U301-U302 represent the output variables used to measure the efficiency of the port.

**Figure 8.16:** Original data as captured by questionnaire for the port node

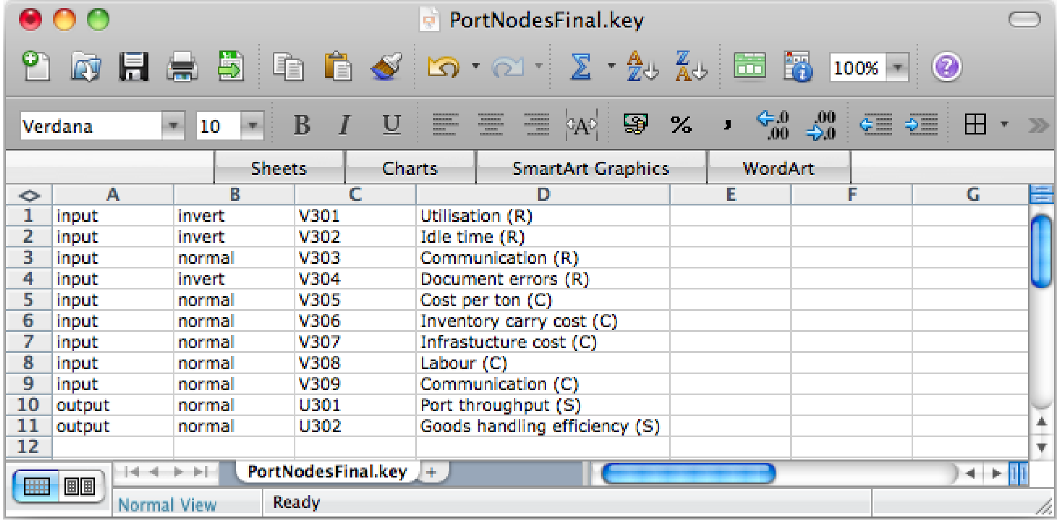


| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 98.84% | 90.93% | 98.84% | 99.83% | 91.43% | 85.99% | 74.06% | 97.46% | 72.74% |
| 2 | 75.00% | 69.75% | 79.00% | 89.00% | 78.90% | 78.75% | 64.44% | 88.20% | 87.43% |
| 3 | 4 | 3 | 8 | 6 | 4 | 3 | 3 | 3 | 5 |
| 4 | 96.50% | 87.82% | 99.40% | 88.78% | 95.51% | 98.40% | 88.57% | 94.43% | 82.01% |
| 5 | 3.429 | 3.189 | 4.114 | 2.914 | 3.577 | 4.914 | 2.173 | 4.114 | 4.098 |
| 6 | 8 000 000 | 7 280 000 | 9 200 000 | 8 000 000 | 10 550 000 | 7 280 000 | 6 266 500 | 8 648 000 | 6 479 200 |
| 7 | 2 000 000 000 | 2 780 000 000 | 2 560 000 000 | 1 700 000 000 | 2 100 000 000 | 1 380 000 000 | 2 638 000 000 | 2 377 000 000 | 1 995 200 000 |
| 8 | 50 000 000 | 46 000 000 | 65 000 000 | 48 000 000 | 59 500 000 | 42 000 000 | 55 250 000 | 29 280 000 | 28 520 000 |
| 9 | 4100000 | 3649000 | 6847000 | 4920000 | 3700000 | 4715000 | 4516000 | 6230770 | 4225890 |
| 10 | 96.67% | 97.97% | 98.60% | 86.03% | 91.36% | 98.60% | 93.09% | 70.01% | 85.65% |
| 11 | 83.33% | 77.50% | 90.00% | 73.33% | 81.55% | 80.83% | 93.82% | 90.00% | 71.93% |
| 12 | | | | | | | | | |

Figure 8.18 shows the transformed data as used by the program for the port node. The complete set of the transformed data used to determine the efficiency of the port node can be found in Appendix E.

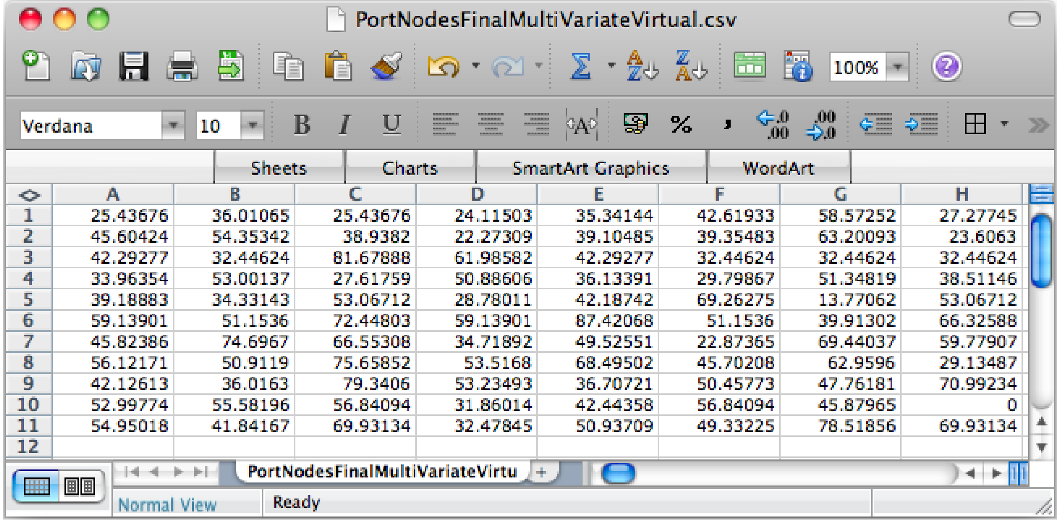
After the data was added to Excel, the software tool developed by Gerber (2009) was used to run the data through the composite supply chain efficiency model. The software program was developed using the *Python Programming Language (2009)*, *Pulp (2005)* (an opensource linear programming development library) and an opensource linear programming solver named *GLPK (2008)*. The working

**Figure 8.17:** Key for data captured by questionnaire for the port



| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | input | invert | V301 | Utilisation (R) | | | |
| 2 | input | invert | V302 | Idle time (R) | | | |
| 3 | input | normal | V303 | Communication (R) | | | |
| 4 | input | invert | V304 | Document errors (R) | | | |
| 5 | input | normal | V305 | Cost per ton (C) | | | |
| 6 | input | normal | V306 | Inventory carry cost (C) | | | |
| 7 | input | normal | V307 | Infrastucture cost (C) | | | |
| 8 | input | normal | V308 | Labour (C) | | | |
| 9 | input | normal | V309 | Communication (C) | | | |
| 10 | output | normal | U301 | Port throughput (S) | | | |
| 11 | output | normal | U302 | Goods handling efficiency (S) | | | |
| 12 | | | | | | | |

**Figure 8.18:** Transformed input data of the port node for efficiency analysis program



| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | 25.43676 | 36.01065 | 25.43676 | 24.11503 | 35.34144 | 42.61933 | 58.57252 | 27.27745 |
| 2 | 45.60424 | 54.35342 | 38.9382 | 22.27309 | 39.10485 | 39.35483 | 63.20093 | 23.6063 |
| 3 | 42.29277 | 32.44624 | 81.67888 | 61.98582 | 42.29277 | 32.44624 | 32.44624 | 32.44624 |
| 4 | 33.96354 | 53.00137 | 27.61759 | 50.88606 | 36.13391 | 29.79867 | 51.34819 | 38.51146 |
| 5 | 39.18883 | 34.33143 | 53.06712 | 28.78011 | 42.18742 | 69.26275 | 13.77062 | 53.06712 |
| 6 | 59.13901 | 51.1536 | 72.44803 | 59.13901 | 87.42068 | 51.1536 | 39.91302 | 66.32588 |
| 7 | 45.82386 | 74.6967 | 66.55308 | 34.71892 | 49.52551 | 22.87365 | 69.44037 | 59.77907 |
| 8 | 56.12171 | 50.9119 | 75.65852 | 53.5168 | 68.49502 | 45.70208 | 62.9596 | 29.13487 |
| 9 | 42.12613 | 36.0163 | 79.3406 | 53.23493 | 36.70721 | 50.45773 | 47.76181 | 70.99234 |
| 10 | 52.99774 | 55.58196 | 56.84094 | 31.86014 | 42.44358 | 56.84094 | 45.87965 | 0 |
| 11 | 54.95018 | 41.84167 | 69.93134 | 32.47845 | 50.93709 | 49.33225 | 78.51856 | 69.93134 |
| 12 | | | | | | | | |

of the program was verified by comparing its results with the results of other DEA case studies from literature references. Data provided in literature was incorporated into the program and results were generated. Exactly the same results as achieved in the literature were generated by the program developed for all examples that were conducted. In addition, further verification of the program was done by comparing the results obtained with the results achieved if the composite supply chain efficiency model was run through the well-known computer program DEA-P (2003) as well as a program written for Excel by Naude (2009). In both cases similar results to those obtained by the program written by Gerber (2009) were achieved.

## 8.10 Analysis of results

Table 8.3 shows the output of an efficiency analysis using an input-oriented envelopment DEA model for the mine, rail and port nodes of the Sishen-Saldanha iron ore supply chain. From the analysis it is clear that none of the mine nodes are operating efficiently. However, the average efficiency of the mines are still higher than that of the port.

**Table 8.3:** Efficiency analysis

| Mine Nodes | Efficiency |
|---|---|
| DMU1 | 98.61% |
| DMU2 | 99.15% |
| DMU3 | 97.58% |
| DMU4 | 94.78% |
| DMU5 | 94.73% |
| DMU6 | 97.03% |
| Rail Nodes | Efficiency |
| DMU1 | 100.00% |
| DMU2 | 90.44% |
| DMU3 | 100.00% |
| DMU4 | 100.00% |
| DMU5 | 94.30% |
| DMU6 | 100.00% |
| DMU7 | 93.98% |
| DMU8 | 100.00% |
| Port Nodes | Efficiency |
| DMU1 | 98.67% |
| DMU2 | 93.37% |
| DMU3 | 95.63% |
| DMU4 | 96.55% |
| DMU5 | 89.34% |
| DMU6 | 100.00% |
| DMU7 | 95.45% |
| DMU8 | 100.00% |
| DMU9 | 89.98% |

The rail leg operated efficiently for DMU1, DMU3, DMU4, DMU6 and DMU8 and the port operated efficiently for DMU6 and DMU7. 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 the country. An additional factor 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.

The slack analysis depicted in Tables 8.4, 8.5 and 8.6 are presented in the virtual form. This allows the firm to identify exactly what variables are causing the bottlenecks in the supply chain and in so doing allows them to take the necessary steps to improve their efficiency. For example, within DMU6 of the mine, i.e. year 6, slack variable $s_1^-$ or system uptime is the biggest problem area for the mine, followed by slack variable $s_3^-$ (utilisation) and slack variable $s_8^-$ (labour in terms of cost). Within DMU5 of the rail leg, slack variable $s_2^+$ (throughput efficiency in terms of reliability) is the main cause for concern followed by slack variable $s_5^-$ (cost per ton) and slack variable $s_4^-$ (communication in terms of reliability). Within DMU2 of the port slack variable $s_7^-$ (infrastructure cost) is the biggest problem followed by slack variable $s_4^-$ (documentation errors) and slack variable $s_2^-$ (idle time).

**Table 8.4:** Mine node slacks analysis results

| Measure | Slack | DMU1 | DMU2 | DMU3 | DMU4 | DMU5 | DMU6 |
|---|---|---|---|---|---|---|---|
| System uptime (R) | $s_1^-$ | 17.673 | 4.575 | 15.238 | 21.438 | 25.266 | 39.565 |
| Idle time (R) | $s_2^-$ | 0 | 2.297 | 0 | 3.477 | 0 | 0 |
| Utilisation (R) | $s_3^-$ | 14.287 | 3.153 | 10.968 | 16.738 | 24.347 | 31.416 |
| Communication links (R) | $s_4^-$ | 0 | 0 | 0 | 2.098 | 0 | 0 |
| Document errors (R) | $s_5^-$ | 4.372 | 2.697 | 0 | 8.567 | 13.452 | 8.747 |
| Extraction cost / ton (C) | $s_6^-$ | 5.671 | 1.728 | 4.230 | 14.206 | 15.325 | 11.651 |
| Infrastructure cost (C) | $s_7^-$ | 1.521 | 0.344 | 0 | 17.971 | 25.706 | 0 |
| Labour (C) | $s_8^-$ | 7.416 | 0 | 11.37 | 1.764 | 0 | 18.137 |
| Communication (C) | $s_9^-$ | 6.571 | 2.528 | 6.275 | 29.174 | 33.999 | 11.149 |
| Throughtput efficiency (R) | $s_1^+$ | 7.874 | 2.479 | 6.826 | 10.012 | 13.681 | 17.577 |
| Extraction time (S) | $s_2^+$ | 0 | 0 | 0 | 0 | 18.123 | 7.0947 |
| Goods handling efficiency (S) | $s_3^+$ | 0 | 0 | 1.841 | 0 | 0 | 0 |

Comparison of the slack results for the historical data of the three links or nodes identifies the areas of concern within each link or node. Table 8.4 shows that for the mine the three areas on which 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). Table 8.5 shows that the three areas of importance for the rail operator are communication (in terms of cost efficiency), throughput

**Table 8.5:** Rail node slacks analysis results

| **Measure** | **Slack** | **DMU2** | **DMU5** | **DMU7** |
|---|---|---|---|---|
| Variability (R) | $s_1^-$ | 0 | 8.611 | 0 |
| Utilization (R) | $s_2^-$ | 1.100 | 0 | 5.314 |
| Idle time (R) | $s_3^-$ | 1.473 | 2.445 | 0 |
| Communication (R) | $s_4^-$ | 26.139 | 11.314 | 32.182 |
| Cost per ton (C) | $s_5^-$ | 11.402 | 12.349 | 10.845 |
| Infrastructure cost (C) | $s_6^-$ | 13.634 | 4.529 | 14.913 |
| Labour (C) | $s_7^-$ | 9.378 | 0 | 4.943 |
| Perfect shipments (R) | $s_1^+$ | 0 | 0 | 0 |
| Thoughput efficiency (R) | $s_2^+$ | 14.871 | 21.290 | 18.504 |
| Transit time (S) | $s_3^+$ | 0 | 0 | 0 |
| Goods handling efficiency (S) | $s_4^+$ | 18.559 | 7.144 | 5.134 |

**Table 8.6:** Port node slacks analysis results

| **Measure** | **Var.** | **Slk.** | **DMU1** | **DMU2** | **DMU3** | **DMU4** | **DMU5** | **DMU7** | **DMU9** |
|---|---|---|---|---|---|---|---|---|---|
| Utilisation | V301 | $s_1^-$ | 0.0 | 0.0 | 0.0 | 0.0 | 1.303 | 13.947 | 14.481 |
| Idle time | V302 | $s_2^-$ | 3.359 | 11.450 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Communication | V303 | $s_3^-$ | 14.685 | 7.574 | 32.918 | 28.638 | 17.015 | 15.497 | 27.081 |
| Document errors | V304 | $s_4^-$ | 3.227 | 15.141 | 4.591 | 0.482 | 0.0 | 10.128 | 8.283 |
| Cost per ton | V305 | $s_5^-$ | 3.765 | 0.0 | 15.273 | 0.0 | 9.208 | 0.0 | 12.430 |
| Inventory carry cost | V306 | $s_6^-$ | 0.0 | 1.264 | 4.926 | 0.0 | 28.914 | 0.224 | 0.0 |
| Infrastucture cost | V307 | $s_7^-$ | 19.763 | 53.325 | 38.384 | 3.802 | 29.689 | 16.571 | 23.401 |
| Labour | V308 | $s_8^-$ | 0.151 | 0.0 | 6.649 | 16.946 | 14.886 | 3.494 | 4.239 |
| Communication | V309 | $s_9^-$ | 0.0 | 0.0 | 20.822 | 11.154 | 0.0 | 3.046 | 9.332 |
| Port throughput | U301 | $s_1^+$ | 0.0 | 0.0 | 0.0 | 0.0 | 11.290 | 14.708 | 1.061 |
| Handling efficiency | U302 | $s_2^+$ | 0.0 | 7.336 | 0.0 | 3.883 | 0.0 | 0.0 | 1.476 |

efficiency (in terms of reliability efficiency) and cost per ton of iron ore transported (in terms of cost efficiency). Table 8.6 shows that 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).

Table 8.7 to 8.12 show the processed slacks results for the mine nodes, while Table 8.13 to 8.15 show the same for the rail nodes and Table 8.16 to 8.22 show the same for the port nodes. The above mentioned tables show a representation of the data that was collected through the questionnaires in comparison with what the performance levels should be in order for the mine, rail leg or port node to be operating efficiently. The column labelled "Measured Actual" is the actual data collected. The column labelled "Virtual" is the transformed data. The column labelled "Slacks Virtual" are the slacks results of the transformed data and the column labelled "Required Actual" are the performance levels that need to be achieved in order to be operating efficiently. While Table 8.4 to 8.6 gives a clear indication of where the problem areas lie in the supply chain, Table 8.7 to 8.22 provide firms with an indication of what levels of performance they need to achieve per variable in order to operate at one hundred percent efficiency.

For example, Table 8.8 identified that for DMU2 of the mine the biggest cause for concern was the document errors. In DMU2 of the mine, the mine experienced document errors in 39.6% of the documents drawn up. However, in the year when the mine operated optimally in terms of document errors, it only experienced document errors in 6.74% of the documents drawn up.

If the composite supply chain efficiency model is used by firms in practice, they will be able to compare the results obtained from the model with actual events. This will enable them to identify reasons why the firm did not operate at one hundred percent efficiency during a specific year. For the purpose of this dissertation, the author was only provided with data pertaining to specific questions that were asked in the questionnaires. Therefore, it is not possible for the author to expand on the reasons why the firm operarated efficiently during some years and not in others.

**Table 8.7:** Summary of processed slacks results for mine node 1

| DMU1 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured Actual** | **Measured Virtual** | **Slacks Virtual** | **Required Actual** |
| V101 | System uptime (R) | 0.99 | 31.57 | 0 | 1 |
| V102 | Idle time (R) | 0.99 | 23.13 | 0 | 0.99 |
| V103 | Utilisation (R) | 0.93 | 32.13 | 14.29 | 1 |
| V104 | Communication links (R) | 11 | 75.64 | 0 | 11 |
| V105 | Document errors (R) | 0.99 | 29.62 | 4.37 | 1 |
| V106 | Extraction cost / ton (C) | 150 | 73.85 | 5.67 | 138 |
| V107 | Infrastructure cost (C) | 15000000000 | 64.74 | 1.52 | 14726094847 |
| V108 | Labour (C) | 150000000 | 47.74 | 7.42 | 142822308 |
| V109 | Communication (C) | 10000000 | 59.57 | 6.57 | 9493467 |
| U101 | Throughtput efficiency (R) | 0.99 | 71.97 | 7.87 | 1 |
| U102 | Extraction time (S) | 0.99 | 52.41 | 0 | 0.99 |
| U103 | Goods handling efficiency (S) | 0.99 | 76.55 | 0 | 0.99 |

**Table 8.8:** Summary of processed slacks results for mine node 2

| **DMU2** | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V101 | System uptime (R) | 0.94 | 41.16 | 4.58 | 0.96 |
| V102 | Idle time (R) | 0.79 | 65.03 | 2.3 | 0.8 |
| V103 | Utilisation (R) | 0.84 | 43.34 | 3.15 | 0.86 |
| V104 | Communication links (R) | 6 | 53.14 | 0 | 6 |
| V105 | Document errors (R) | 0.4 | 68.44 | 2.7 | 0.44 |
| V106 | Extraction cost / ton (C) | 105 | 53.2 | 1.73 | 101 |
| V107 | Infrastructure cost (C) | 12000000000 | 48.07 | 0.34 | 11937976230 |
| V108 | Labour (C) | 135000000 | 32.24 | 0 | 135000003 |
| V109 | Communication (C) | 9000000 | 46.6 | 2.53 | 8805073 |
| U101 | Throughtput efficiency (R) | 0.89 | 49.09 | 2.48 | 0.9 |
| U102 | Extraction time (S) | 0.9 | 52.38 | 0 | 0.9 |
| U103 | Goods handling efficiency (S) | 0.88 | 59.83 | 0 | 0.88 |

**Table 8.9:** Summary of processed slacks results for mine node 3

| **DMU3** | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V101 | System uptime (R) | 0.81 | 66.11 | 15.24 | 0.89 |
| V102 | Idle time (R) | 0.8 | 62.93 | 0 | 0.8 |
| V103 | Utilisation (R) | 0.69 | 61.26 | 10.97 | 0.78 |
| V104 | Communication links (R) | 4 | 44.14 | 0 | 4 |
| V105 | Document errors (R) | 0.59 | 55.5 | 0 | 0.59 |
| V106 | Extraction cost / ton (C) | 83 | 43.11 | 4.23 | 74 |
| V107 | Infrastructure cost (C) | 8100000000 | 26.41 | 0 | 8099999373 |
| V108 | Labour (C) | 180000000 | 78.74 | 11.38 | 168986675 |
| V109 | Communication (C) | 8000000 | 33.63 | 6.28 | 7516248 |
| U101 | Throughtput efficiency (R) | 0.82 | 33.07 | 6.83 | 0.85 |
| U102 | Extraction time (S) | 0.84 | 52.36 | 0 | 0.84 |
| U103 | Goods handling efficiency (S) | 0.78 | 44.62 | 1.84 | 0.79 |

**Table 8.10:** Summary of processed slacks results for mine node 4

| **DMU4** | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured Actual** | **Measured Virtual** | **Slacks Virtual** | **Required Actual** |
| V101 | System uptime (R) | 1 | 29.63 | 0 | 1 |
| V102 | Idle time (R) | 0.94 | 33.51 | 3.48 | 0.96 |
| V103 | Utilisation (R) | 1 | 23.54 | 0 | 1 |
| V104 | Communication links (R) | 12 | 80.14 | 2.1 | 12 |
| V105 | Document errors (R) | 0.99 | 29.91 | 8.57 | 1 |
| V106 | Extraction cost / ton (C) | 160 | 78.43 | 14.21 | 129 |
| V107 | Infrastructure cost (C) | 14700000000 | 63.07 | 17.97 | 11464728238 |
| V108 | Labour (C) | 144000000 | 41.54 | 1.76 | 142292077 |
| V109 | Communication (C) | 10500000 | 66.06 | 29.17 | 8251174 |
| U101 | Throughtput efficiency (R) | 1 | 74.28 | 0 | 1 |
| U102 | Extraction time (S) | 0.95 | 52.4 | 0 | 0.95 |
| U103 | Goods handling efficiency (S) | 1 | 78.09 | 0 | 1 |

**Table 8.11:** Summary of processed slacks results for mine node 5

| **DMU5** | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured Actual** | **Measured Virtual** | **Slacks Virtual** | **Required Actual** |
| V101 | System uptime (R) | 1 | 29.63 | 0 | 1 |
| V101 | System uptime (R) | 0.84 | 59.9 | 25.27 | 0.97 |
| V102 | Idle time (R) | 0.82 | 59.91 | 0 | 0.82 |
| V103 | Utilisation (R) | 0.65 | 65.97 | 24.35 | 0.85 |
| V104 | Communication links (R) | 4 | 44.14 | 0 | 4 |
| V105 | Document errors (R) | 0.38 | 69.79 | 13.45 | 0.58 |
| V106 | Extraction cost / ton (C) | 110 | 55.5 | 15.33 | 77 |
| V107 | Infrastructure cost (C) | 16500000000 | 73.07 | 25.71 | 11872362610 |
| V108 | Labour (C) | 155000000 | 52.91 | 0 | 155000000 |
| V109 | Communication (C) | 11380000 | 77.48 | 34 | 8759289 |
| U101 | Throughtput efficiency (R) | 0.82 | 31.71 | 13.68 | 0.88 |
| U102 | Extraction time (S) | 0.92 | 52.39 | 18.12 | 1 |
| U103 | Goods handling efficiency (S) | 0.79 | 46.51 | 0 | 0.79 |

**Table 8.12:** Summary of processed slacks results for mine node 6

| DMU6 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured Actual** | **Measured Virtual** | **Slacks Virtual** | **Required Actual** |
| V101 | System uptime (R) | 0.74 | 80.06 | 39.57 | 0.94 |
| V102 | Idle time (R) | 0.9 | 42.6 | 0 | 0.9 |
| V103 | Utilisation (R) | 0.64 | 67.09 | 31.42 | 0.9 |
| V104 | Communication links (R) | 10 | 71.14 | 0 | 10 |
| V105 | Document errors (R) | 0.6 | 55.2 | 8.75 | 0.73 |
| V106 | Extraction cost / ton (C) | 158 | 77.51 | 11.65 | 133 |
| V107 | Infrastructure cost (C) | 9800000000 | 35.85 | 0 | 9799999494 |
| V108 | Labour (C) | 160000000 | 58.07 | 18.14 | 142445961 |
| V109 | Communication (C) | 8730000 | 43.1 | 11.15 | 7870561 |
| U101 | Throughtput efficiency (R) | 0.89 | 48.85 | 17.58 | 0.97 |
| U102 | Extraction time (S) | 0.85 | 52.36 | 7.09 | 0.91 |
| U103 | Goods handling efficiency (S) | 1 | 77.42 | 0 | 1 |

**Table 8.13:** Summary of processed slacks results for rail node 2

| DMU2 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured Actual** | **Measured Virtual** | **Slacks Virtual** | **Required Actual** |
| V201 | Variability (R) | 0.91 | 42.93 | 0 | 0.91 |
| V202 | Utilization (R) | 0.98 | 32.69 | 1.1 | 0.99 |
| V203 | Idle time (R) | 0.97 | 27.92 | 1.47 | 0.98 |
| V204 | Communication (R) | 12 | 75.91 | 26.14 | 7 |
| V205 | Cost per ton (C) | 30 | 46.7 | 11.4 | 27 |
| V206 | Infrastructure cost (C) | 5000000000 | 39.55 | 13.63 | 4389190205 |
| V207 | Labour (C) | 128000000 | 59.13 | 9.38 | 106681416 |
| U201 | Perfect shipments (R) | 0.91 | 46.17 | 0 | 0.91 |
| U202 | Thoughput efficiency (R) | 0.96 | 47.36 | 14.87 | 1 |
| U203 | Transit time (S) | 21 | 42.39 | 0 | 21 |
| U204 | Goods handling efficiency (S) | 0.55 | 43.11 | 18.56 | 0.74 |

**Table 8.14:** Summary of processed slacks results for rail node 5

| DMU5 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V201 | Variability (R) | 0.73 | 72.76 | 8.61 | 0.78 |
| V202 | Utilization (R) | 0.97 | 34.13 | 0 | 0.97 |
| V203 | Idle time (R) | 1 | 23.32 | 2.45 | 1 |
| V204 | Communication (R) | 5 | 42.26 | 11.31 | 3 |
| V205 | Cost per ton (C) | 24 | 21.79 | 12.35 | 21 |
| V206 | Infrastructure cost (C) | 5500000000 | 50.71 | 4.53 | 5297098998 |
| V207 | Labour (C) | 64000000 | 30.97 | 0 | 63999996 |
| U201 | Perfect shipments (R) | 0.73 | 22.68 | 0 | 0.73 |
| U202 | Thoughput efficiency (R) | 0.86 | 46.12 | 21.29 | 1 |
| U203 | Transit time (S) | 32 | 66.3 | 0 | 32 |
| U204 | Goods handling efficiency (S) | 0.38 | 26.81 | 7.14 | 0.46 |

**Table 8.15:** Summary of processed slacks results for rail node 7

| DMU7 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V201 | Variability (R) | 1 | 28.02 | 0 | 1 |
| V202 | Utilization (R) | 0.79 | 61.32 | 5.31 | 0.82 |
| V203 | Idle time (R) | 0.78 | 60.62 | 0 | 0.78 |
| V204 | Communication (R) | 2 | 27.84 | 0 | 2 |
| V205 | Cost per ton (C) | 33 | 59.16 | 10.85 | 30 |
| V206 | Infrastructure cost (C) | 6000000000 | 61.87 | 14.91 | 5331915496 |
| V207 | Labour (C) | 166400000 | 76.02 | 4.94 | 155163495 |
| U201 | Perfect shipments (R) | 0.99 | 56.74 | 0 | 0.99 |
| U202 | Thoughput efficiency (R) | 0.86 | 46.07 | 18.5 | 1 |
| U203 | Transit time (S) | 27 | 55.43 | 0 | 27 |
| U204 | Goods handling efficiency (S) | 0.71 | 59.41 | 5.13 | 0.77 |

**Table 8.16:** Summary of processed slacks results for port node 1

| DMU1 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V301 | Utilisation (R) | 0.99 | 25.44 | 0 | 0.99 |
| V302 | Idle time (R) | 0.75 | 45.6 | 3.36 | 0.77 |
| V303 | Communication (R) | 4 | 42.29 | 14.69 | 2.51 |
| V304 | Document errors (R) | 0.96 | 33.96 | 3.23 | 0.98 |
| V305 | Cost per ton (C) | 3.43 | 39.19 | 3.77 | 3.24 |
| V306 | Inventory carry cost (C) | 8000000 | 59.14 | 0 | 8000000 |
| V307 | Infrastucture cost (C) | 2000000000 | 45.82 | 19.76 | 1466088938 |
| V308 | Labour (C) | 50000000 | 56.12 | 0.15 | 49883780 |
| V309 | Communication (C) | 4100000 | 42.13 | 0 | 4100000 |
| U301 | Port throughput (S) | 0.97 | 53 | 0 | 0.97 |
| U302 | Goods handling efficiency (S) | 0.83 | 54.95 | 0 | 0.83 |

**Table 8.17:** Summary of processed slacks results for port node 2

| DMU2 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V301 | Utilisation (R) | 0.91 | 36.01 | 0 | 0.91 |
| V302 | Idle time (R) | 0.7 | 54.35 | 11.45 | 0.77 |
| V303 | Communication (R) | 3 | 32.45 | 7.57 | 2.23 |
| V304 | Document errors (R) | 0.88 | 53 | 15.14 | 0.95 |
| V305 | Cost per ton (C) | 3.19 | 34.33 | 0 | 3.19 |
| V306 | Inventory carry cost (C) | 7280000 | 51.15 | 1.26 | 7165957 |
| V307 | Infrastucture cost (C) | 2780000000 | 74.7 | 53.33 | 1339403162 |
| V308 | Labour (C) | 46000000 | 50.91 | 0 | 46000003 |
| V309 | Communication (C) | 3649000 | 36.02 | 0 | 3649000 |
| U301 | Port throughput (S) | 0.98 | 55.58 | 0 | 0.98 |
| U302 | Goods handling efficiency (S) | 0.78 | 41.84 | 7.34 | 0.81 |

**Table 8.18:** Summary of processed slacks results for port node 3

| DMU3 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V301 | Utilisation (R) | 0.99 | 25.44 | 0 | 0.99 |
| V302 | Idle time (R) | 0.79 | 38.94 | 0 | 0.79 |
| V303 | Communication (R) | 8 | 81.68 | 32.92 | 4.66 |
| V304 | Document errors (R) | 0.99 | 27.62 | 4.59 | 1.00 |
| V305 | Cost per ton (C) | 4.11 | 53.07 | 15.27 | 3.36 |
| V306 | Inventory carry cost (C) | 9200000 | 72.45 | 4.93 | 8755800 |
| V307 | Infrastucture cost (C) | 2560000000 | 66.55 | 38.38 | 1523050613 |
| V308 | Labour (C) | 65000000 | 75.66 | 6.65 | 59894645 |
| V309 | Communication (C) | 6847000 | 79.34 | 20.82 | 5309994 |
| U301 | Port throughput (S) | 0.99 | 56.84 | 0 | 0.99 |
| U302 | Goods handling efficiency (S) | 0.9 | 69.93 | 0 | 0.9 |

**Table 8.19:** Summary of processed slacks results for port node 4

| DMU4 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V301 | Utilisation (R) | 1 | 24.12 | 0 | 1 |
| V302 | Idle time (R) | 0.89 | 22.27 | 0 | 0.89 |
| V303 | Communication (R) | 6 | 61.99 | 28.64 | 3.09 |
| V304 | Document errors (R) | 0.89 | 50.89 | 0.48 | 0.89 |
| V305 | Cost per ton (C) | 2.91 | 28.78 | 0 | 2.91 |
| V306 | Inventory carry cost (C) | 8000000 | 59.14 | 0 | 8000000 |
| V307 | Infrastucture cost (C) | 1700000000 | 34.72 | 3.8 | 1597282168 |
| V308 | Labour (C) | 48000000 | 53.52 | 16.95 | 34988941 |
| V309 | Communication (C) | 4920000 | 53.23 | 11.15 | 4096663 |
| U301 | Port throughput (S) | 0.86 | 31.86 | 0 | 0.86 |
| U302 | Goods handling efficiency (S) | 0.73 | 32.48 | 3.88 | 0.75 |

**Table 8.20:** Summary of processed slacks results for port node 5

| DMU5 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V301 | Utilisation (R) | 0.91 | 35.34 | 1.3 | 0.92 |
| V302 | Idle time (R) | 0.79 | 39.1 | 0 | 0.79 |
| V303 | Communication (R) | 4 | 42.29 | 17.02 | 2.27 |
| V304 | Document errors (R) | 0.96 | 36.13 | 0 | 0.96 |
| V305 | Cost per ton (C) | 3.58 | 42.19 | 9.21 | 3.12 |
| V306 | Inventory carry cost (C) | 10550000 | 87.42 | 28.91 | 7942986 |
| V307 | Infrastucture cost (C) | 2100000000 | 49.53 | 29.69 | 1297948910 |
| V308 | Labour (C) | 59500000 | 68.5 | 14.89 | 48070495 |
| V309 | Communication (C) | 3700000 | 36.71 | 0 | 3700000 |
| U301 | Port throughput (S) | 0.91 | 42.44 | 11.29 | 0.97 |
| U302 | Goods handling efficiency (S) | 0.82 | 50.94 | 0 | 0.82 |

**Table 8.21:** Summary of processed slacks results for port node 7

| DMU7 | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V301 | Utilisation (R) | 0.86 | 42.62 | 13.95 | 0.96 |
| V302 | Idle time (R) | 0.79 | 39.35 | 0 | 0.79 |
| V303 | Communication (R) | 3 | 32.45 | 15.5 | 1.43 |
| V304 | Document errors (R) | 0.98 | 29.8 | 10.13 | 1.00 |
| V305 | Cost per ton (C) | 4.91 | 69.26 | 0 | 4.91 |
| V306 | Inventory carry cost (C) | 7280000 | 51.15 | 0.22 | 7259745 |
| V307 | Infrastucture cost (C) | 1380000000 | 22.87 | 16.57 | 932318134 |
| V308 | Labour (C) | 42000000 | 45.7 | 3.49 | 39317233 |
| V309 | Communication (C) | 4715000 | 50.46 | 3.05 | 4490130 |
| U301 | Port throughput (S) | 0.99 | 56.84 | 14.71 | 1.00 |
| U302 | Goods handling efficiency (S) | 0.81 | 49.33 | 0 | 0.81 |

**Table 8.22:** Summary of processed slacks results for port node 9

| **DMU9** | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Measurement** | **Measured** | | **Slacks** | **Required** |
| | | **Actual** | **Virtual** | **Virtual** | **Actual** |
| V301 | Utilisation (R) | 0.74 | 58.57 | 14.48 | 0.85 |
| V302 | Idle time (R) | 0.64 | 63.2 | 0 | 0.64 |
| V303 | Communication (R) | 3 | 32.45 | 27.08 | 0.25 |
| V304 | Document errors (R) | 0.89 | 51.35 | 8.28 | 0.92 |
| V305 | Cost per ton (C) | 2.17 | 13.77 | 12.43 | 1.56 |
| V306 | Inventory carry cost (C) | 6266500 | 39.91 | 0 | 6266500 |
| V307 | Infrastucture cost (C) | 2638000000 | 69.44 | 23.4 | 2005808447 |
| V308 | Labour (C) | 55250000 | 62.96 | 4.24 | 51994672 |
| V309 | Communication (C) | 4516000 | 47.76 | 9.33 | 3827093 |
| U301 | Port throughput (S) | 0.93 | 45.88 | 1.06 | 0.94 |
| U302 | Goods handling efficiency (S) | 0.94 | 78.52 | 1.48 | 0.94 |

Although the separation of supply chain activities among different companies enables specialization and economies of scale (Trkman, Stemberger & Jaklic, 2005); when a supply chain consists of more than one organisation the firms often tend to optimise their own performance, disregarding the effect on the entire supply chain. The problem involved becomes more complicated when the participants in the supply chain pursue individual profits or objectives that differ from the overall objective of the supply chain. The Sishen-Saldanha iron ore supply chain consists of links and nodes that are provided by the private sector, while the others are provided by the public sector. 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. Link providers need to take the efficiency of the entire chain into account rather than that of individual activities. This is supported by the results obtained from the composite supply chain efficiency model.

Table 8.23 shows a representation of the overall efficiency of the Sishen-Saldanha supply chain for the six years of actual data collected. DMU1 and DMU3 operated efficiently across the entire supply chain. The rail operator also operated efficiently as an individual link for DMU1 and DMU3. However, even though the rail operator operated efficiently as an individual link in DMU4 and DMU6 the entire supply chain was inefficient. In addition, the port node was efficient as an individual node in DMU6, but the entire supply chain did not operate at maximum efficiency.

**Table 8.23:** Overall efficiency analysis

| Overall | Efficiency |
|---|---|
| DMU1 | 100% |
| DMU2 | 97.96% |
| DMU3 | 100.00% |
| DMU4 | 92.10% |
| DMU5 | 94.35% |
| DMU6 | 94.88% |

## 8.11 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 on the subject 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.

## 8.12 Conclusion

This chapter serves to test the functioning of the composite supply chain efficiency model. It provides a case study of the Sishen-Saldanha iron ore supply chain. Historical data was collected for the mine, rail operator and port node through questionnaires. Due to insufficient data obtained to test the functioning of the composite supply chain efficiency model, additional data was generated by using the multivariate normal distribution. Given the means and covariance matrix, R 2.9.2 (2009) was used to statistically generate more data following the same multivariate normal distribution. The mean of each attribute is needed to ensure that the newly generated data have similar means, and the covariance matrix ensures that the correlation between attributes is taken into consideration in the generation of new data.

Before R 2.9.2 (2009) could be used to generate additional data, it was important to prove that the original data did in fact follow a multivariate normal distribution. All the data was tested and three problem variables were identified, i.e. imbalances in cargo flows, percentage defective goods and percentage of goods damaged. Due to the nature of the commodity and the characteristics of the supply chain under investigation it was decided to remove all three variables from the evaluation. After the three variables had been removed, all the remaining data met the requirements to be considered to follow a multivariate normal distribution (A strength of the composite supply chain efficiency model is that the user is able to include or remove variables as necessary with minimal effort. The inclusion or exclusion of a variable has no impact on the robustness of the composite supply chain efficiency model). The generic nature of the composite supply chain efficiency model means that it can be used to measure supply chain efficiency across various different types of supply chains. In addition, the composite supply chain efficiency model 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.

The composite supply chain efficiency model's reliability was proven through test-retest reliability and alternative-form reliability and its validity was proven through content validity and concurrent validity. The example provided shows that the model developed in this dissertation can be used to measure the efficiency across an entire supply chain. The composite supply chain efficiency model can also pinpoint areas of weakness along the supply chain.

# CHAPTER 9

# Conclusions and Recommendations

## 9.1 Conclusions

Private enterprises and public corporations face an increasingly challenging market position, with a growing field of competitors, higher customer expectations and complex supplier relationships. As competition and complexity has increased, supply chain management has emerged as an increasingly important issue for the parties concerned. The challenge of supply chain management is to identify and implement strategies that minimise the costs while maximising flexibility in an increasingly competitive and complex market.

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. The composite supply chain efficiency model developed in this dissertation can be used to evaluate both domestic and international supply chains and in so doing can provide entire South African supply chains with the information necessary to identify bottlenecks as well as make recommendations of ways to improve their shortcomings.

Secondly, a literature review was conducted on all the relevant research. The literature review served as a starting point for identifying areas of weakness in supply chains both in South Africa and throughout the rest of the world. It also investigated traditional and innovative methods and models that are currently being used by firms to measure supply chain performance and efficiency. Each method or model was analysed and the strengths and weaknesses were identified. Once the strengths of the various methods and models were known, they were listed as possible functions to be included in the composite supply chain efficiency model. Special care was taken to avoid incorporating any of the weaknesses.

Thirdly, in order to validate information obtained through the literature review, interviews were conducted with experts in the field. Twelve bottlenecks experienced by South African supply chains were identified as variables to be included in the composite supply chain efficiency model and formulas were chosen to measure their effect on the efficiency of a supply chain. The composite supply chain efficiency model measures the overall efficiency of a South African supply chain based on three criteria, namely, reliability efficiency, cost efficiency and speed efficiency.

Although firms have certain goals that they set out to achieve, they are not always aware of whether they have been successful in their endeavours or not. A point of departure for determining the true success of a firm is to evaluate its performance against functions that are essential to its efficiency. In order for efficiency measures to be incorporated in firms they must be user friendly, i.e. easily understood by the people who are working with them, they must provide meaningful results and they must be affordable.

Collaboration along a supply chain has been shown to be an imperative to overall efficiency. Open communication, coordination and functional integration across all links and nodes in the supply chain need to be planned to function with the aim of maximising the efficiency of the overall supply chain. They orchestrate to supply a product efficiently to customers. Supply chains compete with one another, and supply chain members complement one another. Therefore comparisons must be made in terms of product versus product and not firm versus firm. The composite supply chain efficiency model can be used to achieve this.

Fourth, for the purpose of this study a supply chain was divided into five main categories of links or nodes, i.e. sources/suppliers, points of production, transport nodes, points of storage and/or transhipment and markets/customers, and formulas were identified to measure the performance of the various links or nodes. By dividing a supply chain into five links or nodes it makes it easier to develop a generic model for measuring efficiency across an entire supply chain. A firm wanting to use the composite supply chain efficiency model will need to determine which of the links or nodes it is classified as and then select the formulas relevant to that link or node to determine the data required to evaluate its efficiency. Once the necessary data has been identified and included in the composite supply chain efficiency model, the firm will get the desired results. Similarly, a supply chain can benefit from the generic nature of the composite supply chain efficiency model by selecting the specific combination of links or nodes that represent its design and entering the necessary data in order to be evaluated.

South African supply chains can be made up of both public and private enterprises. This complicates the focus of the overall supply chain as public and private enterprises have different objectives. Transnet is responsible for ensuring that the rail, port and pipeline operations in South Africa perform to world-class standards. However, because it is a State-owned company, Transnet finds itself wrestling with social and economic issues, i.e. maximising efficiency through necessary job cuts in the face of union opposition. The description of the variables included in the composite supply chain efficiency model allows firms to choose those variables which are most important to their needs and in so doing allows firms to evaluate their own performance based on factors that are relevant to their specific circumstances. In order for the model to provide optimal results, the firms along the supply chain must be prepared to share information with one another.

Finally, after the relevant links or nodes have been identified for the specific supply chain under investigation as well as the subsequent formulas required to evaluate each of the links or nodes in the supply chain, DEA is applied to the formulas. DEA determines the optimal supply chain in terms of efficiency, so that each link or node could be benchmarked against the optimal solution. DEA not only provides a measure of efficiency for the overall supply chain, but it pinpoints the bottlenecks either in individual firms or along the supply chain as a whole and in so doing helps to focus efforts to improve the overall efficiency of a supply chain. All the steps taken in measuring the overall efficiency of a South African supply chain form part of the composite supply chain efficiency model developed in this dissertation.

## 9.2 Overview of Contributions

The composite supply chain efficiency model adds value for a number of reasons. Firstly, it was developed based on the strengths of other methods and models that are already used by firms throughout the world to measure supply chain efficiency. However, it excludes many of the weaknesses incurred by the other methods and models. For example, a large number of methods or models currently in use only have the ability to measure supply chain performance in terms of costs, while the composite supply chain efficiency model can measure efficiency across the entire supply chain. Another weakness that is overcome by the composite supply chain efficiency model is the fact that certain models in use try to improve efficiency levels without identifying the cause of the inefficiency. The composite supply chain efficiency model identifies the bottlenecks in the supply chain and therefore makes it easier for firms to make the necessary improvements. When compared to the Balanced Scorecard method the composite supply chain efficiency model has two main advantages. Firstly, the Balanced Scorecard method does not take a firm's competitors into account, while the composite supply chain efficiency model does and secondly, when a firm uses the Balanced Scorecard method, the firm selects its own goals and then chooses the measurements used to determine its performance. This can lead to a biased view of how the firm is performing. The composite supply chain efficiency model uses the same criteria for measuring supply chain efficiency for all firms and therefore excludes the possibility of obtaining biased results. DEA, the mathematical technique used for the later stages of the composite supply chain efficiency model, does not require assigned numeric weights or modelling preferences for analysis. DEA automatically assigns the weights that gives the highest possible efficiency score to a DMU, while keeping the efficiency scores of all DMUs less than or equal to one under the same set of weights. This helps prevent discrimination of criteria based on the analysts' individual perspectives. This is an advantage over any method that requires the analyst to select the order of importance of all the variables used to measure a firm's performance.

Secondly, the composite supply chain efficiency model was specifically developed for the South African market, i.e. it includes the factors identified by industry experts that are the main causes of inefficiency along South African supply chains. Thirdly, the composite supply chain efficiency model is simple to use and does not require either an advanced degree in mathematics or an extended training period for employees before it can be implemented by a firm (this is an advantage over the SCOR model, which is currently used as the cross-industry standard for measuring supply chain performance both internationally and in South Africa). Once the data has been collected by a firm or supply chain the computer program developed by Gerber (2009) can be used to obtain results at the click of a button.

Fourth, it is an inexpensive model and therefore can be utilized by small firms with a limited budget (this is another advantage over the SCOR model). Fifth, its generic nature means that it can be used to measure supply chain efficiency across various different types of supply chains. Sixth, 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.

The composite supply chain efficiency model is a simple, systematic and inexpensive model that 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.

## 9.3 Recommendations

South African firms need to recognise the importance of evaluating their performance and determining their efficiency levels. Without acknowledgement of this fact, South African firms are going to continue to miss the opportunity of gathering important information about their operations and learning from their mistakes.

South African firms need to become more vertically integrated along a supply chain. This is complicated by the fact that South African supply chains are made up by both public and private enterprises; each of which strive for different objectives. Private firms strive to maximise profit, while public firms take social costs into account as well. For South African supply chains to be competitive internationally all firms along a supply chain will have to agree on and strive towards the same objectives.

## 9.4 Future Work

Although DEA has a number of advantages, it does have some limitations. Firstly, standard DEA models do not take stochastic variation in the data into account. They assume that any deviation to the best practice frontier is due to inefficiency. Secondly, DEA assumes that it is possible to fully characterise goods or services by identifying a set of inputs and outputs for the goods or services. However, some of the outputs of some companies are not easily quantifiable. In addition, there are a number of factors which influence this transformation and which may affect the linear input-output relationship (Ferreira, Santos & Rodrigues, 2009).

Future research to improve the composite supply chain efficiency model could investigate possible methods to take stochastic variations in data into account. One such method is Analytic Hierarchy Process (AHP).

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# APPENDIX A

## Questionnaire

The information collected in this survey will be used as part of a measurement tool to determine the level of efficiency throughout the entire supply chain. The aim of this survey is to collect accurate, relevant information to use to the benefit of all members and customers of the supply chain. The information provided herein will be treated as STRICTLY CONFIDENTIAL.

I thank you in advance for your time and cooperation in completing this questionnaire. I can assure you that the information will be used constructively to advise all the role players along the supply chain.

Should you require clarification of any part of this questionnaire, please do not hesitate to contact me at the following contact details:

Phone: 021 808 2252
Fax: 021 808 3406
Email: leila@sun.ac.za

Thank You
Leila Gerber

## PART A - CONTACT INFORMATION

| | | | |
|---|---|---|---|
| PLEASE PROVIDE THE FOLLOWING INFORMATION: | | | |
| Name: | | Tile: | Designation: |
| Telephone number: | Fax number: | Cell phone number: | E-mail address: |
| Organisation name: | Postal address: | | |
| Nature of business: | | | Date: |

(1) Please rank the following service attributes in the order of importance that YOU perceive them to be important to the customer (if you are a customer, please rank them in the order of importance to YOU) from 1 to 17, with 1 = most important and 17 = least important attribute.

(2) Please rate the current service attributes of the (mine), (Transnet Freight Rail), (Road Operator(s)), (Storage facility), (port) out of 10, with 10 = excellent service, 5 = average, and 1 = very poor.

(3) Add any additional comments.

## PART B - SERVICE ATTRIBUTES

| No. | Service attribute | (1) YOUR perceived importance of the service attribute to the customer Ranking (1-17) | (2) YOUR Rating of how the link or node is doing in this attribute on a scale of 1 to 10 | (3) Comment |
|---|---|---|---|---|
| 1 | Idle time | | | |
| 2 | Availability of adequacy of infrastructure | | | |
| 3 | Transport productivity | | | |
| 4 | Goods handling | | | |
| 5 | Throughput | | | |
| 6 | Turnaround time | | | |
| 7 | Utilisation | | | |
| 8 | Interface problems and time sensitivities | | | |
| 9 | Understanding customer requirements | | | |
| 10 | Capability of staff | | | |

| No. | Service attribute | YOUR perceived importance of the service attribute to the customer Ranking (1-17) | YOUR Rating of how the link or node is doing in this attribute on a scale of 1 to 10 | Comment |
|---|---|---|---|---|
| 12 | Communication | | | |
| 13 | Imbalances in goods flows | | | |
| 14 | Documentation | | | |
| 15 | Reliability / Consistency of service | | | |
| 16 | Tariffs | | | |
| 17 | Speed / responsiveness | | | |
| 18 | OTHER attributes that may be of importance to you, please specify | | | |

# APPENDIX B

## Questionnaire

The information collected in this survey will be used as part of a measurement tool to determine the level of efficiency throughout the entire supply chain. The aim of this survey is to collect accurate, relevant information to use to the benefit of all members and customers of the supply chain. The information provided herein will be treated as STRICTLY CONFIDENTIAL.

I thank you in advance for your time and cooperation in completing this questionnaire. I can assure you that the information will be used constructively to advise all the role players along the supply chain.

Should you require clarification of any part of this questionnaire, please do not hesitate to contact me at the following contact details:

Phone: 021 808 2252
Fax: 021 808 3406
Email: leila@sun.ac.za

Thank You
Leila Gerber

## PART A - CONTACT INFORMATION

|  |  |  |  |
|---|---|---|---|
| PLEASE PROVIDE THE FOLLOWING INFORMATION: |  |  |  |
| Name: |  | Tile: | Designation: |
| Telephone number: | Fax number: | Cell phone number: | E-mail address: |
| Organisation name: | Postal address: |  |  |
| Nature of business: |  |  | Date: |

## PART B - MINE NODE

Complete all the sections. Participants are urged to give clear, consistent and objective answers.

### RELIABILITY EFFICIENCY

| Data Required | Answers |
|---|---|
| Maximum delivery time at the mine: | |
| Minimum delivery time at the mine: | |
| Number of orders delivered in full: | |
| Total quantity of commodity supplied: | |
| Number of defectives in commodity supplied: | |
| Idle time (% of time employees and equipment are available for work, but are not required to work: | |
| Actual throughput of commodity (time): | |
| Optimal throughput of commodity (time): | |
| Number of documents with errors: | |
| Total document flow: | |
| Hours that a system is available in a period: | |
| Total hours in that period: | |
| Delays incurred in the employment of mining equipment: | |
| Total time mining equipment employed: | |

## COST EFFICIENCY

| Data Required | Answers |
|---|---|
| Price charged by supplier per ton of commodity: | |
| Goods handling costs per ton of commodity: | |
| Actual throughput of commodity (rands/ton): | |
| Optimal throughput of commodity (rands/ton): | |
| Labour costs incurred through workers remuneration: | |
| Communication cost as a percentage of revenue: | |
| Total cost of commodity mined (operating cost): | |
| Infrastructure cost (investment costs both the costs of current infrastructure and the cost of additional infrastructure if possible): | |
| Total tons of commodity mined: | |
| Total cost of defectives shipped from mine: | |
| Total cost of commodity shipped from mine: | |

**SPEED EFFICIENCY**

| Data Required | Answers |
|---|---|
| Throughput time: | |
| Idle time (% of time employees and equipment are available for work, but are not required to work): | |
| Order processing time: | |
| Goods handling time: | |
| Total extraction time: | |
| Actual throughput of commodity (time): | |
| Optimal throughput of commodity (time): | |

## PART B - RAIL LINK

Complete all the sections. Participants are urged to give clear, consistent and objective answers.

### RELIABILITY EFFICIENCY

| Data Required | Answers |
|---|---|
| Maximum transit time: | |
| Minimum transit time: | |
| Number of perfect shipments: | |
| Total number of shipments: | |
| Delays incurred in the transport means that were employed: | |
| Total time transport means were employed: | |
| Idle time (% of time employees and equipment are available for work, but are not required to work): | |
| Actual throughput of commodity (time): | |
| Optimal throughput of commodity (time): | |
| Number of documents with errors: | |
| Total document flow: | |

### COST EFFICIENCY

| Data Required | Answers |
|---|---|
| Total transport cost: | |
| Number of tons of commodity transported: | |
| Goods handling costs (operating): | |
| Infrastructure cost (investment costs both the costs of current infrastructure and the cost of additional infrastructure if possible): | |
| Cost of commodity handled during transport: | |
| Total cost of commodity moved: | |
| Ton kilometres utilized: | |
| Ton kilometres available: | |
| Actual throughput of commodity (rands/ton): | |
| Optimal throughput of commodity (rands/ton): | |
| Labour costs incurred through workers remuneration: | |
| Communication cost as a percentage of revenue: | |

## SPEED EFFICIENCY

| Data Required | Answers |
|---|---|
| Total transit time: | |
| Idle time (% of time employees and equipment are available for work, but are not required to work): | |
| Goods handling time: | |
| Actual throughput of commodity (time): | |
| Optimal throughput of commodity (time): | |

## PART B - PORT NODE

Complete all the sections. Participants are urged to give clear, consistent and objective answers.

### RELIABILITY EFFICIENCY

| Data Required | Answers |
|---|---|
| Number of goods damaged in storage at the port: | |
| Total number of goods stored at the port: | |
| Delays incurred in the employment of the stockpile equipment: | |
| Total time stockpile equipment was employed: | |
| Idle time (% of time employees and equipment are available for work, but are not required to work): | |
| Actual throughput of commodity (time): | |
| Optimal throughput of commodity (time): | |
| Number of documents with errors: | |
| Total document flow: | |

## COST EFFICIENCY

| Data Required | Answers |
|---|---|
| Total operating cost in the port: | |
| Number of tons handled in the port : | |
| Inventory carrying costs (operating costs): | |
| Infrastructure cost (investment costs both the costs of current infrastructure and the cost of additional infrastructure if possible): | |
| Goods handling costs: | |
| Total cost of goods damaged while stored in the port : | |
| Total cost of goods stored in the port: | |
| Actual throughput of commodity (rands/ton): | |
| Optimal throughput of commodity (rands/ton): | |
| Labour costs incurred through workers remuneration: | |
| Communication cost as a percentage of revenue: | |

### SPEED EFFICIENCY

| Data Required | Answers |
|---|---|
| Vessel loading time: | |
| Stockpile throughput (time): | |
| Port throughput (time): | |
| Idle time (% of time employees and equipment are available for work, but are not required to work): | |
| Goods handling time: | |
| Average ship carrying capacity: | |
| Average time to fill one ship: | |

# APPENDIX C

## Mine Nodes Virtual Data

| DMU1 | DMU2 | DMU3 | DMU4 | DMU5 | DMU6 | DMU7 | DMU8 | DMU9 | DMU10 |
|---|---|---|---|---|---|---|---|---|---|
| 31.565 | 41.161 | 66.111 | 29.627 | 59.899 | 80.063 | 53.088 | 58.554 | 86.613 | 42.623 |
| 23.129 | 65.028 | 62.933 | 33.508 | 59.913 | 42.603 | 78.147 | 48.671 | 55.349 | 60.593 |
| 32.135 | 43.336 | 61.259 | 23.544 | 65.973 | 67.095 | 59.196 | 61.468 | 83.801 | 47.493 |
| 75.645 | 53.143 | 44.143 | 80.145 | 44.143 | 71.144 | 37.207 | 45.673 | 46.061 | 51.138 |
| 29.619 | 68.444 | 55.503 | 29.915 | 69.791 | 55.203 | 81.231 | 50.540 | 66.607 | 63.814 |
| 73.845 | 53.203 | 43.111 | 78.432 | 55.496 | 77.515 | 44.310 | 47.913 | 58.018 | 57.642 |
| 64.737 | 48.072 | 26.408 | 63.070 | 73.069 | 35.851 | 59.356 | 49.641 | 50.412 | 72.270 |
| 47.742 | 32.243 | 78.739 | 41.542 | 52.908 | 58.074 | 42.240 | 75.940 | 75.813 | 40.124 |
| 59.575 | 46.601 | 33.628 | 66.061 | 77.478 | 43.099 | 63.443 | 51.134 | 59.557 | 75.503 |
| 71.972 | 49.087 | 33.068 | 74.284 | 31.712 | 48.846 | 29.279 | 37.056 | 24.943 | 43.991 |
| 52.410 | 52.381 | 52.362 | 52.396 | 52.387 | 52.364 | 47.690 | 60.609 | 34.768 | 35.107 |
| 76.550 | 59.826 | 44.622 | 78.086 | 46.512 | 77.418 | 41.684 | 45.918 | 49.080 | 52.616 |

| DMU11 | DMU12 | DMU13 | DMU14 | DMU15 | DMU16 | DMU17 | DMU18 | DMU19 | DMU20 |
|---|---|---|---|---|---|---|---|---|---|
| 43.883 | 72.831 | 48.226 | 51.523 | 49.337 | 6.569 | 27.728 | 44.822 | 20.671 | 66.690 |
| 60.567 | 60.418 | 36.737 | 74.535 | 45.808 | 11.839 | 39.811 | 47.541 | 54.450 | 38.300 |
| 53.921 | 63.387 | 52.699 | 52.981 | 40.786 | 7.564 | 32.112 | 41.882 | 32.461 | 60.796 |
| 47.349 | 51.488 | 69.343 | 43.978 | 65.252 | 86.555 | 66.008 | 63.197 | 46.945 | 66.583 |
| 71.834 | 55.889 | 60.515 | 73.998 | 38.588 | 8.022 | 41.717 | 47.901 | 52.156 | 48.326 |
| 58.159 | 52.110 | 80.319 | 46.930 | 60.612 | 81.413 | 70.503 | 62.155 | 44.050 | 73.559 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 85.192 | 23.996 | 83.787 | 47.060 | 32.540 | 82.731 | 86.309 | 47.342 | 66.444 | 55.304 |
| 34.139 | 75.104 | 26.599 | 43.443 | 63.669 | 43.638 | 39.536 | 49.756 | 43.566 | 60.891 |
| 86.001 | 33.404 | 80.464 | 51.139 | 36.940 | 78.375 | 87.604 | 48.502 | 60.102 | 60.743 |
| 40.187 | 35.878 | 58.496 | 36.361 | 56.400 | 88.263 | 61.356 | 56.004 | 51.919 | 49.571 |
| 60.061 | 38.088 | 50.400 | 33.702 | 65.693 | 70.319 | 50.013 | 54.366 | 52.959 | 77.233 |
| 50.684 | 53.145 | 76.449 | 48.502 | 65.162 | 80.551 | 63.545 | 65.495 | 47.743 | 68.812 |

| DMU21 | DMU22 | DMU23 | DMU24 | DMU25 | DMU26 | DMU27 | DMU28 | DMU29 | DMU30 |
|---|---|---|---|---|---|---|---|---|---|
| 97.005 | 69.329 | 61.215 | 40.490 | 57.137 | 76.371 | 88.338 | 32.168 | 55.462 | 62.517 |
| 72.855 | 57.212 | 57.297 | 20.306 | 38.046 | 78.791 | 56.079 | 40.704 | 67.179 | 23.922 |
| 82.424 | 64.182 | 61.444 | 37.230 | 58.838 | 86.638 | 76.575 | 29.765 | 52.504 | 50.168 |
| 44.983 | 52.035 | 48.286 | 76.702 | 61.678 | 17.163 | 59.696 | 75.252 | 50.585 | 84.099 |
| 71.382 | 59.880 | 60.542 | 24.641 | 53.862 | 83.060 | 67.502 | 44.092 | 67.770 | 32.003 |
| 48.489 | 55.230 | 53.195 | 75.059 | 67.627 | 28.596 | 67.729 | 77.223 | 48.990 | 90.758 |
| 5.269 | 36.036 | 50.938 | 58.248 | 61.048 | 57.069 | 30.454 | 69.485 | 28.646 | 60.951 |
| 81.768 | 65.893 | 62.364 | 59.915 | 51.666 | 79.617 | 61.881 | 30.417 | 47.750 | 58.609 |
| 19.162 | 42.008 | 55.500 | 56.316 | 58.942 | 63.737 | 39.884 | 70.850 | 30.017 | 69.403 |
| 21.913 | 37.682 | 36.764 | 69.533 | 50.781 | 4.744 | 36.576 | 68.384 | 42.850 | 64.226 |
| 28.956 | 60.744 | 43.427 | 40.645 | 69.042 | 71.116 | 53.428 | 62.132 | 30.717 | 57.317 |
| 50.262 | 55.519 | 50.369 | 76.017 | 66.934 | 18.793 | 66.858 | 76.570 | 57.461 | 83.397 |

| DMU31 | DMU32 | DMU33 | DMU34 | DMU35 | DMU36 | DMU37 | DMU38 | DMU39 | DMU40 |
|---|---|---|---|---|---|---|---|---|---|
| 53.980 | 48.187 | 49.814 | 81.639 | 49.362 | 35.057 | 10.072 | 49.230 | 64.896 | 57.700 |
| 33.888 | 30.821 | 42.198 | 49.870 | 51.050 | 53.403 | 43.174 | 64.843 | 51.802 | 77.820 |
| 47.139 | 41.776 | 49.404 | 78.673 | 42.323 | 38.617 | 14.621 | 55.515 | 57.997 | 65.791 |
| 75.689 | 74.713 | 55.069 | 54.175 | 64.607 | 57.083 | 67.789 | 48.285 | 64.502 | 28.327 |
| 41.916 | 34.170 | 37.687 | 65.501 | 47.898 | 52.909 | 35.838 | 76.446 | 61.371 | 76.594 |
| 80.748 | 74.939 | 56.307 | 67.333 | 63.166 | 60.693 | 65.942 | 55.428 | 69.603 | 35.698 |
| 61.092 | 52.818 | 56.908 | 58.740 | 40.239 | 72.376 | 81.486 | 64.479 | 44.330 | 59.720 |
| 49.137 | 56.263 | 75.049 | 63.834 | 52.135 | 41.728 | 32.467 | 32.366 | 46.108 | 61.543 |
| 65.590 | 54.917 | 61.683 | 66.450 | 44.848 | 75.027 | 81.054 | 63.747 | 48.896 | 65.633 |
| 61.229 | 64.001 | 46.292 | 33.070 | 54.935 | 51.829 | 69.659 | 40.967 | 49.051 | 20.136 |
| 49.219 | 71.113 | 65.568 | 45.671 | 52.225 | 52.870 | 59.198 | 79.169 | 50.444 | 46.074 |
| 77.174 | 75.144 | 51.114 | 58.332 | 66.305 | 56.548 | 63.892 | 55.406 | 70.714 | 29.255 |

| DMU41 | DMU42 | DMU43 | DMU44 | DMU45 | DMU46 | DMU47 | DMU48 | DMU49 | DMU50 |
|---|---|---|---|---|---|---|---|---|---|
| 27.585 | 52.702 | 51.588 | 78.484 | 82.305 | 11.654 | 47.234 | 73.580 | 88.470 | 57.434 |
| 32.412 | 48.480 | 44.092 | 36.474 | 52.564 | 6.007 | 63.699 | 69.192 | 57.736 | 85.198 |
| 20.373 | 50.880 | 52.138 | 60.658 | 71.187 | 13.711 | 53.955 | 67.879 | 84.581 | 73.305 |
| 83.468 | 61.409 | 64.415 | 82.761 | 66.090 | 92.661 | 40.881 | 44.046 | 49.132 | 18.370 |
| 30.581 | 52.886 | 57.569 | 50.636 | 69.801 | 13.947 | 65.412 | 67.179 | 76.733 | 93.615 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 78.376 | 67.949 | 71.060 | 86.582 | 72.482 | 93.874 | 42.244 | 47.198 | 57.309 | 27.499 |
| 52.252 | 65.337 | 65.699 | 27.681 | 28.910 | 98.173 | 51.456 | 29.249 | 31.053 | 62.764 |
| 35.965 | 50.245 | 39.727 | 50.074 | 47.185 | 31.840 | 54.087 | 69.373 | 61.708 | 50.409 |
| 51.689 | 71.082 | 65.746 | 33.727 | 33.277 | 93.123 | 50.366 | 38.218 | 33.426 | 62.110 |
| 78.838 | 48.970 | 53.568 | 60.378 | 45.487 | 90.514 | 37.104 | 28.985 | 30.112 | 13.672 |
| 73.384 | 78.194 | 69.063 | 49.735 | 53.339 | 69.895 | 35.726 | 71.906 | 63.344 | 35.944 |
| 84.436 | 62.011 | 69.477 | 91.081 | 77.192 | 89.248 | 44.388 | 47.170 | 59.981 | 24.766 |

| DMU51 | DMU52 | DMU53 | DMU54 | DMU55 | DMU56 | DMU57 | DMU58 | DMU59 | DMU60 |
|---|---|---|---|---|---|---|---|---|---|
| 35.291 | 85.310 | 56.978 | 35.974 | 9.376 | 77.769 | 84.460 | 58.379 | 26.022 | 36.205 |
| 28.363 | 59.442 | 55.910 | 56.877 | 0.000 | 69.830 | 54.458 | 41.721 | 26.158 | 36.374 |
| 24.239 | 74.975 | 47.224 | 41.116 | 8.120 | 71.980 | 71.158 | 44.951 | 35.016 | 40.228 |
| 88.265 | 58.085 | 63.195 | 57.231 | 93.294 | 38.803 | 64.328 | 83.055 | 68.766 | 75.592 |
| 27.022 | 71.971 | 51.016 | 64.664 | 0.000 | 65.384 | 65.825 | 52.977 | 40.765 | 55.321 |
| 85.822 | 64.808 | 63.832 | 60.397 | 84.793 | 39.199 | 69.715 | 84.391 | 70.024 | 87.925 |
| 54.564 | 27.266 | 38.529 | 65.874 | 71.128 | 17.290 | 24.393 | 36.641 | 79.253 | 100.000 |
| 40.713 | 55.915 | 55.661 | 27.431 | 48.708 | 81.304 | 56.264 | 31.492 | 36.102 | 16.615 |
| 58.019 | 34.271 | 47.463 | 63.299 | 62.698 | 25.295 | 31.937 | 39.270 | 68.880 | 100.000 |
| 78.777 | 37.164 | 49.768 | 53.487 | 95.333 | 24.610 | 42.696 | 67.625 | 68.751 | 65.365 |
| 63.844 | 48.414 | 100.000 | 57.767 | 40.417 | 85.724 | 65.277 | 63.502 | 64.640 | 31.377 |
| 87.773 | 67.229 | 64.053 | 62.800 | 89.353 | 41.893 | 72.936 | 91.629 | 72.463 | 79.103 |

| DMU61 | DMU62 | DMU63 | DMU64 | DMU65 | DMU66 | DMU67 | DMU68 | DMU69 | DMU70 |
|---|---|---|---|---|---|---|---|---|---|
| 52.141 | 57.885 | 92.998 | 33.220 | 57.821 | 69.546 | 66.744 | 60.019 | 35.707 | 44.798 |
| 65.165 | 31.284 | 82.450 | 55.979 | 46.237 | 83.232 | 58.504 | 47.984 | 43.123 | 47.472 |
| 52.844 | 50.456 | 90.538 | 41.408 | 58.988 | 65.732 | 56.680 | 56.908 | 36.013 | 45.795 |
| 46.656 | 78.158 | 27.898 | 50.747 | 60.507 | 33.870 | 54.637 | 57.367 | 69.672 | 58.807 |
| 62.591 | 43.860 | 83.672 | 58.914 | 60.116 | 75.313 | 51.991 | 51.098 | 47.576 | 51.797 |
| 49.813 | 84.200 | 40.963 | 53.821 | 70.913 | 33.148 | 52.272 | 61.047 | 75.822 | 58.954 |
| 51.695 | 60.108 | 42.350 | 71.914 | 72.817 | 16.984 | 20.003 | 49.863 | 80.890 | 51.819 |
| 55.091 | 46.695 | 80.280 | 39.706 | 45.137 | 68.392 | 72.258 | 63.293 | 34.240 | 49.291 |
| 57.199 | 63.528 | 58.237 | 70.328 | 76.073 | 24.786 | 27.719 | 54.597 | 84.493 | 50.337 |
| 37.903 | 62.318 | 5.744 | 48.610 | 46.683 | 23.045 | 41.393 | 44.843 | 61.070 | 52.958 |
| 77.231 | 62.783 | 54.584 | 62.346 | 80.139 | 41.856 | 48.873 | 38.475 | 32.118 | 50.199 |
| 47.775 | 81.522 | 29.568 | 52.454 | 63.982 | 38.104 | 56.470 | 58.646 | 69.322 | 62.257 |

| DMU71 | DMU72 | DMU73 | DMU74 | DMU75 | DMU76 | DMU77 | DMU78 | DMU79 | DMU80 |
|---|---|---|---|---|---|---|---|---|---|
| 25.941 | 54.587 | 41.007 | 72.811 | 48.112 | 44.603 | 4.983 | 55.468 | 54.378 | 45.635 |
| 39.994 | 41.604 | 42.722 | 56.942 | 41.224 | 100.000 | 39.772 | 50.299 | 58.207 | 39.169 |
| 22.058 | 66.281 | 35.904 | 68.562 | 40.279 | 63.382 | 15.735 | 52.336 | 47.475 | 43.622 |
| 70.541 | 46.398 | 70.224 | 53.825 | 74.444 | 0.000 | 59.814 | 52.408 | 53.111 | 78.123 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 31.260 | 56.175 | 42.778 | 66.179 | 42.443 | 86.384 | 33.238 | 43.317 | 45.777 | 58.277 |
| 61.756 | 60.274 | 67.700 | 61.131 | 78.063 | 0.000 | 54.947 | 53.052 | 50.437 | 85.895 |
| 42.637 | 94.541 | 46.312 | 44.975 | 60.238 | 46.941 | 79.664 | 46.610 | 33.219 | 72.466 |
| 49.069 | 62.148 | 45.602 | 57.819 | 45.872 | 72.207 | 40.816 | 75.829 | 72.124 | 18.557 |
| 40.977 | 95.867 | 46.964 | 51.008 | 67.224 | 47.910 | 73.219 | 53.669 | 41.795 | 71.346 |
| 69.990 | 35.736 | 63.359 | 37.140 | 61.285 | 3.807 | 67.244 | 42.002 | 43.200 | 66.492 |
| 39.153 | 55.358 | 35.458 | 49.892 | 48.745 | 16.223 | 30.233 | 55.181 | 55.242 | 39.592 |
| 70.080 | 45.392 | 72.579 | 59.043 | 74.238 | 0.000 | 56.229 | 49.368 | 50.855 | 85.812 |

| DMU81 | DMU82 | DMU83 | DMU84 | DMU85 | DMU86 | DMU87 | DMU88 | DMU89 | DMU90 |
|---|---|---|---|---|---|---|---|---|---|
| 75.244 | 79.527 | 38.537 | 3.512 | 4.461 | 44.695 | 34.132 | 84.384 | 68.159 | 57.262 |
| 63.819 | 48.624 | 48.810 | 28.598 | 20.441 | 71.482 | 23.381 | 48.527 | 59.573 | 35.929 |
| 78.707 | 71.135 | 38.478 | 3.255 | 9.835 | 46.872 | 32.011 | 82.384 | 70.049 | 52.928 |
| 42.118 | 57.800 | 55.234 | 80.682 | 80.956 | 44.739 | 75.198 | 52.960 | 46.767 | 67.316 |
| 79.795 | 55.109 | 39.759 | 20.715 | 19.790 | 65.075 | 23.153 | 64.954 | 71.288 | 42.145 |
| 54.519 | 64.455 | 52.436 | 68.944 | 80.226 | 48.439 | 73.969 | 69.559 | 55.602 | 72.329 |
| 58.703 | 39.890 | 51.533 | 56.762 | 96.793 | 59.296 | 66.050 | 69.020 | 54.995 | 59.628 |
| 54.506 | 72.696 | 64.361 | 33.513 | 32.644 | 48.352 | 58.534 | 67.346 | 55.127 | 60.755 |
| 62.782 | 48.680 | 54.486 | 49.279 | 92.936 | 66.394 | 66.112 | 79.086 | 58.355 | 64.146 |
| 26.174 | 37.945 | 51.013 | 86.918 | 82.891 | 37.607 | 69.185 | 29.690 | 33.043 | 53.499 |
| 34.539 | 70.623 | 53.429 | 44.914 | 27.219 | 65.344 | 66.978 | 53.110 | 32.359 | 51.987 |
| 48.916 | 60.367 | 52.197 | 79.684 | 75.725 | 44.357 | 71.918 | 55.201 | 52.261 | 67.516 |

| DMU91 | DMU92 | DMU93 | DMU94 | DMU95 | DMU96 | DMU97 | DMU98 | DMU99 | DMU100 |
|---|---|---|---|---|---|---|---|---|---|
| 36.413 | 38.620 | 45.285 | 62.535 | 24.555 | 33.761 | 44.696 | 25.455 | 50.394 | 36.215 |
| 62.001 | 6.889 | 30.049 | 36.570 | 43.199 | 48.667 | 36.917 | 13.067 | 40.898 | 45.509 |
| 46.447 | 24.811 | 46.205 | 55.920 | 34.697 | 36.854 | 40.400 | 25.547 | 44.344 | 30.044 |
| 45.864 | 98.266 | 71.569 | 73.379 | 59.872 | 57.765 | 66.579 | 85.414 | 65.444 | 73.094 |
| 68.401 | 8.081 | 42.816 | 53.514 | 53.279 | 46.766 | 31.933 | 20.575 | 36.491 | 45.623 |
| 49.629 | 93.790 | 78.447 | 76.200 | 61.171 | 57.571 | 67.419 | 87.100 | 66.472 | 67.378 |
| 68.670 | 51.408 | 77.913 | 41.733 | 76.020 | 62.805 | 59.945 | 84.986 | 53.185 | 37.470 |
| 35.609 | 55.867 | 44.975 | 44.095 | 29.594 | 48.263 | 65.543 | 42.581 | 65.665 | 35.730 |
| 65.383 | 52.712 | 77.856 | 39.993 | 67.740 | 62.849 | 65.925 | 82.162 | 60.104 | 35.522 |
| 44.100 | 87.450 | 61.149 | 59.672 | 61.076 | 54.589 | 56.808 | 80.065 | 54.031 | 68.623 |
| 62.951 | 62.386 | 60.526 | 44.214 | 48.738 | 65.390 | 70.890 | 64.463 | 31.630 | 45.853 |
| 50.363 | 96.207 | 72.985 | 82.263 | 64.199 | 57.451 | 62.249 | 83.083 | 62.484 | 78.182 |

# APPENDIX D

## Rail Nodes Virtual Data

| DMU1 | DMU2 | DMU3 | DMU4 | DMU5 | DMU6 | DMU7 | DMU8 | DMU9 | DMU10 |
|---|---|---|---|---|---|---|---|---|---|
| 42.930 | 72.761 | 28.015 | 72.757 | 36.958 | 66.178 | 27.762 | 41.797 | 63.649 | 58.612 |
| 32.695 | 34.126 | 61.317 | 63.521 | 30.192 | 39.072 | 70.172 | 47.246 | 22.190 | 54.091 |
| 27.923 | 23.318 | 60.618 | 58.960 | 29.693 | 29.069 | 56.029 | 34.500 | 11.599 | 58.249 |
| 75.909 | 42.263 | 27.844 | 71.103 | 51.876 | 32.650 | 61.490 | 32.650 | 39.320 | 33.422 |
| 46.701 | 21.786 | 59.159 | 55.007 | 55.007 | 25.938 | 59.159 | 25.938 | 13.923 | 52.254 |
| 39.549 | 50.710 | 61.871 | 39.549 | 28.388 | 54.170 | 68.010 | 19.459 | 49.656 | 44.560 |
| 59.126 | 30.971 | 76.019 | 36.514 | 63.525 | 31.543 | 74.303 | 49.008 | 33.447 | 49.736 |
| 46.172 | 22.683 | 56.741 | 57.377 | 51.796 | 25.497 | 57.916 | 53.046 | 16.534 | 52.326 |
| 47.364 | 46.118 | 46.066 | 46.098 | 47.261 | 46.341 | 47.645 | 47.888 | 47.536 | 45.297 |
| 42.385 | 66.305 | 55.432 | 51.083 | 27.163 | 75.003 | 48.909 | 31.512 | 66.774 | 52.180 |
| 43.111 | 26.812 | 59.409 | 26.677 | 71.833 | 46.381 | 64.286 | 66.510 | 34.720 | 33.215 |

| DMU11 | DMU12 | DMU13 | DMU14 | DMU15 | DMU16 | DMU17 | DMU18 | DMU19 | DMU20 |
|---|---|---|---|---|---|---|---|---|---|
| 42.493 | 59.219 | 46.241 | 41.250 | 34.980 | 16.405 | 42.093 | 12.271 | 58.547 | 66.457 |
| 47.341 | 18.607 | 44.160 | 58.168 | 47.780 | 40.107 | 42.884 | 20.828 | 55.107 | 58.861 |
| 42.912 | 9.484 | 36.723 | 57.423 | 46.361 | 39.495 | 31.015 | 17.377 | 43.766 | 51.571 |
| 67.809 | 48.908 | 55.236 | 51.345 | 66.108 | 39.366 | 26.219 | 67.279 | 43.739 | 100.000 |
| 55.949 | 23.586 | 43.588 | 64.766 | 62.063 | 54.725 | 27.287 | 51.249 | 41.563 | 60.739 |
| 54.577 | 47.024 | 26.564 | 70.043 | 30.630 | 31.750 | 53.210 | 21.117 | 76.559 | 53.427 |
| 64.224 | 42.573 | 50.870 | 67.853 | 67.172 | 76.291 | 54.251 | 84.353 | 46.349 | 46.002 |
| 49.534 | 20.501 | 54.107 | 50.587 | 64.849 | 60.787 | 34.779 | 56.959 | 31.295 | 53.324 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 19.744 | 34.983 | 53.636 | 25.997 | 59.517 | 81.390 | 26.415 | 61.206 | 58.796 | 52.232 |
| 47.326 | 57.380 | 34.929 | 59.686 | 27.222 | 26.412 | 57.294 | 9.232 | 80.764 | 55.367 |
| 42.412 | 37.014 | 61.349 | 45.811 | 61.470 | 86.342 | 56.548 | 75.975 | 41.146 | 18.602 |
| DMU21 | DMU22 | DMU23 | DMU24 | DMU25 | DMU26 | DMU27 | DMU28 | DMU29 | DMU30 |
| 62.062 | 59.093 | 43.120 | 96.817 | 47.188 | 27.911 | 72.844 | 39.379 | 39.905 | 45.215 |
| 47.720 | 45.200 | 38.247 | 22.149 | 52.204 | 76.385 | 30.305 | 56.361 | 23.037 | 40.875 |
| 37.714 | 35.233 | 28.671 | 11.942 | 40.170 | 58.992 | 23.036 | 46.494 | 16.062 | 43.001 |
| 28.825 | 39.201 | 33.446 | 74.937 | 19.794 | 51.985 | 57.522 | 59.103 | 34.154 | 26.759 |
| 29.530 | 26.146 | 35.850 | 24.747 | 31.686 | 49.351 | 30.741 | 51.296 | 27.017 | 46.626 |
| 50.946 | 19.306 | 39.578 | 59.552 | 38.600 | 40.782 | 36.278 | 21.965 | 42.577 | 27.537 |
| 33.914 | 36.418 | 53.244 | 13.016 | 45.718 | 65.944 | 31.123 | 58.906 | 55.513 | 57.395 |
| 33.682 | 48.540 | 40.869 | 8.152 | 45.338 | 69.947 | 31.403 | 66.909 | 30.626 | 53.432 |
| 50.262 | 33.563 | 62.690 | 47.003 | 61.252 | 34.571 | 31.958 | 53.110 | 36.881 | 28.726 |
| 68.277 | 38.749 | 47.088 | 83.489 | 52.171 | 37.116 | 54.112 | 25.657 | 47.333 | 33.495 |
| 53.424 | 49.247 | 68.877 | 5.305 | 72.840 | 76.796 | 30.822 | 68.581 | 57.682 | 55.285 |
| DMU31 | DMU32 | DMU33 | DMU34 | DMU35 | DMU36 | DMU37 | DMU38 | DMU39 | DMU40 |
| 67.188 | 40.088 | 73.053 | 68.719 | 57.522 | 36.468 | 14.583 | 11.075 | 26.757 | 49.111 |
| 73.351 | 47.396 | 31.773 | 23.916 | 42.298 | 58.640 | 52.664 | 62.971 | 61.575 | 44.830 |
| 58.678 | 35.607 | 32.089 | 13.586 | 40.091 | 57.645 | 59.239 | 59.714 | 63.037 | 33.721 |
| 61.077 | 44.483 | 49.151 | 32.643 | 70.723 | 59.595 | 69.109 | 64.016 | 42.205 | 71.884 |
| 43.826 | 39.291 | 43.574 | 14.309 | 60.834 | 62.595 | 75.725 | 77.038 | 65.025 | 48.260 |
| 54.315 | 59.297 | 50.999 | 59.378 | 54.798 | 37.844 | 19.784 | 79.219 | 50.773 | 44.764 |
| 37.977 | 60.414 | 38.967 | 30.575 | 50.587 | 68.058 | 87.186 | 96.009 | 76.383 | 55.544 |
| 51.396 | 39.658 | 30.036 | 11.062 | 43.428 | 67.560 | 84.931 | 61.104 | 65.690 | 47.000 |
| 56.311 | 31.103 | 63.960 | 78.497 | 38.100 | 63.276 | 72.923 | 61.036 | 32.240 | 66.626 |
| 65.356 | 56.759 | 63.495 | 78.541 | 56.035 | 33.489 | 6.054 | 50.338 | 39.629 | 46.103 |
| 33.064 | 54.271 | 23.328 | 31.931 | 46.146 | 51.943 | 65.543 | 63.658 | 59.864 | 48.712 |
| DMU41 | DMU42 | DMU43 | DMU44 | DMU45 | DMU46 | DMU47 | DMU48 | DMU49 | DMU50 |
| 38.828 | 85.704 | 36.306 | 55.281 | 67.600 | 63.577 | 47.662 | 59.479 | 39.119 | 15.967 |
| 45.025 | 51.726 | 26.181 | 53.736 | 53.460 | 38.004 | 74.741 | 51.529 | 71.500 | 41.044 |
| 39.753 | 46.636 | 20.922 | 44.980 | 48.399 | 34.462 | 65.320 | 47.382 | 67.096 | 42.163 |
| 85.068 | 79.985 | 45.010 | 23.952 | 88.922 | 57.994 | 43.659 | 46.990 | 79.208 | 32.670 |
| 63.999 | 52.757 | 42.037 | 44.704 | 53.910 | 40.858 | 50.365 | 53.464 | 74.362 | 56.699 |
| 35.579 | 56.086 | 48.774 | 61.426 | 47.954 | 33.544 | 45.170 | 55.238 | 75.024 | 81.950 |
| 65.973 | 28.308 | 60.098 | 47.750 | 43.261 | 37.652 | 52.044 | 50.420 | 70.370 | 88.884 |
| 60.759 | 38.981 | 35.014 | 37.657 | 50.581 | 43.167 | 63.325 | 44.132 | 60.440 | 39.451 |
| 38.986 | 19.247 | 47.527 | 19.446 | 38.462 | 51.459 | 57.465 | 34.872 | 78.978 | 72.107 |
| 29.311 | 69.004 | 48.724 | 67.505 | 53.141 | 48.401 | 50.856 | 58.889 | 61.547 | 60.978 |
| 57.381 | 14.067 | 69.345 | 61.880 | 16.071 | 41.083 | 55.593 | 42.239 | 42.514 | 55.562 |
| DMU51 | DMU52 | DMU53 | DMU54 | DMU55 | DMU56 | DMU57 | DMU58 | DMU59 | DMU60 |
| 43.095 | 30.800 | 58.487 | 51.907 | 52.188 | 46.747 | 35.376 | 52.403 | 61.147 | 50.219 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 68.665 | 53.453 | 29.510 | 25.077 | 62.935 | 46.210 | 40.700 | 42.253 | 66.466 | 36.789 |
| 57.202 | 45.035 | 14.751 | 22.554 | 52.937 | 42.369 | 22.526 | 37.316 | 59.831 | 25.974 |
| 38.843 | 41.286 | 64.176 | 83.297 | 41.982 | 51.502 | 58.854 | 35.197 | 43.478 | 52.113 |
| 44.275 | 44.625 | 23.568 | 59.806 | 41.990 | 49.504 | 31.255 | 34.657 | 47.639 | 27.963 |
| 65.989 | 56.636 | 35.881 | 41.095 | 41.281 | 39.295 | 48.924 | 20.185 | 73.870 | 50.682 |
| 59.623 | 69.024 | 37.486 | 57.052 | 47.314 | 55.234 | 61.305 | 43.971 | 46.469 | 48.647 |
| 49.344 | 49.346 | 31.733 | 42.099 | 54.628 | 51.589 | 39.442 | 51.250 | 41.770 | 33.139 |
| 57.862 | 49.489 | 65.343 | 24.447 | 38.563 | 59.239 | 41.294 | 60.675 | 24.909 | 22.654 |
| 64.344 | 50.304 | 50.898 | 38.953 | 50.057 | 43.374 | 46.806 | 36.240 | 76.897 | 55.841 |
| 45.853 | 55.851 | 45.714 | 49.884 | 52.054 | 53.112 | 58.466 | 56.371 | 29.217 | 38.602 |

| DMU61 | DMU62 | DMU63 | DMU64 | DMU65 | DMU66 | DMU67 | DMU68 | DMU69 | DMU70 |
|---|---|---|---|---|---|---|---|---|---|
| 27.962 | 30.004 | 57.312 | 66.544 | 49.318 | 44.086 | 39.862 | 16.407 | 56.974 | 39.922 |
| 23.450 | 43.243 | 48.996 | 49.184 | 44.017 | 47.899 | 10.342 | 45.189 | 48.970 | 22.261 |
| 17.309 | 44.270 | 28.162 | 36.867 | 40.709 | 34.854 | 2.774 | 45.195 | 42.981 | 16.831 |
| 52.422 | 59.906 | 50.020 | 57.953 | 55.234 | 66.799 | 44.158 | 21.532 | 61.581 | 59.365 |
| 40.208 | 68.573 | 19.356 | 30.502 | 48.357 | 42.823 | 22.713 | 51.867 | 53.934 | 43.446 |
| 22.567 | 51.787 | 53.939 | 31.159 | 41.599 | 25.779 | 11.599 | 45.094 | 26.547 | 5.224 |
| 70.903 | 77.181 | 42.441 | 32.273 | 52.007 | 51.913 | 52.258 | 79.512 | 45.521 | 52.602 |
| 48.799 | 55.419 | 31.779 | 45.234 | 48.671 | 56.444 | 37.125 | 55.896 | 57.001 | 53.150 |
| 58.105 | 36.415 | 10.201 | 53.404 | 68.741 | 35.897 | 51.123 | 36.727 | 24.150 | 31.623 |
| 20.136 | 38.346 | 62.202 | 50.002 | 47.296 | 31.800 | 23.162 | 35.583 | 35.993 | 14.765 |
| 65.241 | 61.022 | 35.898 | 39.032 | 49.740 | 64.715 | 66.294 | 78.571 | 59.912 | 82.565 |

| DMU71 | DMU72 | DMU73 | DMU74 | DMU75 | DMU76 | DMU77 | DMU78 | DMU79 | DMU80 |
|---|---|---|---|---|---|---|---|---|---|
| 64.604 | 34.462 | 56.719 | 100.000 | 43.950 | 56.967 | 14.645 | 63.448 | 47.290 | 75.455 |
| 18.924 | 65.191 | 41.982 | 25.954 | 31.008 | 33.025 | 59.469 | 10.011 | 47.487 | 28.826 |
| 9.864 | 61.306 | 36.358 | 20.815 | 24.954 | 26.508 | 49.470 | 4.882 | 32.998 | 22.756 |
| 62.121 | 41.785 | 69.417 | 74.521 | 54.548 | 31.406 | 42.936 | 65.295 | 26.029 | 54.305 |
| 29.005 | 63.973 | 48.133 | 31.507 | 35.871 | 20.999 | 53.664 | 28.824 | 18.715 | 26.792 |
| 8.818 | 63.008 | 25.378 | 51.656 | 32.863 | 19.362 | 45.819 | 21.672 | 36.082 | 17.454 |
| 29.679 | 72.500 | 46.261 | 11.470 | 55.610 | 36.965 | 80.523 | 35.614 | 44.632 | 23.660 |
| 38.370 | 57.906 | 53.454 | 16.252 | 43.222 | 41.086 | 63.846 | 29.443 | 41.277 | 37.465 |
| 43.451 | 59.626 | 35.984 | 33.006 | 53.722 | 37.516 | 46.633 | 34.232 | 58.868 | 64.427 |
| 32.133 | 53.379 | 34.461 | 77.098 | 37.630 | 39.538 | 33.848 | 38.617 | 50.369 | 44.649 |
| 61.075 | 58.175 | 47.198 | 2.582 | 47.227 | 48.433 | 81.832 | 43.887 | 55.644 | 37.320 |

| DMU81 | DMU82 | DMU83 | DMU84 | DMU85 | DMU86 | DMU87 | DMU88 | DMU89 | DMU90 |
|---|---|---|---|---|---|---|---|---|---|
| 27.138 | 49.393 | 65.748 | 16.995 | 55.873 | 17.774 | 67.878 | 39.445 | 91.922 | 58.548 |
| 45.171 | 51.658 | 13.996 | 58.741 | 0.000 | 36.129 | 14.398 | 39.250 | 46.605 | 14.756 |
| 29.735 | 39.069 | 5.713 | 47.531 | 2.944 | 21.255 | 2.966 | 45.540 | 42.093 | 1.489 |
| 43.173 | 56.921 | 53.507 | 25.694 | 53.268 | 74.027 | 8.165 | 25.629 | 41.672 | 23.165 |
| 40.139 | 41.654 | 24.561 | 39.575 | 29.919 | 39.852 | 0.194 | 61.777 | 32.205 | 0.000 |
| 55.021 | 43.339 | 12.694 | 35.468 | 6.862 | 38.085 | 18.021 | 58.857 | 80.626 | 38.092 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 66.761 | 48.379 | 28.191 | 72.674 | 41.626 | 74.507 | 21.372 | 68.010 | 21.074 | 33.915 |
| 42.360 | 47.933 | 31.742 | 62.464 | 34.292 | 51.082 | 18.518 | 43.770 | 15.086 | 13.619 |
| 20.686 | 32.517 | 34.627 | 65.521 | 34.378 | 44.913 | 44.092 | 50.169 | 64.057 | 50.201 |
| 49.053 | 49.433 | 36.858 | 32.773 | 23.803 | 28.271 | 50.890 | 53.858 | 100.000 | 58.913 |
| 79.952 | 58.399 | 60.022 | 82.909 | 48.330 | 70.456 | 59.015 | 60.015 | 0.000 | 41.786 |
| DMU91 | DMU92 | DMU93 | DMU94 | DMU95 | DMU96 | DMU97 | DMU98 | DMU99 | DMU100 |
| 69.434 | 58.538 | 71.179 | 43.911 | 22.680 | 60.171 | 60.285 | 41.635 | 34.896 | 55.455 |
| 48.108 | 53.139 | 69.112 | 60.819 | 62.993 | 28.527 | 34.908 | 53.778 | 36.801 | 26.074 |
| 43.018 | 43.091 | 51.510 | 50.165 | 58.483 | 16.661 | 28.620 | 45.959 | 33.387 | 16.610 |
| 34.066 | 70.824 | 30.096 | 19.342 | 46.626 | 67.242 | 31.988 | 34.539 | 34.425 | 59.844 |
| 36.517 | 46.760 | 23.416 | 34.521 | 62.319 | 30.790 | 27.488 | 45.825 | 46.510 | 27.740 |
| 63.376 | 46.264 | 64.897 | 63.543 | 59.577 | 48.774 | 27.635 | 63.866 | 63.288 | 38.313 |
| 36.353 | 44.346 | 28.293 | 54.636 | 81.150 | 40.979 | 38.570 | 57.312 | 67.613 | 44.531 |
| 30.218 | 48.319 | 34.334 | 41.579 | 61.675 | 27.566 | 38.941 | 42.205 | 36.155 | 31.987 |
| 64.471 | 48.432 | 37.147 | 41.218 | 54.615 | 41.701 | 58.084 | 25.844 | 20.052 | 46.620 |
| 77.078 | 53.457 | 82.788 | 66.776 | 44.691 | 58.084 | 46.102 | 63.006 | 56.101 | 48.235 |
| 30.132 | 41.762 | 33.815 | 52.763 | 61.167 | 38.657 | 47.244 | 61.677 | 57.919 | 38.260 |

# APPENDIX E

## Port Nodes Virtual Data

| DMU1 | DMU2 | DMU3 | DMU4 | DMU5 | DMU6 | DMU7 | DMU8 | DMU9 | DMU10 |
|---|---|---|---|---|---|---|---|---|---|
| 25.437 | 36.011 | 25.437 | 24.115 | 35.341 | 42.619 | 58.573 | 27.277 | 60.334 | 22.403 |
| 45.604 | 54.353 | 38.938 | 22.273 | 39.105 | 39.355 | 63.201 | 23.606 | 24.890 | 27.255 |
| 42.293 | 32.446 | 81.679 | 61.986 | 42.293 | 32.446 | 32.446 | 32.446 | 52.139 | 59.297 |
| 33.964 | 53.001 | 27.618 | 50.886 | 36.134 | 29.799 | 51.348 | 38.511 | 65.730 | 44.707 |
| 39.189 | 34.331 | 53.067 | 28.780 | 42.187 | 69.263 | 13.771 | 53.067 | 52.731 | 35.601 |
| 59.139 | 51.154 | 72.448 | 59.139 | 87.421 | 51.154 | 39.913 | 66.326 | 42.272 | 66.886 |
| 45.824 | 74.697 | 66.553 | 34.719 | 49.526 | 22.874 | 69.440 | 59.779 | 45.646 | 61.507 |
| 56.122 | 50.912 | 75.659 | 53.517 | 68.495 | 45.702 | 62.960 | 29.135 | 28.145 | 52.353 |
| 42.126 | 36.016 | 79.341 | 53.235 | 36.707 | 50.458 | 47.762 | 70.992 | 43.832 | 67.194 |
| 52.998 | 55.582 | 56.841 | 31.860 | 42.444 | 56.841 | 45.880 | 0.000 | 31.101 | 30.465 |
| 54.950 | 41.842 | 69.931 | 32.478 | 50.937 | 49.332 | 78.519 | 69.931 | 29.314 | 55.260 |

| DMU11 | DMU12 | DMU13 | DMU14 | DMU15 | DMU16 | DMU17 | DMU18 | DMU19 | DMU20 |
|---|---|---|---|---|---|---|---|---|---|
| 26.362 | 24.179 | 38.104 | 29.150 | 39.903 | 26.391 | 49.892 | 71.106 | 30.955 | 25.135 |
| 51.439 | 0.000 | 53.756 | 19.734 | 7.636 | 43.760 | 37.794 | 53.745 | 26.021 | 43.152 |
| 50.776 | 72.079 | 65.002 | 55.107 | 100.000 | 38.790 | 26.499 | 22.196 | 24.574 | 60.930 |
| 17.166 | 29.652 | 40.246 | 35.021 | 54.407 | 45.811 | 44.171 | 46.126 | 21.143 | 19.049 |
| 28.039 | 85.834 | 17.086 | 56.732 | 73.229 | 22.585 | 58.933 | 63.485 | 71.955 | 71.220 |
| 69.795 | 66.297 | 56.870 | 51.587 | 60.194 | 59.549 | 50.287 | 24.590 | 68.753 | 63.816 |
| 38.749 | 23.265 | 69.479 | 41.184 | 40.186 | 63.732 | 61.118 | 25.312 | 17.396 | 46.598 |
| 84.519 | 28.395 | 79.101 | 34.188 | 47.508 | 57.695 | 29.232 | 36.785 | 37.065 | 63.873 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 61.432 | 85.547 | 62.452 | 84.049 | 70.062 | 53.397 | 59.907 | 31.014 | 55.722 | 67.714 |
| 68.456 | 9.454 | 63.152 | 19.730 | 33.532 | 43.270 | 17.978 | 55.881 | 26.479 | 47.542 |
| 87.240 | 49.094 | 78.948 | 69.713 | 15.259 | 57.654 | 67.595 | 43.827 | 60.706 | 61.773 |
| DMU21 | DMU22 | DMU23 | DMU24 | DMU25 | DMU26 | DMU27 | DMU28 | DMU29 | DMU30 |
| 33.895 | 20.077 | 59.589 | 45.089 | 24.822 | 65.902 | 30.764 | 39.918 | 42.541 | 49.454 |
| 29.633 | 34.748 | 55.798 | 64.016 | 42.837 | 24.931 | 29.903 | 38.173 | 38.239 | 69.274 |
| 73.722 | 46.871 | 35.832 | 38.614 | 50.836 | 31.098 | 61.361 | 39.736 | 41.589 | 30.464 |
| 59.976 | 38.343 | 49.980 | 42.534 | 57.851 | 49.089 | 36.680 | 53.275 | 41.358 | 51.326 |
| 23.656 | 35.139 | 45.523 | 34.034 | 0.000 | 79.859 | 53.305 | 23.011 | 55.204 | 46.558 |
| 59.080 | 56.356 | 43.024 | 39.370 | 58.098 | 62.100 | 68.852 | 67.771 | 49.525 | 35.053 |
| 60.448 | 32.582 | 65.984 | 67.028 | 91.778 | 35.621 | 54.663 | 40.173 | 41.612 | 95.506 |
| 58.589 | 51.733 | 55.581 | 62.341 | 57.193 | 23.763 | 50.623 | 65.483 | 45.957 | 43.459 |
| 51.013 | 44.572 | 51.835 | 50.138 | 62.627 | 34.866 | 60.231 | 31.461 | 54.350 | 41.376 |
| 46.062 | 48.180 | 50.443 | 59.591 | 34.753 | 18.735 | 31.296 | 58.124 | 41.462 | 39.096 |
| 35.942 | 43.369 | 57.807 | 65.410 | 70.348 | 38.124 | 58.987 | 31.715 | 49.212 | 60.426 |
| DMU31 | DMU32 | DMU33 | DMU34 | DMU35 | DMU36 | DMU37 | DMU38 | DMU39 | DMU40 |
| 58.565 | 57.385 | 22.682 | 41.804 | 16.471 | 13.505 | 20.051 | 100.000 | 11.830 | 3.020 |
| 42.857 | 30.055 | 13.271 | 45.070 | 34.278 | 30.313 | 46.611 | 71.858 | 48.818 | 25.064 |
| 64.353 | 58.684 | 38.012 | 45.381 | 63.402 | 29.868 | 57.351 | 43.554 | 28.028 | 67.154 |
| 59.890 | 46.795 | 59.850 | 45.308 | 28.797 | 41.686 | 23.237 | 100.000 | 30.633 | 13.381 |
| 32.170 | 52.269 | 41.579 | 22.045 | 56.480 | 21.640 | 30.386 | 7.383 | 29.513 | 66.587 |
| 43.549 | 35.344 | 51.559 | 72.873 | 80.444 | 75.364 | 98.379 | 3.133 | 73.718 | 73.786 |
| 25.766 | 9.404 | 42.686 | 76.588 | 66.859 | 46.315 | 49.795 | 75.011 | 36.930 | 37.976 |
| 69.226 | 47.276 | 20.051 | 63.286 | 58.310 | 48.442 | 97.736 | 49.915 | 67.013 | 56.074 |
| 26.747 | 50.070 | 53.234 | 51.854 | 61.470 | 39.964 | 46.067 | 0.000 | 24.048 | 80.035 |
| 80.002 | 58.713 | 13.428 | 39.496 | 30.001 | 32.474 | 68.597 | 79.219 | 59.279 | 32.199 |
| 16.376 | 38.956 | 23.982 | 77.271 | 60.470 | 49.991 | 60.095 | 14.170 | 39.678 | 65.678 |
| DMU41 | DMU42 | DMU43 | DMU44 | DMU45 | DMU46 | DMU47 | DMU48 | DMU49 | DMU50 |
| 33.301 | 0.146 | 57.688 | 44.003 | 44.136 | 29.779 | 33.818 | 56.220 | 52.523 | 26.117 |
| 41.922 | 35.194 | 47.022 | 48.854 | 25.196 | 49.405 | 52.220 | 33.326 | 39.996 | 38.360 |
| 42.294 | 58.403 | 17.953 | 41.836 | 39.893 | 19.699 | 32.428 | 39.473 | 37.132 | 14.868 |
| 59.262 | 8.697 | 59.287 | 50.001 | 56.782 | 44.189 | 37.706 | 52.749 | 44.749 | 29.682 |
| 25.274 | 61.222 | 45.782 | 46.708 | 34.516 | 21.143 | 22.882 | 65.537 | 40.828 | 47.719 |
| 55.645 | 95.093 | 9.168 | 33.214 | 45.253 | 63.584 | 57.286 | 45.689 | 61.072 | 53.752 |
| 61.759 | 36.413 | 59.814 | 50.798 | 36.754 | 58.390 | 54.703 | 46.976 | 40.248 | 39.426 |
| 47.905 | 76.116 | 15.013 | 42.106 | 32.504 | 54.413 | 60.096 | 31.175 | 54.555 | 34.671 |
| 27.469 | 55.023 | 61.740 | 42.007 | 49.478 | 34.385 | 43.919 | 47.631 | 40.520 | 57.053 |
| 43.276 | 48.663 | 25.423 | 47.995 | 32.041 | 44.150 | 51.610 | 29.219 | 48.080 | 26.868 |
| 30.375 | 54.672 | 60.678 | 41.102 | 43.977 | 56.670 | 70.985 | 38.451 | 54.401 | 70.461 |
| DMU51 | DMU52 | DMU53 | DMU54 | DMU55 | DMU56 | DMU57 | DMU58 | DMU59 | DMU60 |
| 26.080 | 44.016 | 48.740 | 48.990 | 39.570 | 57.255 | 36.356 | 27.264 | 33.708 | 0.000 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 51.775 | 36.107 | 29.779 | 34.693 | 60.366 | 51.924 | 21.682 | 33.195 | 51.907 | 24.124 |
| 52.559 | 59.103 | 39.725 | 59.632 | 24.608 | 13.196 | 32.300 | 35.228 | 39.921 | 51.717 |
| 46.197 | 42.746 | 57.402 | 50.967 | 59.996 | 39.813 | 47.826 | 17.454 | 29.746 | 0.000 |
| 9.911 | 58.634 | 44.109 | 26.396 | 15.417 | 51.885 | 55.741 | 70.726 | 70.488 | 85.850 |
| 51.351 | 63.134 | 58.559 | 69.036 | 47.646 | 52.344 | 71.582 | 77.422 | 46.925 | 86.214 |
| 76.656 | 41.452 | 45.269 | 74.151 | 92.172 | 48.321 | 37.166 | 48.314 | 36.418 | 30.192 |
| 67.395 | 53.670 | 41.030 | 61.719 | 47.129 | 45.316 | 35.901 | 44.842 | 53.947 | 54.028 |
| 63.185 | 36.836 | 38.251 | 67.771 | 33.036 | 40.969 | 39.776 | 66.664 | 42.542 | 80.862 |
| 52.186 | 47.213 | 35.128 | 36.029 | 38.631 | 41.496 | 24.018 | 20.133 | 55.870 | 24.793 |
| 71.734 | 36.188 | 32.618 | 75.544 | 56.769 | 64.607 | 30.937 | 80.213 | 37.083 | 69.879 |
| DMU61 | DMU62 | DMU63 | DMU64 | DMU65 | DMU66 | DMU67 | DMU68 | DMU69 | DMU70 |
| 49.442 | 35.080 | 52.263 | 53.584 | 34.043 | 52.367 | 29.621 | 41.611 | 51.000 | 60.499 |
| 37.006 | 32.760 | 32.511 | 48.857 | 42.463 | 63.325 | 20.899 | 69.558 | 28.257 | 44.025 |
| 36.426 | 59.534 | 32.132 | 61.757 | 82.037 | 14.857 | 68.609 | 31.744 | 40.016 | 10.550 |
| 47.850 | 34.879 | 45.385 | 52.345 | 37.167 | 47.837 | 50.294 | 47.818 | 54.378 | 66.412 |
| 45.295 | 54.745 | 56.092 | 25.287 | 35.963 | 18.895 | 39.684 | 10.999 | 55.175 | 9.446 |
| 62.713 | 73.888 | 53.375 | 60.896 | 57.976 | 46.263 | 54.728 | 58.393 | 47.715 | 32.721 |
| 57.538 | 56.998 | 27.914 | 74.886 | 50.940 | 58.167 | 22.871 | 79.590 | 22.195 | 34.935 |
| 44.200 | 59.916 | 38.764 | 72.510 | 78.471 | 59.345 | 50.995 | 77.739 | 34.665 | 33.497 |
| 46.659 | 65.551 | 40.058 | 54.971 | 64.897 | 33.305 | 45.822 | 33.923 | 29.704 | 21.106 |
| 31.100 | 36.115 | 38.874 | 55.234 | 65.434 | 59.092 | 50.184 | 66.766 | 41.988 | 48.067 |
| 58.146 | 61.959 | 42.534 | 65.029 | 58.956 | 65.830 | 22.706 | 62.982 | 20.584 | 46.344 |
| DMU71 | DMU72 | DMU73 | DMU74 | DMU75 | DMU76 | DMU77 | DMU78 | DMU79 | DMU80 |
| 17.781 | 37.494 | 46.174 | 5.354 | 68.986 | 24.285 | 29.998 | 22.279 | 29.014 | 61.857 |
| 39.246 | 32.755 | 30.549 | 49.302 | 23.642 | 27.356 | 29.571 | 36.467 | 53.825 | 46.706 |
| 52.048 | 37.620 | 47.782 | 44.112 | 54.224 | 32.652 | 45.877 | 49.645 | 50.164 | 24.131 |
| 44.388 | 46.625 | 53.002 | 38.794 | 59.710 | 32.949 | 30.670 | 27.221 | 26.056 | 51.074 |
| 32.364 | 48.364 | 47.356 | 41.287 | 59.869 | 40.722 | 65.507 | 56.353 | 44.635 | 54.088 |
| 70.260 | 68.676 | 51.785 | 71.307 | 39.597 | 62.886 | 55.438 | 64.877 | 79.430 | 26.115 |
| 55.826 | 74.038 | 23.941 | 65.755 | 29.721 | 7.605 | 21.216 | 47.715 | 79.835 | 39.794 |
| 63.350 | 41.931 | 44.563 | 61.219 | 33.383 | 49.183 | 45.640 | 52.687 | 75.891 | 32.104 |
| 40.133 | 63.414 | 28.467 | 28.724 | 51.719 | 40.596 | 56.116 | 62.466 | 63.219 | 46.973 |
| 48.942 | 17.191 | 49.927 | 47.450 | 37.315 | 48.334 | 41.815 | 36.402 | 45.281 | 42.414 |
| 33.545 | 62.241 | 20.994 | 25.389 | 35.284 | 41.724 | 42.910 | 61.885 | 81.003 | 49.908 |
| DMU81 | DMU82 | DMU83 | DMU84 | DMU85 | DMU86 | DMU87 | DMU88 | DMU89 | DMU90 |
| 18.409 | 28.824 | 29.741 | 44.246 | 22.295 | 41.149 | 48.437 | 60.824 | 47.036 | 51.723 |
| 34.878 | 42.879 | 30.566 | 52.260 | 16.821 | 45.280 | 80.305 | 27.183 | 43.035 | 24.810 |
| 32.587 | 58.775 | 60.693 | 62.533 | 53.792 | 39.615 | 34.677 | 34.960 | 57.955 | 39.755 |
| 16.811 | 32.871 | 37.881 | 50.008 | 62.513 | 37.248 | 28.500 | 71.880 | 57.326 | 61.317 |
| 76.937 | 29.130 | 61.283 | 12.873 | 25.456 | 42.402 | 33.453 | 44.139 | 46.655 | 31.487 |
| 51.824 | 67.803 | 59.967 | 47.828 | 47.594 | 58.037 | 46.613 | 39.499 | 54.738 | 71.620 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.000 | 43.821 | 49.556 | 76.357 | 63.481 | 51.649 | 78.516 | 67.201 | 89.761 | 46.627 |
| 44.693 | 74.436 | 47.321 | 72.928 | 29.886 | 56.683 | 79.454 | 16.702 | 45.319 | 45.431 |
| 47.524 | 52.146 | 61.030 | 68.643 | 73.441 | 53.877 | 54.982 | 51.013 | 53.660 | 32.966 |
| 49.846 | 60.807 | 33.714 | 58.432 | 15.445 | 45.721 | 69.462 | 12.107 | 27.997 | 33.570 |
| 35.762 | 62.850 | 47.107 | 76.928 | 44.548 | 65.907 | 92.866 | 43.066 | 52.374 | 36.578 |

| DMU91 | DMU92 | DMU93 | DMU94 | DMU95 | DMU96 | DMU97 | DMU98 | DMU99 | DMU100 |
|---|---|---|---|---|---|---|---|---|---|
| 22.061 | 24.174 | 21.960 | 31.268 | 48.228 | 51.747 | 56.207 | 22.101 | 34.249 | 50.292 |
| 60.252 | 32.773 | 34.751 | 53.605 | 44.860 | 50.781 | 67.226 | 31.897 | 40.587 | 50.185 |
| 30.279 | 65.604 | 54.355 | 61.144 | 36.900 | 38.414 | 11.306 | 63.362 | 67.490 | 31.962 |
| 28.694 | 31.124 | 34.965 | 45.772 | 28.535 | 45.082 | 40.696 | 52.961 | 47.678 | 60.253 |
| 30.616 | 66.574 | 36.831 | 22.998 | 55.663 | 31.765 | 39.506 | 19.700 | 44.070 | 25.491 |
| 61.095 | 79.776 | 70.723 | 75.309 | 57.199 | 50.925 | 42.802 | 79.540 | 65.233 | 33.398 |
| 64.489 | 72.874 | 46.925 | 93.055 | 33.332 | 76.577 | 62.295 | 82.321 | 59.235 | 77.923 |
| 63.229 | 58.198 | 62.487 | 77.317 | 62.569 | 52.503 | 53.251 | 62.085 | 67.482 | 38.312 |
| 43.195 | 71.935 | 54.999 | 50.226 | 61.707 | 63.749 | 39.403 | 55.425 | 45.515 | 54.800 |
| 50.998 | 26.100 | 45.428 | 49.795 | 54.012 | 37.061 | 52.304 | 32.422 | 53.957 | 34.216 |
| 72.864 | 59.926 | 55.455 | 63.932 | 68.098 | 86.454 | 71.953 | 52.795 | 32.869 | 64.286 |

# APPENDIX F

## Supply Chain Efficiency Analysis Program - User Manual

### F.1 System Requirements

A system that is able to install and run Enthough's Python Distribution (EPD).

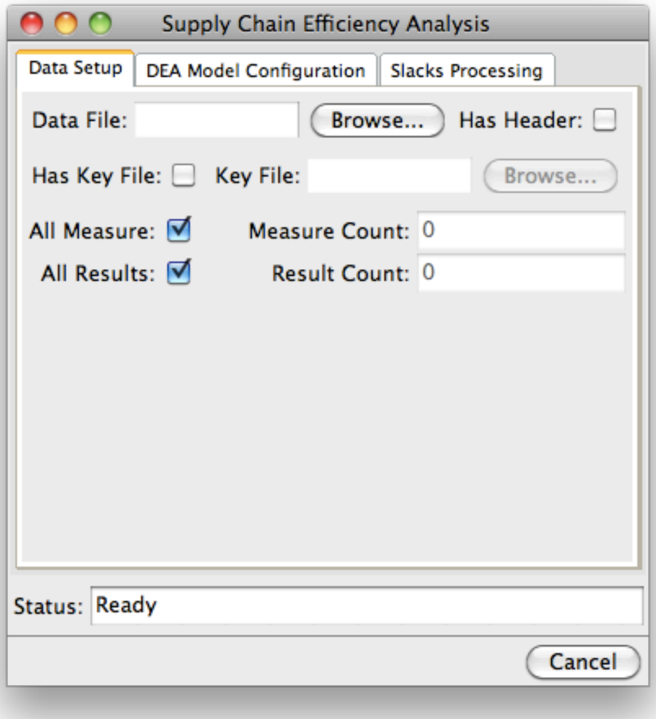
### F.2 Program Structure

The Supply Chain Efficiency Analysis Program provides three tabs that can be used to configure and run the efficiency analysis.

### F.3 Data Setup Tab

Figure F.1 shows the **Data Setup Tab**. This tab is used to configure the data that will be used during the efficiency analysis.

**Figure F.1:** Data Setup Tab.



Data File:
Has Header: ☐
Has Key File: ☐
Key File:
All Measure: ☑
Measure Count: 0
All Results: ☑
Result Count: 0
Status: Ready

To do an efficiency analysis of a given set of DMUs the users has to provide a **Data File** as well as a **Key File**. These should both be comma separated files with the following structure:

### F.3.1 Data File Format

The columns in this file represent the individual DMUs, while the row represents a specific measurement for a specific input or output variable per DMU.

### F.3.2 Key File Format

The key file provides the key for the rows of the data file. The first column of the key file specifies whether or not the associated row of the data file should be handled as an input or output. The second column specifies if a variable should be inverted or not. The third column specifies the name of the variable as it would be used in the linear problem solver, while the forth column gives a description for the measurement associated with the specific row.

The Measurement and Results options allow the user to specify the number of DMUs that should be included in the analysis and specify the number of DMUs results that will be shown. These options are useful if insufficient data was available and additional data was generated. In this case by specifying the number of results that should be included, the generated DMU's results can be excluded.

### F.3.3 Examples of the data files

Table F.1 shows an example of a datafile.

**Table F.1:** Example Data File.

| | | | |
|---|---|---|---|
| 31.56531 | 41.16126 | 66.11073 | 29.62673 |
| 23.12859 | 65.02758 | 62.93263 | 33.50811 |
| 32.13472 | 43.33625 | 61.2587 | 23.54358 |
| 73.84502 | 53.2028 | 43.11105 | 78.43218 |
| 64.7366 | 48.07181 | 26.40758 | 63.07011 |
| 71.97222 | 49.0871 | 33.06751 | 74.28384 |

Table F.2 shows an example key file.

**Table F.2:** Example Key File.

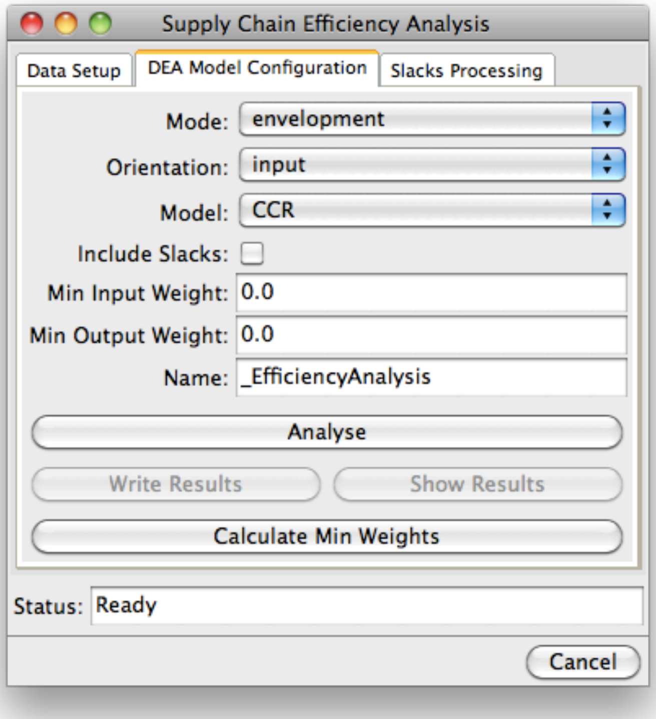
| | | | |
|---|---|---|---|
| input | invert | V101 | System uptime (R) |
| input | invert | V102 | Idle time (R) |
| input | invert | V103 | Utilisation (R) |
| output | normal | U101 | Throughtput efficiency (R) |
| output | normal | U102 | Extraction time (S) |
| output | normal | U103 | Goods handling efficiency (S) |

### F.3.4 DEA Model Configuration Tab

Figure F.2 shows the **DEA Model Configuration Tab**. Here the user can configure the DEA model properties as well as run the efficiency analysis.

The **Mode** option allows the user to specify whether the envelopment or multiplier mode will be used. The **Orientation** option allows the user to specify if the analysis will be input oriented or output oriented. The **Model** option can be set to CCR or BCC so that either the Charnes, Cooper and Rhodes or the Banker, Charnes and Cooper model can be used. The **Include Slacks** option lets the user decide if slacks analysis should be included during the efficiency analysis. **Min and Max**

**Figure F.2:** DEA Model Configuration Tab.



Mode: envelopment
Orientation: input
Model: CCR
Include Slacks: ☐
Min Input Weight: 0.0
Min Output Weight: 0.0
Name: _EfficiencyAnalysis
Status: Ready

**Input and Output Weight** allows the user to restrict the weights that can be assigned to a given measurement of the DMUs.

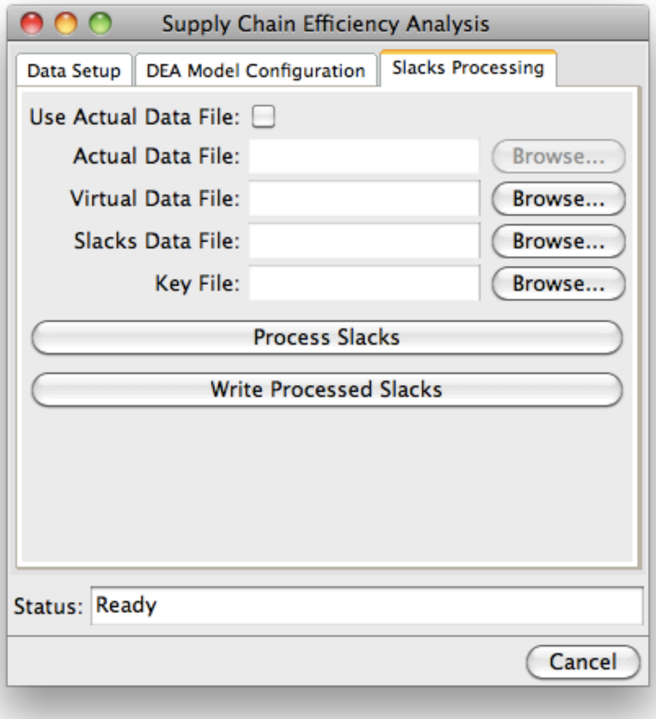
All options cannot be used together, but the program will guide the user to select the correct options that are compatible with one another.

The efficiency analysis can be run by clicking the **Analyse** button. The Status message will update and inform the user when the analysis has been completed. Once the analysis has been completed the results can be written to file by clicking on the **Write Results** button. The results can also be viewed by clicking the **View Results** button.

### F.3.5 Slacks Processing Tab

Figure F.3 below shows the **Slacks Processing Tab**, which can be used to configure the processing of slack results if virtual data was used. The main purpose of this tab is to convert virtual slack values back to actual slack values (if virtual data was specified in the Data Setup Tab) so the required adjustments can be made to improve efficiency. This tab should only be used if slacks were included during the efficiency analysis. All the required fields will be filled with the correct values if an analysis that included slacks was completed successfully. However, the user can also specify the correct files and manually perform the slacks processing.

**Figure F.3:** Slacks Processing Tab.



Use Actual Data File: ☐
Actual Data File:
Virtual Data File:
Slacks Data File:
Key File:
Status: Ready

The slacks processing can be performed by pressing the **Process Slacks** button, while the results can be written by pressing the **Write Processed Slacks** button

## F.4 Support

If you have any questions about the program or have any suggestions you can contact us at **support@retiefgerber.co.za**.