DEVELOPMENT OF NETWORK THEORY APPROACHES TO ANALYSE CAUSE AND EFFECT RELATIONSHIPS IN COMPLEX INTEGRATED SUGARCANE SUPPLY AND PROCESSING SYSTEMS

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February 2013

PREFACE

DECLARATION

I, ***THAWANI M. SANJIKA***, declare that:

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- I am grateful to my family, the Sanjika family, for their love, support, encouragement, well wishes and prayers.
- Lastly but very important, my sincere appreciation goes to my wife and children for their love, support and encouragement even when the physical distance between us was agonizing.

DEDICATION

This thesis is dedicated to my beloved children, Erhlapo and Tadala.

ABSTRACT

Network theory has been widely and successfully used to model, analyse and visualise complex systems. This study aimed to develop approaches to analyse complex integrated sugarcane supply and processing systems. A literature review includes network theory, complex systems, the Theory of constraints, indicator analysis and root cause analysis. The cause-and-effect networks of four sugarcane milling areas in South Africa; *viz*. Eston, Felixton, Komati and Umfolozi were developed, where the factors that negatively affected the performance of the milling areas were represented by vertices, the relationships among the factors by arcs and the strength of these relationships by weights. Three network theory based analytical tools namely; (a) primary influence vertex analysis, (b) indicator vertex analysis and (c) root cause vertex analysis were developed to analyse the networks. The results from the analyses indicate variations in the numbers and strengths of primary influence factors, problem indicator factors and root causes of problems between the four milling areas. Rainfall, drought and high soil content in sugarcane were identified as the strongest primary influences in the respective milling areas. High crush rate variability, low cutter productivity, running behind allocation and increases in operating costs were identified as the strongest indicators of poor performance in the respective milling areas. Rainfall was found to be the most dominating root cause of poor performance in all the milling areas. Since the South African integrated sugarcane production and processing system is complex, it is likely that the unique approaches developed in this study can be used successfully to also analyse other relatively complex systems. It is recommended that these approaches be tested within other systems. The main contribution of this study is in the form of a relatively easy-to-use network theory based comprehensive systems analyses tool. This analytical approach has, to the author's knowledge, not been used in any agri-industrial application previously.

LIST OF ACRONYMS

BHTCD:	Burn Harvest to Crush Delay
CEA:	Cause-and-Effect Analysis
CED:	Cause-and-Effect Diagram
CLR:	Categories of Legitimate Reservations
CRT:	Current Reality Tree
ERC:	Estimated Recoverable Crystal
FFS:	Five Focussing Steps
IA:	Indicator Analysis
ID:	Interrelationship Diagram
I_I:	Indicator Index
I_{PI}:	Primary Influence Index
I_{RC}:	Root Cause Index
ISSPS:	Integrated Sugarcane Supply and Processing System
LOMS:	Length of Milling Season
PI:	Primary Influence
RC:	Root Cause
RCA:	Root Cause Analysis
RV:	Recoverable Value
SA:	South Africa
TOC:	Theory of Constraints
TP:	Thinking Process
UDE:	Undesirable Effect

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1. INTRODUCTION

Integrated sugarcane supply and processing systems ISSPSs are complex systems (Lisson *et al*., 2000). They consist of fragmented and continuously evolving systems that involve a number of role players with different and often misaligned business objectives (Higgins *et al*., 2007; Bezuidenhout, 2008; Le Gal *et al*., 2008; Lejars *et al*., 2008; Le Gal *et al*., 2009). Additionally, ISSPSs are composed of multiple factors (*e.g*. biophysical, social, economic and environmental) that interrelate in a complex cause-and-effect manner to determine the overall performance of the systems. The complexity of the ISSPSs makes it challenging to comprehend, manage, control and improve these systems (Choi *et al*., 2001; Higgins *et al*., 2007; Archer *et al*., 2009; Higgins *et al*., 2010).

Complexity negatively affects the management capability and performance of systems (Frizelle and Woodcock, 1995; Cilliers, 2000; Choi *et al*., 2001; Frizelle and Suhov, 2008; Archer *et al*., 2009). Integrated sugarcane supply and processing systems are no exception. Higgins *et al*. (2007) and Le Gal *et al*. (2008) argue that there is a potential to minimise the production costs in sugar industries by improving the performance of the sugarcane supply chains. The large volume of literature on sugarcane supply chains (*e.g*. Everingham *et al*., 2002; Gaucher *et al*., 2003; Stutterheim *et al*., 2006; Bezuidenhout, 2008; Le Gal *et al*., 2009; Higgins *et al*., 2010; Stray *et al*., 2012) indicates that this argument is accepted by many practitioners in the sugar industry. It is however acknowledged that the complexity of ISSPSs presents challenges to improving the performance of sugarcane supply chains (Choi *et al*., 2001; Higgins *et al*., 2007; Archer *et al*., 2009; Higgins *et al*., 2010). Choi *et al*. (2001) observe that complexity has often frustrated attempts to improve the performance of supply chains. Higgins *et al*. (2007) and Archer *et al*. (2009) argue that the complexity of the sugar industry is one of the factors that contribute to the limited adoption of research results, despite the significant potential gains highlighted in literature. Notable examples of the potential gains include; an increase in economic benefits by about AU$1.00 and AU$2.50 per tonne of sugarcane (Grimley and Horton, 1997; Higgins *et al*., 2004), a 13.5% reduction in road vehicle waiting time (Iannoni and Morabito, 2006), a 35% increase in transport capacity (Le Gal *et al*., 2004), and a 40% reduction in delay between harvesting and milling (Hansen *et al*., 1998). Higgins *et al*. (2010) claim that that the limited adoption of research results in agricultural value chains has partly been due to the fact that most research work undertaken so far has not taken the complexity of agricultural industries into account. They propose that any research aimed at improving the performance of agricultural value chains should take complexity issues into account.

Several tools have been used to analyse complex systems with varying degrees of success. These tools include; the network theory (Albert and Barabasi, 2002; Newman, 2003; Li and Cai, 2004; Xu *et al*., 2004; Battini *et al*., 2007; Suderman and Hallett, 2007; Zhao *et al*., 2007; Costa *et al*., 2011), the Theory of Constraints (Blackstone, 2001; Mabin and Baldestone, 2003; Watson *et al*., 2007), indicator analysis (Pannell and Glenn, 2000; Eggleston *et al*., 2004; Peris-Mora *et al*., 2005; Grabowski *et al*., 2007; Cai *et al*., 2009; Lin *et al*., 2009; Perera *et al*., 2012; Reiman and Pietikainen, 2012; Sano and Medina, 2012) and root cause analysis (Paradies and Busch, 1988; Woloshynowych *et al*., 2005; Uberio *et al*., 2007; Iedema *et al*., 2008; Al-Mamory and Zang, 2009; Kumar and Schmitz, 2011; Nicoloni *et al*., 2011; Simms *et al*., 2012). However, the management of complex systems in general and ISSPSs in particular still remains a challenge. This could be an indication that the existing approaches for analysing complex systems have limitations.

A good understanding of the nature of ISSPSs is a prerequisite to their effective management, control and improvement. Effective approaches are therefore needed to help in understanding the nature of ISSPSs. Foremost, the approaches must be capable of handling the complexity issues inherent in ISSPSs if they are to be successful. The approaches for understanding ISSPSs must be equipped with the capabilities to identify (a) the factors that drive ISSPSs, (b) the factors that can be used to monitor the performance of ISSPSs and (c) the factors that may be subtle root causes of poor performance in ISSPSs.

The motivation behind this study was the conviction that ISSPSs can only be improved if their nature is well understood. The study developed comprehensive network theory approaches for analysing ISSPSs. The development of these approaches employed knowledge from various areas of expertise, such as the Theory of Constraints, cause-and-effect analysis, indicator analysis and root cause analysis. The approaches were tested in four sugarcane milling areas in South Africa, thus representing four ISSPSs.

1.1 Aim and Objectives of the Study

The aim of this study was to assist in the understanding of the nature of ISSPSs as a prerequisite to improving their performance. The overall objective of the study was to develop and test comprehensive approaches for analysing complex ISSPSs. The main objectives of the study included:

1. to develop an analytical tool for identifying and ranking the factors that tend to control an ISSPS,
2. to develop an analytical tool for identifying and ranking the factors that can be used as performance indicators in an ISSPS,
3. to develop an analytical tool for identifying and ranking the factors that are the root causes of poor performance in an ISSPS, and
4. to evaluate the above-mentioned tools by applying them in four relatively diverse ISSPSs.

The specific objectives of the study were:

(a) to carry out literature reviews on the various methodology and tools that are used to analyse complex systems, with a particular focus on complexity, network analyses and the Theory of Constrains,

(b) to briefly review the four sugarcane milling areas in which the approaches that were developed in this study were tested and to discuss the main factors and issues in each area,

(c) to draw up an inventory of pertinent factors that negatively affect the performance of ISSPSs,

(d) to develop a generic cause-and-effect network of ISSPSs based on the inventory in the previous step,

(e) to weigh-up the strength of different cause-and-effect pathways within the four sugarcane milling areas,

(f) to identify the driver factors in each of the four sugarcane milling areas,

(g) to identify the factors that can be used as performance indicators in each of the four sugarcane milling areas,

(h) to identify the root causes of problems in each of the four sugarcane milling areas, and

(i) to make recommendations on how to effectively analyse and improve the performance of ISSPSs.

1.2 Scope of the Study

It is important to note the following from the onset of the study:

- Literature reviews were carried out on various approaches and tools that are used to analyse complex systems. Only the literature that was considered pertinent to this study is presented in this thesis.
- Descriptions of the four sugarcane milling areas that were studied have been provided, but it should be noted that these descriptions do not provide all the details about the milling areas.
- This study concerned primarily the development of new methodologies and not the analyses of the specific mill areas that were used as case studies. For that reason the approaches that were developed in this study were applied in four sugarcane milling areas in South Africa to test their effectiveness. It was not the objective of this study to provide a comprehensive analysis of specific milling area issues, but rather to evaluate the methodologies that were developed.
- Basic mathematical expressions have been used to represent the approaches that were developed in this study. It was not the objective of this study to develop rigorous mathematical representations of the approaches.
- Several algorithms and spread sheets were used in this study to facilitate computations. The algorithms and spread sheets are not included in this document so that they do not distract the reader from the purpose of the study. The algorithms and spread sheets will be published on the internet.
- Qualitative data obtained from interviews with stakeholders were used to weigh-up the cause-and-effect pathways in the different mill areas. The data collection process was not a part of this study and the accuracy of the data that were used to construct the milling areas' networks may have had an effect on the results. The data were however deemed to be sufficient for testing the approaches, but not necessarily representative enough to make strong recommendations in the four milling areas.

- No systematic comparisons were made between the approaches that were developed in this study and those that are currently used to analyse complex systems because of time constraints. It is hoped that this would be addressed by future research.
- The approaches developed in this study are not designed to analyse the dynamic behaviour of systems over time. Rather, the approaches are designed for the continuous improvement of the performance of systems, which is an on-going process.

1.3 Roadmap of the Study

This thesis consists of 9 chapters starting with the introduction in Chapter 1 and ending with conclusions and recommendations for future research in Chapter 8. The references cited in the thesis are listed in Chapter 9. The rest of the thesis is arranged as follows. Chapter 2 contains a discussion of network theory and complex systems. The chapter starts with the introduction of the terminologies that are used in network theory. It then discusses the effects that complexity has on the performance and management of systems. Applications of network theory in the management of complex systems are discussed towards the end of the chapter. Chapter 3 contains a review of the Theory of Constraints. The chapter briefly introduces the Theory of Constraints and then discusses the applications of the Theory of Constraints in the continuous improvement of the performance of systems. A detailed discussion is made on how the Theory of Constraints is used to identify root problems in systems. The limitations of the Theory of Constraints are discussed towards the end of the chapter. Chapter 4 contains a discussion of two well established systems analysis methods; *viz*. (a) indicator analysis and (b) root cause analysis. Some of the well known analytical tools that are used for carrying out indicator and root cause analyses in systems are discussed. The weaknesses of the tools are also discussed. Chapter 5 provides a description of four sugarcane milling areas on which the approaches that were developed in this study were tested. The descriptions are limited to the main factors and issues in the milling areas. Chapter 6 contains a description of the processes that were followed to develop the network theory approaches and the procedures that were followed to test the approaches in the four sugarcane milling areas. Chapter 7 contains a discussion of the results that were obtained from the analyses of the sugarcane milling areas.

2. AN INTRODUCTION TO NETWORK THEORY AND COMPLEX SYSTEMS

This chapter contains a discussion of the network theory and complex systems. Section 2.1 contains a description of the terminologies that are used in network theory. Section 2.2 contains a description and examples of complexity and complex systems. Section 2.3 contains a discussion on how complexity affects the performance and management of systems. Section 2.4 contains a discussion on how network theory is applied in the modelling and the analysis of complex systems. Section 2.5 provides a final brief summary of this chapter.

2.1 Network Theory Terminologies

Network theory employs methods from graph theory, algebra and statistics to model and analyse systems. Literature is available that describes the terminologies that are used in network theory (*e.g.* Bollobás, 1998; Diestel, 2000; Gross and Yellen, 2006). Differences in terminologies exist between different authors and disciplines. The following section describes some of these terminologies. The scope of the descriptions has been limited to those terminologies that are used later in this study. It must be mentioned that every effort was made to conform to a standard that is widely accepted. Wherever a new terminology has been used special mention has been made to that effect.

2.1.1 Components of a network

A network ***G*** consists of (a) a collection of objects in the system being modelled and (b) a collection of pair-wise relationships between the objects in the system. Networks can be represented graphically in the form of network diagrams, otherwise simply called networks. The objects are represented in a network by dots called vertices (vertex for singular). The pair-wise relationships among the objects are represented by either lines called edges or unidirectional arrows called arcs. An edge is used where the relationship between two objects is mutual, while an arc is used where the direction of a relationship is important. For example, if person A and person B are friends, the relationship between A and B is represented in a network by an edge drawn between A and B. On the other hand, if event A affects or causes event B, then the relationship between A and B is represented in a network by an arc drawn from A to B. The vertex located at the tail of an arc is called the initial vertex or the sender vertex. Conversely, the vertex located at the head of the arc is called the terminal vertex or the receiver vertex. The terms sender vertex and receiver vertex will be used in this study. When relationships between objects are represented by arcs in a network, such a network is said to be directed. Undirected networks (with edges) were not used in this study.

A collection of vertices in a network is called a vertex set V, while a collection of arcs is called an arc set, A. A vertex v_i in a network is said to be an element of V ($v_i \in V$), and likewise an arc a_i is an element of A ($a_i \in A$). A network, $\boldsymbol{G}$, can therefore be considered as a pair $\boldsymbol{G} = (V, A)$, where A comprises ordered pairs of vertices (*e.g.* vertices v_x and v_y) such that $v_xv_y \in A$. Note that $v_xv_y \in A$ is different from $v_yv_x \in A$. For the purpose of this study, any two vertices v_x and v_y can only be joined by one arc (*i.e.* arcs v_xv_y and v_yv_x cannot occur simultaneously in a network). This is because this study does not allow direct cause and effect reversal between pairs of factors. This study does also not allow a vertex to be joined to itself by an arc (*i.e.* an arc v_xv_x is not permissible). This is because this study assumes that a factor cannot have an effect on itself. Two vertices v_i and v_j are said to be adjacent if they are connected by an arc v_iv_j. The arc v_iv_j is said to be incident to v_i and v_j.

When a network is used to model a system where the relationships among the objects in the system are of a cause-and-effect nature, the sender and receiver vertices represent the cause and effect, respectively. For example, in an ISSPS, drought may cause low sugarcane yields. Hence the relationship between drought (say v_x) and low sugarcane yield (say v_y) would be represented in a network by an arc ($v_xv_y \in A$), where drought and low sugarcane yields are the sender and receiver vertices, respectively. The size of a network is denoted by $|V(\boldsymbol{G})|$ and represents the number of its vertices. The number of arcs in a network is denoted by $|A(\boldsymbol{G})|$.

2.1.2 Weighted networks

When a network has real values assigned to its arcs, such a network is termed a weighted network. An arc a_i in a weighted network is assigned a numerical value (usually a real number) termed a weight. The weight w_i of an arc a_i between two vertices v_x and v_y is denoted $w(a_i)$ or $w(v_xv_y)$. The weight of an arc typically represents the magnitude of the effect that the sender vertex has on the receiver vertex. Figure 2.1 shows an example of a weighted network. The network has a vertex set $V = \{v_1, v_2, v_3, v_4, v_5, v_6, v_7\}$ and an arc set $A = \{v_1v_2, v_2v_3, v_2v_6, v_3v_1, v_3v_4, v_3v_5, v_6v_5, v_7v_6\}$. The numbers on the arcs reflect the arc weights. The weights of the arcs in the network are; $w(v_1v_2) = 2$, $w(v_2v_3) = 5$, $w(v_2v_6) = 3$, $w(v_3v_1) = 4$, $w(v_3v_4) = 5$, $w(v_3v_5) = 7$, $w(v_6v_5) = 8$ and $w(v_7v_6) = 6$.

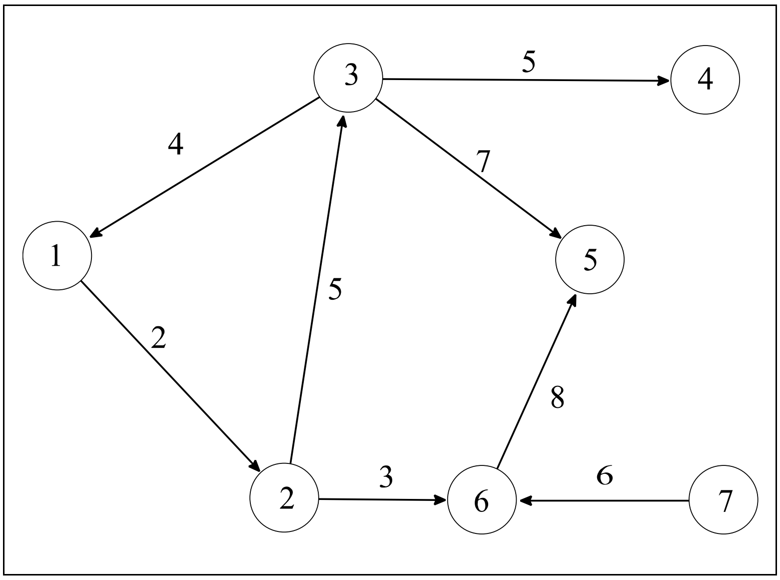


Figure 2.1 An example of a weighted network

2.1.3 Degrees of a vertex

The degree, $d(v_i)$ of a vertex v_i in a network $\boldsymbol{G}$ is the number of arcs incident to v_i. The number of arcs leaving a vertex v_i is termed the out-degree $d^+(v_i)$, whereas the number of arcs entering v_i is termed the in-degree $d^-(v_i)$. The weighted degree $d_w(v_i)$ of a vertex v_i is the sum of the weights of all the arcs incident to v_i. Therefore, the weighted out-degree $d_w^+(v_i)$ of a vertex v_i is the sum of the weights of all the arcs leaving vertex v_i, whereas its weighted in-degree $d_w^-(v_i)$ is the sum of the weights of all the arcs entering v_i. A vertex v_i that has no arc entering it (*i.e.* $d^-(v_i) = 0$) is called a source vertex. A vertex v_i that has no arc leaving it (*i.e.* $d^+(v_i) = 0$) is called a sink vertex. Vertex seven in Figure 2.1 is a source vertex, while v_4 and v_5 are sink vertices. Source vertices of a cause-and-effect network represent the root cause factors of events (good or bad) in the system represented by the network. The term "root cause factor" will be discussed in Section 4.2.

The degree of a network $d(\boldsymbol{G})$ is the sum of the degrees of all the vertices in the network. The general formula for calculating the degree of a network is $d(\boldsymbol{G}) = 2|A(\boldsymbol{G})|$. The average degree of a network $\overline{d(\boldsymbol{G})} = d(\boldsymbol{G})/|V(\boldsymbol{G})|$. The maximum degree of a network $\Delta(\boldsymbol{G})$ is the highest degree across all the vertices in the network, whereas the minimum degree $\delta(\boldsymbol{G})$ is the lowest degree across all the vertices in the network. The foregoing are similarly defined for (d^-) and (d^+) of a network. The respective degree values of the network in Figure 2.1 are shown in Table 2.1.

Table 2.1 Degrees and weighted degrees of the network in Figure 2.1

Degree	**Value**	**Weighted degree**	**Value**
$d^-(G)$	8	$d_w^-(\boldsymbol{G})$	40
$\overline{d^-(G)}$	1	$\overline{d_w^-(G)}$	6
$\Delta^-(\boldsymbol{G})$	2	$\Delta_w^-(\boldsymbol{G})$	15
$\delta^-(\boldsymbol{G})$	0	$\delta_w^-(\boldsymbol{G})$	0
$d^+(\boldsymbol{G})$	8	$d_w^+(\boldsymbol{G})$	40
$\overline{d^+(G)}$	1	$\overline{d_w^+(G)}$	6
$\Delta^+(\boldsymbol{G})$	3	$\Delta_w^+(\boldsymbol{G})$	15
$\delta^+(\boldsymbol{G})$	0	$\delta_w^+(\boldsymbol{G})$	0

The weighted degree of a network $d_w(\boldsymbol{G})$ is the sum of $d_w(v_i)$ for $i = 1 \ldots n$, where $n = |V(\boldsymbol{G})|$. The average weighted degree of a network $\overline{d_w(G)}$ equals $d_w(\boldsymbol{G})/n$. The maximum weighted degree of a network $\Delta_w(\boldsymbol{G})$ is the largest weighted degree over all the vertices in the network, whereas the minimum weighted degree $\delta_w(\boldsymbol{G})$ is the smallest weighted degree over all the vertices in the network. The foregoing are similarly defined for d_w^- and d_w^+ of a network. The respective weighted degree values of the network in Figure 2.1 are shown in Table 2.1.

2.1.4 Importance of a vertex

Numerous measures of the relative importance of individual vertices in networks (and hence the relative importance of factors in systems that the networks represent) can be found in literature. Examples include degree centrality, closeness centrality, betweenness centrality (Freeman, 1978; Bonacich, 1987; Borgatti, 2005; de Nooy *et al.*, 2005; Dall'Asta *et al.*, 2006; Kiss and Bichler, 2008; Opsahl *et al.*, 2010), eigenvector centrality (Ruhnau, 2000; Bonacich, 2007), degree-degree centrality, degree-closeness centrality, degree-betweenness centrality

(Abbas and Hossain, 2013), h-degree (Zhao *et al*., 2011), Weighted Factor Analysis (Hessami and Hunter, 2002), the Authority score and Hub score (Kleinberg, 1999). Most of the measures tend to be suited to specific situations depending on the objectives of the situation. For example, degree centrality is an important measure in social network analysis (de Nooy *et al*., 2005; Abbas and Hossain, 2013). It is used to measure the popularity of an individual in a community, such that the higher the degree centrality of a vertex, the more popular is the individual represented by the vertex. Degree centrality may however not be as useful in other applications. For example, degree centrality may not be a good measure to determine the root cause of problems in a complex system. Additionally, literature (*e.g*. Antoniou and Tsompa, 2008) states that the statistical parameters that are used for analysing non weighted networks may not be sufficient for the analysis of weighted networks, unless all the arcs in the weighted network have equal weights. The aforementioned may explain two issues; (a) the relatively high number of measures of the importance of vertices in a network and (2) the relatively large volume of research on either new measures of the importance of vertices or improvements on the existing ones (*e.g*. Hessami and Hunter, 2002; Canright and Engo-Monsen, 2004; Abbas and Hossain, 2013; Zhao *et al*., 2011). It can therefore be argued that more measures of the importance of vertices will continue being developed to address specific situations.

2.1.5 Path and distance analyses in a network

A path P is an alternating sequence of vertices and arcs where all arcs point in the same direction. The sequence begins and ends with a vertex in such a way that each vertex is incident to both the arc that precedes it and the arc that follows it in sequence. A path on n vertices (where $n > 1$) is denoted P_n. A path exists on n vertices when the vertices can be presented as $\{v_1, v_2, ..., v_n\}$, such that all the arcs $\{v_1v_2, v_2v_3, ..., v_{n-1}v_n\}$ exist within A. The length of a path is the number of arcs it contains. Thus the length of P_n always equals n-1. When a path begins and ends with the same vertex (*i.e*. $v_1v_2, v_2v_3, ..., v_{n-1}v_n, v_nv_1$), then the path is termed a cycle C_n. Some authors (*e.g.* de Nooy *et al*., 2005) use the term feedback loop instead of a cycle.

The distance $l(v_iv_j)$ between two vertices v_i and v_j in a network is the length of the shortest path P_n between the two vertices. When v_i and v_j cannot reach each other, then $l(v_iv_j)=\infty$.

Vertex v_j is said to be reachable from vertex v_i if there is at least one path from v_i to v_j. It is not implicit that if v_i can reach v_j then v_j can also reach v_i.

2.1.6 Neighbours in a network

Most networks and graph theory literature (*e.g*. Bollobás, 1998; Diestel, 2000; Gross and Yellen 2006) call adjacent vertices neighbours. However, some authors (*e.g*. de Nooy *et al*., 2005) use the term neighbours to refer to all vertices that can either reach a given vertex v_i or can be reached from it. This study uses the latter definition for neighbour. Such being the case, v_i is said to be a neighbour of v_j if v_i can reach v_j or if v_j can reach v_i. A neighbour NB of a vertex v_i is denoted $NB(v_i)$. If v_i can reach v_j, then v_i is said to be an in-neighbour $NB^-(v_j)$ of v_j. Otherwise v_j is an out-neighbour $NB^+(v_i)$ of v_i if v_j is reachable from v_i. A k^{th} qualification (where k is the distance) is used to classify the neighbours of a vertex according to their respective distance from the vertex. For example, if a vertex v_i has three out-neighbours v_x, v_y, and v_z located at respective distances of one, two and three from v_i, then v_x, v_y, and v_z are the 1^{st}, 2^{nd} and 3^{rd} out-neighbours of v_i, respectively.

2.1.7 Sub networks

A network $\boldsymbol{H} = (W,F)$ is a sub network of the network $\boldsymbol{G} = (V,A)$ if $W \subseteq V$ and $F \subseteq A$. A sub network is created by either or both of the following procedures; (a) deleting some vertices of a network (all arcs incident to the deleted vertices are automatically removed) or (b) deleting some arcs of a network. A sub network of $\boldsymbol{G}$ that is created by removing a vertex v_i is denoted $\boldsymbol{G}$-v_i, while a sub network that is created by deleting an arc a_i is denoted $\boldsymbol{G}$-a_i.

2.2 A Description and Examples of Complex Systems

Fredendall and Gabriel (2003) and Homer-Dixon (2011) assert that complexity is so difficult to define that some of the world's leading complexity thinkers resort to describing the properties of complex systems. Various descriptions of a complex system can be found in the literature (*e.g*. Frizelle and Woodcock, 1995; Cilliers, 2000; Sivadasan *et al*., 2002; Fredendall and Gabriel, 2003; Valentine, 2003; Christensen and Albert, 2007; Wu *et al*., 2007; Zhang, 2007; Homer-Dixon, 2011). For example, Zhang (2007) describes a complex system as being composed of a large number of components with a high degree of connectivity among the components. Wu *et al*. (2007) describe complexity in supply chain management as implying a large number of components, a high degree of connectivity and interaction among the components, low predictability, high uncertainty and high variety in products and system states. Cilliers (2000) and Homer-Dixon (2011) provide a summary of the general characteristics of a complex system. They explain that a complex system is an open system whose boundaries cannot be easily defined. The system is composed of a large number of components, which interact in a non-linear and dynamic manner. They add that a complex system is characterised by the presence of many direct and indirect feedback loops among its components. They further add that the behaviour of a complex system is determined by how its components interact and hence cannot be predicted from the behaviour of an individual component. In addition, they describe a complex system as being adaptive such that it can self (re)organise its internal structures without external intervention. Furthermore, they state that a complex system has memory which plays an important role in the way it behaves**.**

Christensen and Albert (2007) state that most natural and human made systems are complex. They give examples of complex systems that include; the World Wide Web, the Internet, neural networks, social networks, urban street systems and cellular networks. Choi *et al*. (2001) and Wu *et al*. (2007) indicate that supply chain networks are complex systems. Bezuidenhout (2008), Le Gal *et al*. (2008), Lejars *et al*. (2008) and Le Gal *et al.* (2009) state that the South African sugar industry is a complex system. They add that the complexity of the industry is more evident in its sugarcane supply chains. The foregoing is an agreement with what was earlier explained in Chapter 1.

2.3 Management Challenges in Complex Systems

Complexity affects the way in which systems are managed and how they perform in both a positive and negative way (*cf*. Homer-Dixon, 2011). Due to the nature of this study, this review will dwell on the challenges that complexity has on the management of systems. Literature (*e.g*. Frizelle and Woodcock, 1995; Cilliers, 2000; Choi *et al*., 2001; Frizelle and Suhov, 2008; Archer *et al*., 2009) indicate that complexity generally makes it difficult to manage systems. Homer-Dixon (2011) states that complexity may bring forth a managerial overload which may result in a system breakdown if it exceeds a certain limit. Cilliers (2000) and Homer-Dixon (2011) argue that it is difficult to understand the nature and to accurately predict the behaviour of complex systems. This, they explain, is due to; (a) the dynamic and nonlinear interactions among the components of complex systems and (b) the presence of many feedback loops in complex systems. Frizelle and Woodcock (1995) state that poor understanding of the nature of interactions among the components of a complex system is one of the major challenges that are encountered by managers when developing a management strategy. Choi *et al*. (2001) observe that complexity has often frustrated efforts to improve the performance of supply chains. This is because managers are often unable to predict and control supply chains. Sivadasan *et al*. (2002) explain that the amount of information required to monitor and manage a system increases with an increase in its complexity. Battini *et al*. (2007) argue that the performance of a system is strongly dependent on its level of complexity and that high efficiencies are achieved at low levels of complexity.

The management of complexity has been a subject of interest over the years. Frizelle and Suhov (2008) report that managers of systems are becoming increasingly keen to understand complexity. Theories have been developed, research has been done and publications have been written to assist in understanding the complexity in systems (*e.g*. Frizelle and Woodcock, 1995; Cilliers, 2000; Cilliers, 2001; Battini *et al*., 2007; Christensen and Albert, 2007; Frizelle and Suhov, 2008). However, a good understanding of complexity and how it affects the performance of systems is yet to be achieved. Cilliers (2001) acknowledges that it is difficult to develop comprehensive and accurate models of complex systems. He attributes this partly to the open nature of complex systems and the nonlinear interaction of components in the systems. He explains that the former makes it impossible to accurately define the boundaries of a complex system. The latter, he explains, makes it difficult to determine the components that must be included and excluded in the models. He further explains that under nonlinear conditions what might be excluded from a model on the assumption that it may not be significant may be the most significant component after all. Nonetheless, Wu *et al*. (2007) strongly insist on the need to obtain a clearer understanding of the nature of complexity.

2.4 Applications of Network Theory in Complex Systems

Networks theory has been widely and successfully used to model complex natural and human made systems. Typical network models that can be found in the literature include; social networks, biological networks, communication networks and author co-citation networks (Albert and Barabasi, 2002; Newman, 2003; Li and Cai, 2004; Xu *et al*., 2004; Battini *et al*., 2007; Suderman and Hallett, 2007; Costa *et al*., 2011). The popularity of network theory can partly be attributed to the simple and robust structure of networks (Canright and Engo-Monsen, 2004). This makes the modelling of systems using networks relatively easy.

Network theory has also been used to analyse and solve a variety of problems in a wide range of systems. For example, Brueckner (2005) used network theory to investigate the internalisation of airport congestion costs. Zhao *et al*. (2007) developed network theory based criteria for designing an optimal network structure to minimise traffic congestion. Cohen *et al*. (2001) used network theory to investigate the vulnerability of the internet to breakdown from intentional attacks. Xu and Chen (2003) developed network theory based approaches for analyzing criminal networks. Battini *et al*., (2007) used network theory to study supply chain networks.

In addition to normal statistical analyses, networks also allow for the visual analysis of systems (*e.g*. Xu *et al*., 2004; Suderman and Hallett, 2007; Raymond and Hosie, 2009). Networks provide a powerful tool for visualising and exploring a variety of data in a graphical form. Purchase (2000), de Moya-Anegon *et al*. (2007) and Raymond and Hosie (2007) note that there is a general acceptance (with few exceptions) that data is easier to visualise and comprehend when presented graphically than in a tabular form. There are many and diverse examples of the application of network visualisation. Ma *et al*. (2009) used network analysis techniques to visualise the author co-citation matrix of information science in China. Pilkington and Meredith (2009) used network visualisation to show how the intellectual structure of the operations management field progressed from 1980 to 2006. Ortega and Aguillo (2008) used network visualisation to understand the structural topology of the Nordic academic web. Raymond and Hosie (2009) used network visualisation to reveal marine zooplankton community structures in the Southern ocean.

Several algorithms are used for displaying vertices and arcs to best facilitate visualisation to the user. De Moya-Anegon *et al*. (2007) and Suderman and Hallett (2007) observe that most of the algorithms that are used for the layout of networks are the spring-embedder type (*e.g*. Eades, 1984; Kamada and Kawai, 1989; Fruchterman and Reingold, 1991). These algorithms represent vertices as masses and arcs as springs that pull connected vertices close together and push unconnected ones further apart until the network layout reaches an equilibrium (Kamada and Kawai, 1989; Ebbels *et al*., 2006; Suderman and Hallett, 2007; Pilkington and Meredith, 2009). The Kamada-Kawai algorithm is the most commonly used in the scientific community (de Moya-Anegon *et al*., 2007). Some advantages of the Kamada-Kawai algorithm include; its ability to produce symmetric networks and the relatively low number of crossings of arcs (Kamada and Kawai, 1989). De Moya-Anegon *et al*. (2007) observe that the Kamada-Kawai algorithm is faster and fewer vertices and arcs overlap or cross each other compared to the Fruchterman Reingold algorithm.

Several software packages are used for the analysis and visualisation of networks. The most well-known packages include; UCINET, Pajek and NetMiner (Huisman and Van Duijn, 2005). The Pajek software is popular and widely used in the analysis of networks. The book on Pajek by de Nooy *et al*. (2005) alone has been cited more than 260 times in the formal peer reviewed literature. There are diverse examples in the literature where Pajek was successfully used (*e.g*. Li and Ma, 2008; Ma *et al*., 2009; Nor *et al*., 2009; Piao *et al*., 2009; Gonzalez-Alcaide *et al*., 2010; Graeml *et al*., 2010; Piao *et al*., 2010). For example, Ma *et al*. (2009) used Pajek to analyse author co-citation in the field of information science in China. Piao *et al*. (2009) successfully used Pajek to visualise agent relationships in an e-commerce transaction network. They concluded by proposing the integration of multi-agent modelling, open application programming interfaces and social network analysis as a new way to study large-scale e-commerce systems.

The popularity of Pajek can be attributed to the advantages it offers. The Pajek software has a good capability to handle very large networks (Huisman and Van Duijn, 2005; de Nooy *et al*., 2005; Mueller *et al*., 2007). Xu *et al*. (2010) observe that Pajek software can perform complex network analyses, can facilitate the reduction of a large network into several smaller networks that can further be analysed using sophisticated methods, has powerful network visualisation tools and allows for the implementation of a selection of efficient network algorithms. Additionally, Mueller *et al.* (2007) compared Pajek to other network analysis software and found it to be appropriate for supply chain related research studies. Furthermore, the Pajek software is free of charge for non commercial use (Huisman and Van Duijn, 2005).

2.5 Summary

The discussions in this chapter have revealed that most natural and human made systems are complex. The discussions have also revealed that complexity negatively affects the performance and management of systems. It is acknowledged in the discussions that a good understanding of complexity and how it affects the performance of systems has not yet been achieved. The discussions have further revealed that network theory provides effective tools for modelling and analysing complex systems. Networks may provide a relatively easy tool for modelling systems owing to their simple and robust structure. Network analyses provide statistics for measuring the relative importance of factors in systems. It is, however, acknowledged that most of these statistics tend to be suited to specific applications. It is also acknowledged in the discussions that more statistics for measuring the relative importance of factors in systems will continue being developed to address specific situations.

3. THEORY OF CONSTRAINTS

This chapter contains a discussion of a systems management philosophy named the Theory of Constraints (TOC). The discussion starts with the introduction of the TOC, followed by a description of its underlying principles. The analytical tools that the TOC uses for the management of systems are discussed. The tool that the TOC employs for identifying the root causes of problems in systems is discussed in detail. The limitations of the TOC are outlined towards the end of the chapter.

3.1 Introduction to the Theory of Constraints

The Theory of Constraints is a well adopted management philosophy that was developed by Goldratt (1990) for the continuous improvement of systems performance (Womack and Flowers, 1999; Blackstone, 2001; Fredendall *et al*., 2002; Mabin and Baldestone, 2003; Schaefers *et al*., 2004; Simatupang *et al*., 2004; Gupta and Kline, 2008; Kim *et al*., 2008; Inman *et al*., 2009). The philosophy is based on Systems Thinking (Mabin, 1999; Gupta *et al*., 2002; Mabin and Balderstone, 2003; Scoggin *et al*., 2003; Taylor and Churchwell, 2004). Such being the case, TOC focuses on the overall performance of a system, rather than that of an individual task or component in the system. It is recognised that every system has specific elements that limit its performance. These elements are called constraints (Rahman, 1998; Mabin, 1999; Smith, 2000; Blackstone, 2001; Gupta *et al*., 2002; Mabin and Balderstone, 2003; Schaefers *et al*., 2004; Simatupang *et al*., 2004; Gupta and Kline, 2008). A constraint is defined by Goldratt and Cox (1992) as "any element or factor that limits the system from doing more of what it was designed to accomplish (*i.e*. achieving its goal)". Systems' constraints may be physical (*e.g*. machines, specialised personnel or raw materials), policy (when the policies of an organisation are not adjusted in response to changes taking place within the environment it operates) or behavioural (existing practices in an organisation). Rahman (1998) claims that most organisations have more policy constraints than physical ones. The Theory of Constraints asserts that there are only a few constraints in any given system; usually just one (Mabin and Baldestone, 2003; Schaefers *et al*., 2004; Simatupang *et al*., 2004). Managers are encouraged under the TOC philosophy, to identify and eliminate the constraints in the systems that they manage (Simatupang *et al*., 2004).

3.2 Components of the Theory of Constraints

The Theory of Constraints consists of three components; *viz*. (a) an operational strategy consisting of five focussing steps for the continuous improvement of systems, (b) the Thinking Process tools for investigating, analysing and solving complex problems, and (c) a measurement system for assessing the performance of a system relative its goals (Rahman, 1998; Chaudhari and Mukhopadhyay, 2003; Mabin and Balderstone, 2003). Figure 3.1 shows the three TOC components. These components will be discussed in subsequent sections.

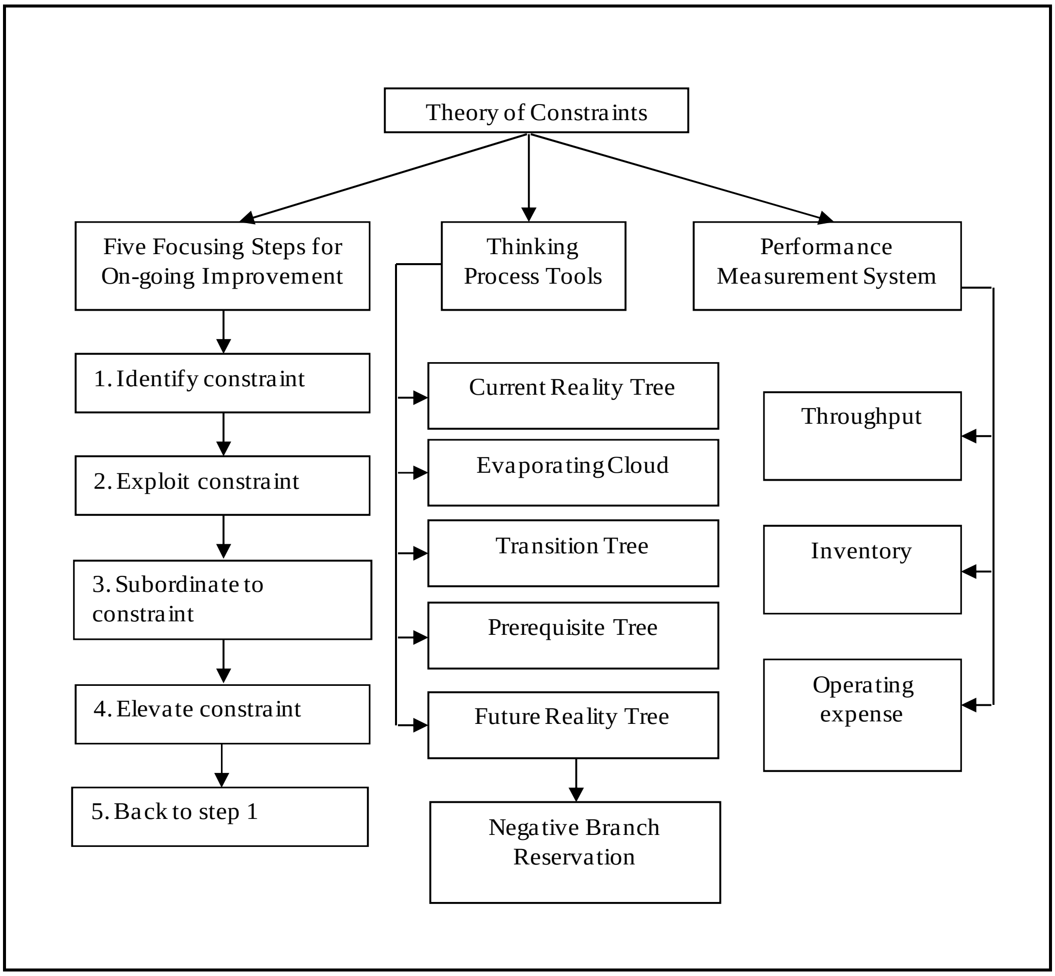


Figure 3.1 Components of the Theory of Constraints

3.2.1 The Theory of Constraints five focussing steps

Theory of Constraints provides a five-step process, called the five focussing steps (FFS), for achieving the continuous improvement of a system's performance (Goldratt and Cox, 1992). The FFS are outlined by Goldratt and Cox (1992) as follows; (1) identify the system's constraint(s), (2) exploit the constraint(s), (3) subordinate to the constraint(s), (4) elevate the constraint(s) and (5) go back to Step (1) and never allow *inertia* to become the next constraint.

The Theory of Constraints FFS process begins by identifying the system's constraint. Once a constraint has been identified, steps are taken to maximise the efficiency of the constraint without using any additional resources - a process called "exploiting the constraint". Thus, in the case of a physical constraint, the constraint is operated in such a way as to obtain the highest output possible from its existing capacity. Policy constraints, on the other hand, must not be exploited, but rather, eliminated from the system as pointed out by Rahman (1998). The third step of the FFS process involves subordinating the performance of non-constraint factors in-line with the constraint. The performance of all non-constraint components is adjusted in such a way as to support the maximum performance of the constraint. Whenever possible, extra non-constraint capacities are utilised to boost the capacity of the constraint. In an event that the previous steps fail to break the constraint, additional capacity must be acquired for the constraint (*i.e*. elevate the constraint). Elevating a constraint may be achieved by among other things investing in new equipment and increasing staff numbers. On the other hand, if a constraint has been broken at any stage of the FFS process, one must go back to Step 1 (identify a new constraint) and repeat the process. Step 5 of the FFS tells TOC users never to allow *inertia* become the next constraint. This fifth step not only ensures continuous improvement of a system's performance but also reminds FFS users that no solution is appropriate for all time or in every situation (Rahman, 1998). Once a constraint has been broken, then another component within the system will become the next constraint according to the TOC philosophy *i.e*. every system has at least one constraint. It is argued (Mabin, 1999; Gupta *et al*., 2002; Davies *et al*., 2005; Gupta and Kline, 2008; Dalton, 2009) that the TOC's FFSs provide a means for continuously identifying and managing systems' constraints.

3.2.2 The Theory of Constraints Thinking Process

Organisations must continuously transform and adapt to their ever changing environment if they are to survive and flourish. Managers must therefore continually assess the performance of their organisations and periodically implement positive changes. Scoggin *et al*. (2003) indicate that successful implementation of positive organisational changes requires managers to possess the capability to; (a) measure, assess and analyse the existing situation in-line with organisational goals, (b) formulate relevant action plans to effectively address organisational problems, and (c) successfully manage the implementation of the formulated action plans. The TOC approach to change management (Goldratt, 1990) involves finding answers to three basic questions; (a) what to change, (b) what to change to, and (c) how to cause the change. Koljonen and Reid (1999) state that the answers to the three questions are the ones that provide managers with a roadmap on how to successfully implement positive organisational changes.

The Theory of Constraints provides a set of logic-based tools called Thinking Process (TP) tools to guide managers to find answers to the three change management questions (Rahman, 1998; Mabin, 1999; Fredendall *et al*., 2002; Mabin and Balderstone, 2003; Scoggin *et al*., 2003; Kim *et al*., 2008). The tools comprise a suite of five cause-and-effect diagrams and an ancillary tool that are constructed to represent situations in systems (Mabin and Balderstone, 2003; Kim *et al*., 2008; Inman *et al*., 2009). It is important to note that the construction of the cause-and-effect diagrams is done manually and as a group work. Strict logic rules called Categories of Legitimate Reservations (CLR) are used in the construction, interpretation and validation of the cause-and-effect diagrams (Scoggin *et al*., 2003). An outline of the five TP tools is provided by Scoggin *et al*. (2003) as; (1) the Current Reality Tree (CRT), (2) the Evaporating Cloud, (3) the Future Reality Tree, (4) the Prerequisite Tree and (5) the Transition Tree. The ancillary tool is called the Negative Branch Reservations. The tools help TOC users to identify problematic symptoms called undesirable effects (UDEs) which act as indicators of the poor performance of a system, find the causes of the UDEs, determine what to do to eliminate the causes, ascertain the impact of interventions designed to eliminate the causes, and map the way forward on how to manage the change process required to improve the performance of the system (Scoggin *et al*., 2003; Kim *et al*., 2008, Inman *et al*., 2009). Mabin (1999) describes TP tools as a roadmap that is used to guide the process of structuring and identifying problems, coming up with solutions to problems, identifying the barriers likely to be encountered in implementing a solution, and ultimately implementing the solution. Table 3.1 shows a summary of the respective roles of TOC TP tools in a change management process, while a roadmap for the TOC TP is presented in Figure 3.2.

Table 3.1 Change sequence, TOC tools and managerial utility relationships (after Scoggin *et al*., 2003)

Change sequence question	Thinking Process tools	Management purposes
What to change?	1. Evaporating Cloud 2. Current Reality Tree	• Establish a basis for understanding system patterns that currently exist • Identify basic conflicts, core problem(s) or the drivers for undesirable effects • Provide entity linkages between the core problem(s) and undesirable effects
What to change to?	1. Future Reality Tree 2. Negative Branch Analysis	• Validate the effectiveness of the proposed solutions • Identify undesirable side-effects of proposed solutions and their corrections
How to cause the change?	1. Prerequisite Tree 2. Transition Tree	• Identify obstacles preventing achievement of a desired course of action • Denote necessary conditions relationships involved in objective attainment • Provide a step-by-step tactical action plan for implementation • Communicate action rationales to others

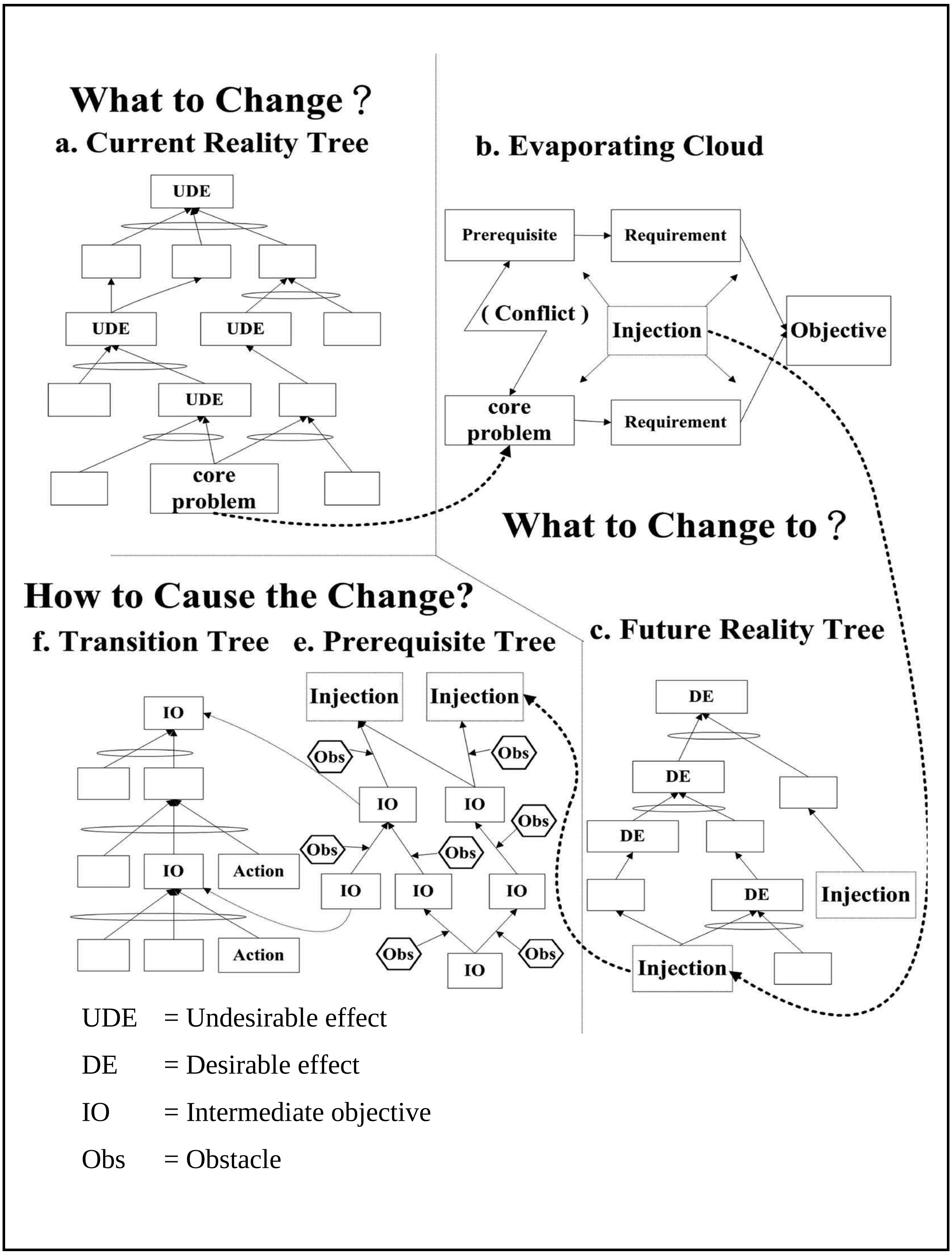


Figure 3.2 Theory of Constraints Thinking Processes roadmap (Lin *et al*., 2009)

The TOC TP is reputed to be powerful and versatile. Noreen *et al*. (1995) describe the TP as "may be the most important intellectual achievement since the invention of calculus". Kim *et al*. (2008) argues that decision makers who possess the knowledge of TP tools can effectively and efficiently solve complex problems. It is further argued (Dettmer, 1999; Mabin and Balderstone, 2000) that TP tools can be applied to a variety of problem situations in any system. He further argues that the broader potential of TP tools application arises from two unique characteristics they possess; *viz*. (a) the ability to handle relatively abstract quality and productivity problems that manifest themselves through paradigm or policy constraints; and (b) their ability to accommodate the interdependent relationships between systems components. Rahman (1998) describes the TP approach as being effective in addressing policy constraints. The ability of TP tools to address policy constraints is considered particularly important considering that most of the physical constraints are brought about by non-physical constraints (Chaudhari and Mukhopadhyay, 2003) and that it is generally difficult to identify non-physical constraints in systems (Rahman, 1998). Davies *et al*. (2005) single out the ability of the TOC TP to provide better understanding of situations as one of its strengths. They explain that TP tools are capable of capturing different perceptions and alternative conceptualisations and at the same time allow for accommodation and consensus to be attained among stakeholders. They further explain that TP tools allow for different sides to be heard and hence achieving greater enlightenment and empowerment. The following paragraphs in this section will discuss the CRT and the CLR because of their relevance to this study.

The Current Reality Tree

The Theory of Constraints is based on the premise that the lowest performing component or process in a system is the constraint. It is therefore argued that any effort aimed at improving the overall performance of a system must be directed at increasing the performance of this constraint (Goldratt, 1990). The argument is supported by Dalton (2009) who states that improving the performance of a non-constraint is wasted effort because the constrained component will still be regulating the performance of the system. Goldratt (1990) further argues that the process of improving the performance of a system must always start with identifying a constraint in the system. The argument is echoed by Rahman (1998) who emphasises the importance of identifying the system’s constraints and the necessity to prioritise them based on their impact on the goal of the system. It is pointed out by Taylor and Churchwell (2004) that most managers are aware of the importance of identifying problems in the systems they manage, but they argue that the major challenge that managers face is to identify the right problem(s) to solve. Many tools have been developed over the years to help managers in identifying constraints in systems, such as cause-and-effect diagrams (Fredendall *et al*., 2002).

The Theory of Constraints uses the CRT to identify constraints in systems (Cox *et al*., 2003; Scoggin *et al*., 2003). The Current Reality Tree is a tree diagram that employs cause-and-effect logic to identify core problems in the system under consideration and to determine what must be changed (Mabin, 1999; Fredendall *et al*., 2002). Mabin (1999) and Fredendall *et al*. (2002) describe the CRT as a cause-and-effect tree diagram that is used to identify core problems in systems and to determine what must be changed. The CRT is specifically designed to identify what needs to be changed to bring about the greatest improvement in the overall performance of a system (Kim *et al*., 2008). It is argued (Kim *et al*., 2008) that the CRT is an effective tool when dealing with policy constraints.

A discussion on how to construct a CRT is given by Fredendall *et al*. (2002). The process involves; (a) coming up with a list of undesirable elements (UDEs) of the problem (*i.e*. the symptoms that indicate that a system is not performing as desired), (b) establishing cause-and-effect connections between the UDEs, (c) constructing cause-and-effect chains to validate the UDEs, and (d) identifying root causes and the core problem. They further use an example of a car failing to start in the morning to give a detailed explanation on how to construct and validate a CRT (see Figures 3.3 and 3.4).

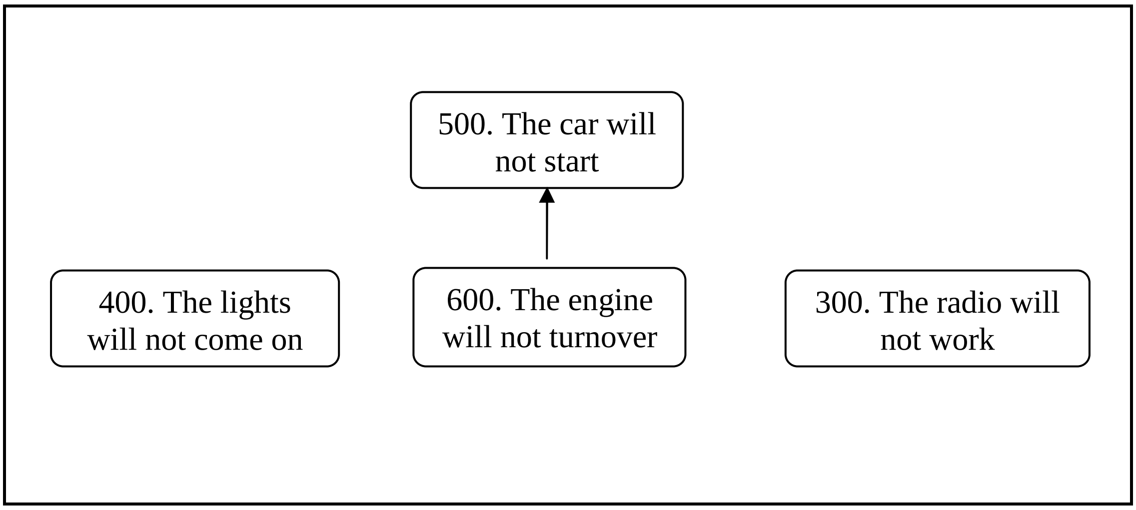


Figure 3.3 Undesirable effects and initial connection for the Current Reality Tree (Fredendall *et al*., 2002)

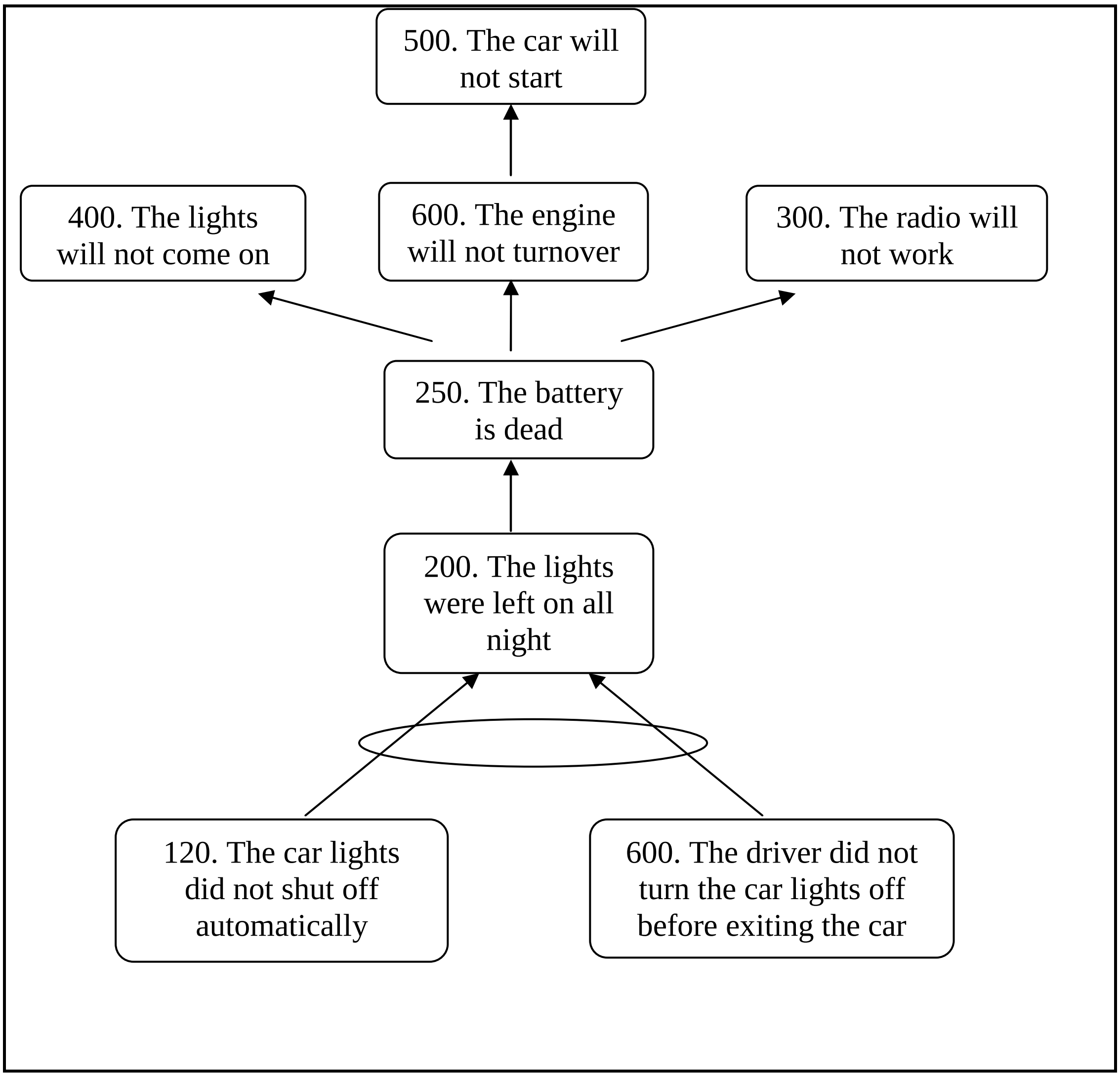


Figure 3.4 Complete Current Reality Tree (Fredendall *et al.*, 2002)

Figure 3.3 contains a list of UDEs for the failure of the car to start in the morning. The list of UDEs may be generated through brainstorming. The UDEs are always numbered to simplify their scrutiny. As an example, the UDE "the car will not start" has been numbered 500. The next step involves the establishment of causal connections between the UDEs. This is done by connecting the UDEs with arrows. For instance, the arrow from 600 to 500 shows that 600 has caused 500. The CRT is read using "*if…then…*" logic from the bottom proceeding upwards. Thus the connection of UDEs in Figure 3.3 would be read as "if the engine will not turn over (600), then the car will not start (500). The next step of the CRT development involves the addition of other entities to the original list of UDEs to ensure that a valid and logical relationship is established between the UDEs. Referring to Figure 3.4, the entity "battery is dead (250)" was added to explain UDEs 300, 400 and 600. Similarly, entities 200, 120 and 110 explain why the battery is dead. Lastly, the CRT development process identifies the root cause of a problem, in this example, why the car is not starting. The Theory of Constraints indicates that the root cause is typically at the bottom of the CRT. Thus, in this example, 110 and 120 (Figure 3.4) would be the most likely candidates for a root cause. The author acknowledges that the example given on how to construct a CRT is simple and straight forward. This example was chosen to convey to the reader the basic principles of CRT construction. Thus, the example may not fully portray the difficulties that are encountered when constructing CRTs for complex systems.

Categories of Legitimate Reservation (CLT)

The CLR are a set of logic rules that are used to scrutinise the cause-and-effect tree diagrams that are used in the TOC TP (Balderstone, 1999; Kim *et al*., 2008). The cause-and-effect relationships in the tree diagrams are verified, validated and interpreted using the CLR and thus rendering the diagrams logically authentic. The CLR comprise a set of eight strict rules for auditing the logic in the TP tree diagrams (Dettmer, 1997). The rules are; (a) clarity, (b) entity existence, (c) causality, (d) cause insufficiency, (e) additional cause, (f) cause-effect reversal, (g) predicted effect existence, and (h) tautology. Dettmer (1997) argues that the use of CLR enhances the accuracy and validity of the TOC's TP. Fredendall *et al*., (2002) observes that CLRs ensure increased communication and understanding among those involved with the problem and hence create a consensus among them. Baldestone (1999) observes that the CLR can also be successfully used to validate cause-and-effect diagrams outside the TOC domain and hence proposes their use in the validation of causal loop influence diagrams used in System Dynamics models.

3.3 Applications of the Theory of Constraints

The Theory of Constraints has been applied to a wide range of organisations. Examples of commercial organisations that are known to have applied TOC to their businesses include; Boeing, Delta Airlines, General Motors, General Electric, Ford Motor Company, 3M and Lucent Technologies (Mabin and Baldestone, 2003). Habitat for Humanity, Pretoria Academic Hospital, British National Health Service, United Nations, NASA, United States Department of Defence and the Israeli Air Force are some examples of not-for-profit organisations that have applied TOC to their operations (Watson *et al*., 2007). Watson *et al*.

(2007) report on a number of Fortune 500 companies that have publicly disclosed significant improvements achieved in their organisations as a result of the use of TOC techniques. They also point out that there are a number of companies that have adopted TOC techniques but have chosen to remain anonymous for competitive reasons. Theory of Constraints has also been applied to a wide range of business areas. Blackstone (2001) reports the application of TOC to business areas that include Operations, Finance and Measures, Projects, Distribution and Supply Chains, Marketing, Strategy and Tactics, Sales, and People Management. A meta-analysis by Mabin and Balderstone (2003) of over 80 successful TOC applications found over 100 descriptions of TOC applications, spanning areas such as manufacturing, re-manufacturing, administration, service, military and education. Interestingly though, despite extensive searches, this review found only one paper (Chaudhari and Mukhopadhyay, 2003) reporting the application of the TOC in agriculture (integrated poultry industry).

The high adoption of the TOC by organisations can be attributed to its proven benefits. Inman *et al*. (2009) point out that unlike other management practices, where research indicates that they failed to result in significant economic benefits, there are documented successes of TOC implementation. The literature indicate that the adoption of TOC results in significant improvement in the performance of systems (*e.g*. Aggarwal, 1985; Gupta *et al*., 2002; Mabin and Balderstone, 2003; Watson *et al*., 2007; Inman *et al*., 2009; Lin *et al*., 2009). A survey (Sale and Inman, 2003) and rigorous academic testing (Mabin and Baldestone, 2000; Mabin and Baldestone, 2003) indicate that manufacturing systems that use TOC perform significantly better than those that use some of the other well-known and established manufacturing methods. Watson and Patti (2008) state that systems that employ TOC techniques produce greater levels of output while at the same time reducing inventory, manufacturing lead time, and the standard deviation of cycle time. A meta-analysis of over 80 successful TOC applications by Mabin and Baldestone (2003) came up with the following results; a 70% mean reduction in lead time, a 65% mean reduction in cycle time, a 49% mean reduction in inventory, a 83% mean increase in revenue, a 65% mean increase in throughput, a 116% mean increase in profitability, and a 44% mean improvement in due date performance. Mabin and Balderstone (2000) and Mabin and Balderstone (2003) state that there is evidence that the FFS have been used successfully to improve the performance of systems. Roybal *et al*. (1999) describe how the FFS were used to improve the performance of a mental health and substance abuse organisation. Pegels and Watrous (2005) describe how the FFS were used to achieve a 26% reduction in the amount of time required to complete a mould change in a manufacturing plant. Many examples on the successful applications of specifically the CRT have been reported in literature (*e.g*. Angst *et al*., 1996; Wagoner, 1998; Cox *et al*., 1998; Lenhartz, 2002; Rahman, 2002; Taylor and Sheffield, 2002; Chaudhari and Mukhopadhyay, 2003; Scoggin *et al*., 2003; Cox and Walker, 2006; Umble *et al*., 2006; Walker and Cox, 2006; Lin *et al*., 2009). This may suggest that the nature of this cause-and-effect based approach is powerful for identifying problems in systems.

3.5 Limitations to the Theory of Constraints

Theory of Constraints is not without criticism. Watson *et al.* (2007) argue that considerable length of training time is required to master the TOC process. Button (2000) and Cox *et al*. (2003) indicate that the construction of the TP tools, such as the CRT, is complicated and time consuming. The foregoing often results in the tendency by many top-level managers of delegating the TOC process to mid-level managers (Button, 2000; Cox *et al*., 2003; Watson *et al*., 2007). This tendency, they argue, removes the necessary top-level management support that is always required to sustain the TOC process. Goldratt (1990) argues that the TOC process cannot succeed in an organisation unless all its members develop an enthusiasm for the TOC as the expert facilitating the process. Button (2000) and Kim *et al*. (2008) report that problems often arise when constructing a CRT in that managers may find it hard to admit a problem exists, more especially if the problem in question is a result of bad management practices.

3.6 Summary

This review has shown that the TOC is a powerful philosophy for the continuous improvement of the performance of relatively complex systems. The five focussing steps of the TOC provide an effective approach to continuously improve the performance of systems. The Thinking Process tools provide a roadmap for structuring and identifying problems, coming up with solutions to problems, identifying the barriers likely to be encountered in implementing a solution, and ultimately implementing the solution. The Current Reality Tree provides a basis for understanding the patterns that currently exist in systems. It also provides an effective method to establish cause-and-effect linkages between the symptoms of poor performance in systems and their root causes. The Categories of Legitimate Reservations ensure that the cause-and-effect relationships in TOC TP diagrams are logically authentic. The review has also highlighted some of the weaknesses of the TOC; *viz*. (1) the considerable length of training time required to achieve its mastery, (2) the considerable length of time required to construct the TP tools, such as the CRT, (3) the considerable length of time required to complete the identification and solving of problems, (4) the need for the cooperation and enthusiasm of all the stakeholders involved with the system, and (5) its over reliance on group work. Additionally, the TOC analyses are done manually.

4. SYSTEMS ANALYSIS TOOLS

This chapter contains a discussion of two systems analysis methods; *viz*. (1) indicator analysis and (2) root cause analysis. The roles that indicator and root cause analyses play in the management of systems are discussed. Also discussed are selected tools that are used for carrying out indicator and root cause analyses. The limitations of these tools are highlighted.

4.1 Indicator Analyses

Reiman and Pietikainen (2012) define an indicator as "any measure – quantitative or qualitative – that seeks to produce information on an issue of interest". For example, gross domestic product is an indicator of the size of a country's economy. Indicators are widely used in systems management. Examples of systems where indicators have been used include; agriculture (Pannell and Glenn, 2000), port management (Peris-Mora *et al*., 2005), virtual organisations (Grabowski *et al*., 2007), ecological systems (Lin *et al*., 2009), supply chains (Cai *et al*., 2009), safety critical organisations, such as oil refineries and nuclear power plants (Reiman and Pietikainen, 2012), the sugar industry (Eggleston *et al*., 2004; Davis and Achary, 2008; Davis *et al*., 2009, Smith *et al*., 2010), health (Perera *et al*., 2012) and integrated coastal management (Sano and Medina, 2012). Indicators are used by organisations in a variety of ways. For example, Reiman and Pietikainen (2012) observe that safety critical organisations use indicators as tools to monitor current safety levels and to predict emerging safety vulnerabilities. Lin *et al*. (2009) report that indicators are widely used to understand and manage complex systems. Eggleston *et al*. (2004) report on the use of indicators to ascertain whether a consignment of freeze-damaged sugarcane delivered to a mill can be processed economically or not. Popova and Sharpanskykh (2010) state that indicators are used to measure and analyse the performance of organisations. Perera *et al*. (2012) report that indicators are used to assess the effectiveness and efficiency of measures that have been put in place to improve the quality of health care. Peris-Mora *et al*. (2005) state that indicators are used in environmental analysis as tools for assessing the state of the environment and to predict the consequences of measures taken on it.

Two main categories of indicators can be found in literature; *viz*. (a) lagging indicators that provide information about what happened in a system in the past and (b) leading indicators that provide information about what is happening currently or what may happen to a system in future (Grabowski *et al*., 2007; Reiman and Pietikainen, 2012). Lagging indicators are useful when monitoring the effectiveness of strategies and measures that have been instituted to improve the performance of a system (Peris-Mora *et al*., 2005; Perera *et al*., 2012). Leading indicators, on the hand, provide information that can be used to predict or forecast the occurrence of events in a system and therefore help managers to take actions that may avert the occurrence of undesirable events.

Indicators play an important role in the management of systems. For example, Popova and Sharpanskykh (2010) highlight the use of indicators in determining whether the goals of an organisation are being achieved. They further add that managers are aware of the importance to identify relevant indicators for the organisations they manage. Reiman and Pietikainen (2012) note that there is a growing interest in the role that indicators can play in predicting important events in systems. However, Cai *et al*. (2009) and Popova and Sharpanskykh (2010) indicate that the process of identifying and selecting appropriate indicators for a system is not easy. This is a great concern considering that the credibility and the usefulness of an indicator largely depend on whether it was appropriately selected for a given purpose (Lin *et al*., 2009; Perera *et al*., 2012).

Several methods are used to identify indicators in systems, such as the Balanced Score Cards, Activity Based Accounting, (Liberatore and Miller, 1998), Performance Measurement Matrix and the performance pyramid (Neely, 2005). Limitations exist in these methods as partly evidenced by the large volume of literature reporting new methods for identifying and selecting indicators in systems (*e.g*. Pannel and Glenn, 2000; Peris-Mora *et al*., 2005; Grabowski *et al*., 2007; Cai *et al*., 2009; Lin *et al*., 2009; Munier, 2011; Sano and Medina, 2012; Perera *et al*., 2012; Reiman and Pietikainen, 2012). It is observed by Popova and Sharpanskykh (2010) that the identification of indicators in systems is mostly done in an informal and ad-hoc way. They further argue that systematic approaches for identifying indicators would be beneficial. Ritchie (2013) describes the General Morphological Analysis (GMA) as one of the structured approaches that can be used by experts but also outlines some of its weaknesses that include; the inevitable need for strong and experienced facilitation and the high time requirements. Perera *et al*. (2012) observe the need to develop new methods for selecting robust indicators in healthcare. Lin *et al*. (2009) argue that problems in ecological indicators selection can best be resolved by employing well-defined protocols with scientific vigour. Popova and Sharpanskykh (2010) also observe that the set of indicators that can be used to monitor a system can be very large, such that it may not be practically feasible and economically viable to monitor all of them. The challenge therefore is to select a small number of key indicators that can be measured and monitored at a reasonable cost but at the same time provide enough information about the overall performance of the system. Anon (2012) suggests that four to ten indicators would suffice for most types of companies. Pannell and Glenn (2000) emphasise that the benefits of monitoring a set of indicators must far exceed the costs. Cai *et al*. (2009) indicates that one of the major challenges for managers in supply chain management is how to determine the relative importance of performance indicators. This is echoed by Neely (2005) who states that there are only a few systematic methods for prioritising indicators. Some notable tools that have been used to weigh-up the importance of indicators in supply chains include the Analytical Hierarchy Process approach (Liberatore and Miller, 1998; Huan *et al*., 2004) and grey relational analysis (Kung and Wen, 2007). The Analytical Hierarchy Process has been criticised for being subjective (Tiryaki and Ahlatcioglu, 2009; Ozcan, *et al*., 2011), while the grey relational analysis has been found to be unsuitable for use in a dynamic supply chain environment (Cao *et al*., 2008).

4.2 Root Cause Analyses

Paradies and Busch (1988) define a root cause (RC) as “the most basic cause that can reasonably be identified and that management has control to fix”. Several definitions of root cause analysis (RCA) can be found in the literature (*e.g*. Paradies and Busch, 1988; Reid and Smyth-Renshaw, 2012; Simms *et al*., 2012). Slight variations in definitions exist between different authors and disciplines. Similarly to indicator analyses, RCAs are widely used in commercial and non-commercial organisations, such as the consumer product industry (Kumar and Schmitz, 2011), healthcare (Woloshynowych *et al*., 2005; Uberio *et al*., 2007; Iedema *et al*., 2008; Nicoloni *et al*., 2011; Simms *et al*., 2012), computer network security (Al-Mamory and Zang, 2009) and high risk industries such as nuclear power plants (Paradies and Busch, 1988). For example, Paradies and Busch (1988) used RCA to evaluate safety issues at a nuclear power reactor. Kumar and Schmitz (2011) used RCA to identify the root causes of recalls of a consumer product. Murugaiah *et al*. (2010) used RCA to eliminate the problem of scrap loss in a lean manufacturing industry. Woloshynowych *et al*. (2005), Uberio *et al*. (2007), Iedema *et al*. (2008), Nicoloni *et al*. (2011) and Simms *et al*. (2012) used RCA to investigate various events in healthcare. Jayswal *et al*. (2011) developed a RCA approach for assessing the sustainability of energy production processes. The popularity of RCA is based on the conviction that the best way to solve a problem is by eliminating its root causes (Dogget, 2005; Reid and Smyth-Renshaw, 2012) rather than addressing the symptoms of the problem.

Root cause analysis can be used in either reactive or proactive modes. The former mode identifies the underlying root causes of a problem that has already occurred (Jayswal *et al*., 2011). The aim is either to solve the problem or to develop mechanisms to prevent the recurrence of the problem. The latter mode identifies potential root causes of problems that may take place in a system with the aim of developing prevention strategies (Uberoi *et al*., 2007).

Several RCA tools are used to carry out RCAs, such as the Pareto charts (Jayswal *et al*., 2005; Murugaiah *et al*., 2010), the 5 Whys (Murugaiah *et al*., 2010) cause-and-effect diagrams, interrelationship diagrams and the current reality tree (Dogget *et al*., 2005). It is reported by Woloshynowych *et al*. (2005) that there are more than 40 tools that are used for root cause analyses. Dogget (2005) argues that cause-and-effect diagram CED, interrelationship diagram ID and the current reality tree CRT are the most effective and popular RCA tools. A head-to-head comparison of the CED, ID and CRT (Dogget, 2005) indicates that the CRT is superior to the CED and ID. The comparison also revealed two notable disadvantages of the CRT; *viz*. (a) more time is required to do a RCA using the CRT and (b) the CRT is difficult to construct.

4.3 Summary

This short chapter has shown two prerequisite requirements for the effective management of systems. The first requirement is the need to continuously monitor the performance of a system relative to its goals. The second requirement is the need to identify the root causes of problems in a system. The former requirement is achieved using the indicator analysis, while root cause analysis is used to achieve the latter. This review has shown that the tools that are used for carrying out indicator and root cause analyses in systems have some limitations and that there is scope to further enhance their capabilities and efficiency. The tools that have been discussed in this chapter can only be used to carry out either root cause analysis or indicator analysis, but not both. Most of the tools do not provide systematic methods for prioritising root cause and indicator factors. Further, most of the tools use manual methods and are dependent on group work. The foregoing discussions suggest that there is a scope to improve the effectiveness and objectivity of systems analyses tools.

5. DESCRIPTIONS OF THE SUGARCANE MILLING AREAS OF THIS STUDY

A sugarcane milling area is described in this study as being made up of a sugar mill and the sugarcane growing areas that supplies cane to the mill. The network analysis approaches that were developed in this study were tested in four sugarcane milling areas in South Africa; *viz*. (1) Eston, (2) Felixton, (3) Komati and (4) Umfolozi. This represents four ISSPSs. This chapter provides a description of these milling areas. Although every milling area is unique and can be discussed in great detail, this chapter aims to briefly introduce each milling area and discuss the main factors and issues in each area. It is important to note that these four sugarcane milling areas were selected because of their relatively diverse configurations, such as different business models, management styles, scale of operation, location and climatic factors. Figure 5.1 shows the locations of the four sugarcane milling areas and Table 5.1 reflects some of the statistics associated with each mill.

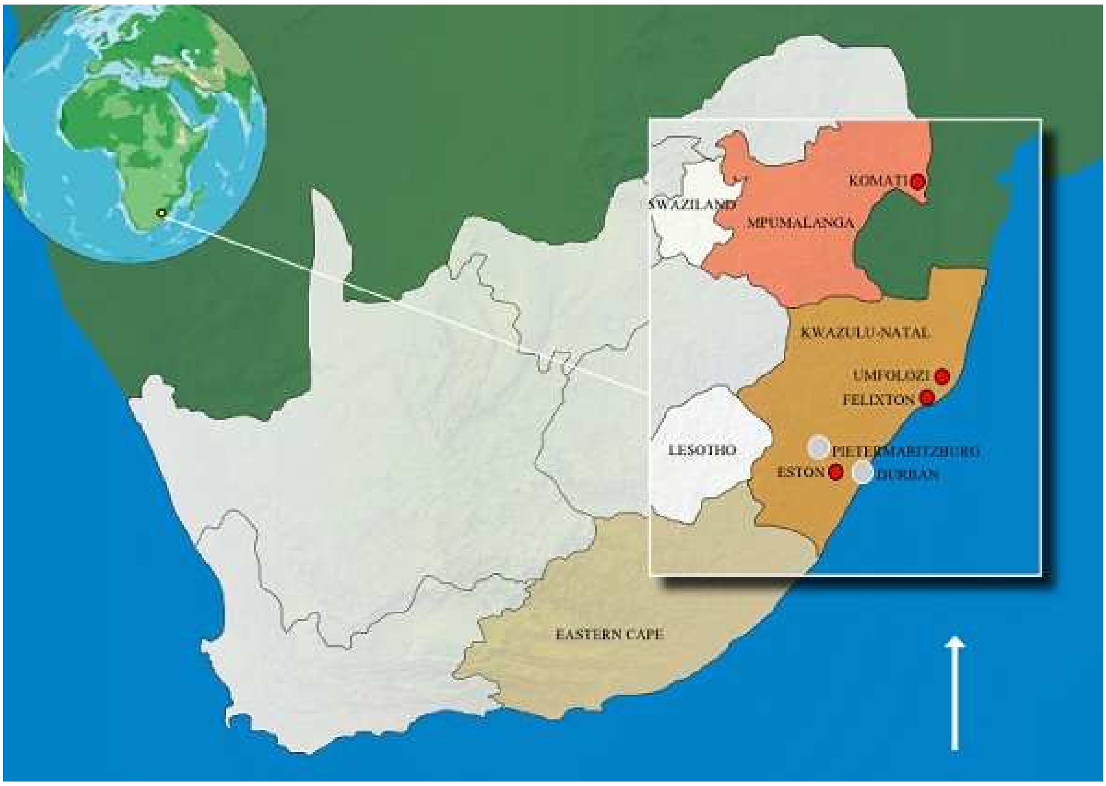


Figure 5.1 Locations of the four sugarcane milling areas used in this study (after the South African Sugar Association, 2012)

Table 5.1 Average mill performance variables over the 2007-2008, 2008-2009, 2009-2010 milling seasons for Eston, Felixton, Komati and Umfolozi (after Davis and Achary, 2008; Davis *et al*., 2009, Smith *et al*., 2010)

	Mill Name			
Performance Variable	**Eston**	**Felixton**	**Komati**	**Umfolozi**
Cane crushed (tonnes)	1319851	1741272	2307288	1048202
Length of milling season (weeks)	38	31	38	36
Overall time efficiency (%)	85.27	71.33	79.14	74.78
Scheduled stops (% gross available time)	4.34	8.23	2.53	2.62
Lack of cane (% gross available time)	6.89	14.19	7.94	12.08
Other stops (% gross available time)	2.59	5.94	9.23	9.53
Foreign matter (% gross available time)	0.90	0.30	1.15	0.98
Lost time (% available crush time)	2.94	7.70	10.42	11.31
Forced majeure stops (hours)	15.90	11.33	43.53	118.60
Sucrose % cane	14.18	13.08	14.15	13.11
Pol % cane	14.12	13.06	14.06	13.04
Fibre % cane	14.34	15.08	13.61	14.44
Brix % cane	16.36	15.79	16.65	15.51
Ash % cane	2.41	1.92	1.11	2.41
Estimated recoverable crystal (ERC) % cane	12.39	11.02	12.20	11.23
ERC % sucrose in cane	87.38	84.24	86.26	85.66
Recoverable value % cane	13.05	11.74	12.91	11.90
Modified Estimated recoverable crystal % cane	12.58	11.05	12.33	11.37

5.1 The Description of the Eston Sugarcane Milling Area

Eston is the Southernmost and highest altitude mill surveyed in this study. The Eston sugarcane milling area is located in the midlands of the KwaZulu-Natal Province. The milling area consists of the Eston mill (Figure 5.2) and sugarcane growing areas that extend to a radius of 50 km from the mill. The Eston mill was commissioned in the mid-nineties after most of the equipment at the coastal Illovo mill, south of Durban, was relocated to Eston. It is the newest sugar mill in the KwaZulu-Natal Province. The mill is owned by Illovo Sugar Limited. The annual sugarcane crushing capacity of the mill is about 1.3 million tonnes. Annual reviews of the milling season in southern Africa (Davis and Achary, 2008; Davis *et al*., 2009, Smith *et al*., 2010) indicate that the Eston mill had an average sugarcane crushing rate of about 1.3 million tonnes per season between 2007/2008 to 2009/2010 milling seasons (see Table 5.1). This shows that the Eston mill is well supplied with sugarcane. The mill keeps a relatively small stockpile of sugarcane in its yard, but prolonged disruptions in sugarcane supply often result in a no-cane mill stop.

Figure 5.2 A photograph of the Eston sugar mill (Source: Panoramio, 2012)

The Eston sugarcane milling area is relatively dry with an average annual rainfall of about 800 mm. The area is cold in the winter and sometimes experiences severe frost. Sugarcane yields can be significantly reduced by frost conditions. This is because the growers are forced to harvest frost damaged sugarcane before it has attained full maturity. On the other hand, the cool weather is responsible for relatively high juice purity (>85 %). Summers are misty and cloudy. The sugarcane growing areas, particularly the midlands, sometimes experience excessive wet conditions during the harvest season. This results in a high percentage of soil in the sugarcane that is delivered to the Eston mill. The high soil content directly or indirectly causes certain problems at the Eston mill; *viz*. (a) high incidences of diffuser flooding, (b) more diffuser residence time, (c) slow diffuser throughput and (d) more wear of hammers and shredders. Wet conditions can also inhibit the burning of sugarcane for harvesting. The area sometimes experiences windy conditions. Windy conditions also inhibit burning prior to harvesting. The following problems are experienced at the mill when sugarcane cannot be harvested due to wet and/or windy conditions; (a) no-cane mill stops, (b) high cane supply variability, (c) lower cane supply reliability, (d) high crush rate variability and (e) reduced throughput of the mill. Cane growers may burn large areas of sugarcane when conditions are favourable and leave it standing in the field in readiness for harvesting. This practice increases the burn, harvest to crush delay (BHTCD) which results in deterioration of the sugarcane.

Sugarcane is predominantly grown under rain fed conditions in the Eston milling area. However, a small amount of sugarcane is irrigated. The mean sugarcane yield in the milling area is about 60 $t.ha^{-1}$. Cane is predominantly supplied to the Eston mill by commercial growers. The milling company also grows a small amount of cane on a nearby estate. Sugarcane is normally harvested at an age of 24 months. The prolonged cropping cycles make the sugarcane stem borer, *Eldana saccharina*, a potential threat. This is because the sugarcane stem borer mainly attacks old sugarcane particularly under stress conditions. However, the stem borer is not a currently widespread problem in the milling area. Sugarcane is harvested manually. The area sometimes faces serious labour shortages for harvesting cane. This is claimed to be due to the availability of alternative and higher paying job opportunities in the nearby cities, especially in the construction industry. Cane is transported to the mill solely by road using a combination of large and small trucks and tractors. The average haul distance is approximately 22 km. The three largest sugarcane hauliers deliver about 30 % of the total cane crushed at the mill. There is a significant number of small hauliers who deliver sugarcane to the mill. Sugarcane is sometimes diverted to other Illovo owned mills (Sezela and Noodsberg) on orders from management. This practice sometimes creates logistical problems.

5.2 The Description of the Felixton Sugarcane Milling Area

The Felixton sugarcane milling area is located on the far North Coast of the KwaZulu-Natal Province. The sugarcane milling area consists of the Felixton mill (see Figure 5.3) and sugarcane growing areas extending as far west as 125 km and 210 km to the north of the mill. The mill as it stands today was commissioned in the mid-eighties. The mill is owned by Tongaat Hulett Limited. The mill has an estimated sugarcane crushing capacity of 3.3 million tonnes per annum. Annual reviews of the milling season in southern Africa (Davis and Achary, 2008; Davis *et al*., 2009, Smith *et al*., 2010) indicate that the Felixton mill had an average sugarcane crushing rate of 1.7 million tonnes per milling season between 2007/2008 to 2009/2010 milling seasons (see Table 5.1). The mill is therefore under supplied with cane.

The mill has two independent lines. Inversion is a significant problem in the diffusers. The area is also rocky, which causes problems when rocks are delivered with the cane. The mill is equipped with a rock removal system. The mill keeps a large stockpile of cane in its yard. The mill can therefore withstand relatively large fluctuations in cane supply. Felixton sells some of its fibre (bagasse) to other industries.

Figure 5.3 A photograph of the Felixton sugar mill (Source: C.N. Bezuidenhout, 2011)

The Felixton sugarcane milling area receives a relatively high amount of rainfall of approximately 1000 mm per annum. The milling area is humid in the summer. Sugarcane is grown either under irrigation or rain fed conditions, with about 40 – 50 % of the area under irrigation. The mean sugarcane yield at Felixton is 60 $t.ha^{-1}$. All the sugarcane is grown by independent growers, of which many are small scale growers. Sugarcane is harvested at an average age of 12 to 15 months. On average the cane that is delivered to the mill during the beginning of the season is older, while that delivered towards the end of the season is younger. Cane lodging and infestations by pests, especially by the eldana are significant problems in the area, especially towards the end of the milling season and in carry-over cane in the next milling season. Although the ideal harvesting age is 15 months, cane is harvested early to avoid severe *Eldana saccharina* incidences. Most of the sugarcane is harvested manually. Harvesting is done by cane cutters who are employed by the growers. The Felixton milling area does not experience severe labour shortages for harvesting cane compared to Eston. This is the case even-though Felixton is located close to the Richards Bay/Empangeni industrial area. Sugarcane is transported to the Felixton mill using both road and railway transport modes. Logistically, the railway transport system is claimed to be less efficient but cost effective from where it sources the cane. On the road, a combination of large and small trucks is used. The haul distance is excessive and comprise one of the longest distances in South Africa, if not in the world. Haul distances of up to 210 km exist and often cane travels past other sugar mills on the way to Felixton.This is mainly due to the fact that the Felixton mill is severely under-supplied and the milling company is willing to subsidise transport in order to secure cane supply. The top three biggest sugarcane hauliers deliver between 50 – 60 % of the sugarcane to the Felixton mill.

5.3 The Description of the Komati Sugarcane Milling Area

The Komati sugarcane milling area is situated in Mpumalanga Province and is the most northern milling area in this study. The Komati mill (see Figure 5.4) was commissioned in the mid-nineties. The mill is currently the most sophisticated in South Africa. The mill is new, well managed and experiences few operational problems. The mill is owned by TSB Sugar Company.

Figure 5.4 A photograph of the Komati sugar mill (Source: Panoramio, 2012)

The annual sugarcane crushing capacity for the Komati mill is 2.6 million tonnes. Annual reviews of the milling season in southern Africa (Davis and Achary, 2008; Davis *et al*., 2009, Smith *et al*., 2010) indicate that the mill crushed an average cane crop of 2.3 million tonnes per milling season between 2007/2008 to 2009/2010 milling seasons (see Table 5.1). This mill is therefore slightly undersupplied with cane. The mill does not have a sugarcane yard and does not stockpile any cane on site (Olwage, 2000). This can be a problem when there are disruptions in the cane supply. The Komati sugarcane milling area is generally dry with cool winters. The area receives an average rainfall of 580 mm per annum. All the sugarcane in the area is grown under irrigation. Water scarcity during droughts can significantly reduce cane yields. The average cane yield is 78 $t.ha^{-1}$. The TSB Sugar Company grows their own cane and there are other relatively large private estates as well. Cane lodging is a significant problem in the area because of the high yields. Sugarcane is prone to flowering due to the climate of the area, which results in a high fibre percentage and hence reduced cane quality. Sugarcane is harvested manually by contractors at an average age of 12 months. Labour for cane harvesting is readily available in the area. Large trucks are used to transport sugarcane directly to the mill. This causes significant soil damage to cane fields. The average haulage distance is generally short. The top three biggest sugarcane hauliers deliver approximately 60 % of cane to the mill. TSB owns a large fleet of sugarcane hauling trucks. This sometimes creates logistical problems in cane supply particularly during shift changes of truck drivers.

5.4 The Description of the Umfolozi Sugarcane Milling Area

Umfolozi sugarcane milling area is located south of Lake St Lucia on the North coast of KwaZulu-Natal Province. The milling area consists of the Umfolozi mill (Figure 5.5) and surrounding sugarcane growing areas. The mill is one of the oldest in the SA sugar industry and has changed ownership several times. During the time of the survey, the mill was prone to breakdowns. The mill is owned by the Umfolozi Sugar Mill (PTY) Limited. Cane growers have a significant shareholding in the mill. The mill has a cane crushing capacity of 1.1 million tonnes per annum and it is relatively fully supplied. Annual reviews of the milling season in southern Africa (Davis and Achary, 2008; Davis *et al*., 2009, Smith *et al*., 2010) indicate that the mill had an average sugarcane crushing rate of slightly more than 1 million tonnes per season between 2007/2008 to 2009/2010 milling seasons (see Table 5.1). The mill keeps a relatively small stockpile of cane in its yard and can experience problems with high fibre content cane. The milling area is generally wet throughout the year. Summers are humid and rainfall ranges from 700 mm in the irrigated dry regions to 1100 mm over the Umfolozi flood plains. About 30 % of the sugarcane is grown under irrigation. Sugarcane is grown by a combination of private estate type large and small scale growers. Some of the sugarcane growers are third to fourth generation growers. Three major shareholders of the Umfolozi mill grow a substantial amount of sugarcane. Most of the sugarcane (about 70 %) is grown on the flood plains of the Umfolozi river (Culverwell, 1992). Sugarcane is first burned and then harvested manually at an average age of 12 months. The wet conditions on the flood plains can result in low sugarcane burning efficiency and a high percentage of trash in the sugarcane is a significant problem at the mill. The soils are dense and silty and may render harvesting of sugarcane impossible during wet conditions. The average sugarcane yield at the Umfolozi sugarcane milling area is 66 $t.ha^{-1}$. Cane harvesting is done by manual labour who are employed by the farmers themselves. Labour for harvesting is readily available. Most of the sugarcane (±70 %) is transported to the mill by a tramway system that operates on the flood plains. The rest is transported by road. The road haulage distance is relatively long stretching from Empangeni in the south to Mkuzi in the north. In-field damage is relatively small on the Umfolozi flood plains because of the use of small tram carriages.

Figure 5.5 A photograph of the Umfolozi sugar mill (Source: alltravels, 2012)

6. DEVELOPMENT AND TESTING OF NETWORK THEORY APPROACHES

This chapter contains a description of (a) the processes that were followed to develop the network theory approaches on which these analyses are based, and (b) the procedures that were followed to test these approaches on four sugarcane milling areas. The rationale behind the use of the processes and procedures is provided. These approaches consist of three analytical tools; *viz*. (1) primary influence vertex analysis, (2) indicator vertex analysis and (3) root cause vertex analysis.

6.1 Development of a Generic Network for Integrated Sugarcane Supply and Processing Systems

A generic network is described in this study as a network that incorporates all the factors and the relationships that may possibly exist in the system that the network represents. Similarly, a generic cause-and-effect network for ISSPSs is a network that incorporates all the factors and the cause-and-effect relationships that may possibly exist in any ISSPS (*i.e*. a sugarcane milling area). Such being the case, a sugarcane milling area network would typically be a sub network of the generic ISSPSs network. This is because not all the factors and the cause-and-effect relationships in the generic ISSPSs network would be present in one specific milling area. A generic cause-and-effect network for ISSPSs can also be viewed from the TOC perspective as a network that incorporates all the possible CRTs that may exist in a sugarcane milling area at any given time.

The factors that negatively affect the performance of ISSPSs (*e.g*. drought, pests, absenteeism of workers, skills shortage, aged equipment and low crush rate of sugarcane mills) were collated and their cause-and-effect relationships were established. This was done by using information that was obtained from the literature and after consultations with experts in the SA sugar industry. The factors that were covered in this study were limited to those that affect the following sectors of the sugar industry; (1) the production of sugarcane, (2) the harvesting of sugarcane, (3) the transportation of sugarcane to mills, and (4) the processing of sugarcane up to the raw sugar stage. The production of raw sugar was chosen as the terminating point because of the following reasons; (1) raw sugar is biologically a relatively stable product that is produced by all sugar mills in South Africa and (2) the study focused on assessing the biophysical drivers of the system, rather than market related drivers, which become part of the system once raw sugar has been produced. The factors and their cause-and-effect relationships were used to construct a generic network for ISSPSs (or simply called the generic network). The factors were represented by vertices and the cause-and-effect relationships between these factors were represented by arcs. The Pajek network analysis software tool (de Nooy *et al.*, 2005) was used to construct the generic network. The software was also used to construct the other networks in this study. Wherever deemed necessary, the Kamada-Kawai algorithm in the Pajek software was used to energise the networks to facilitate their visualisation. It is important to note that the generic network only reflects on problems and problematic cause-and-effect relationships. Figure 6.1 depicts the Kamada-Kawai energised generic network that was constructed in this study. The network has 340 vertices and 643 arcs. Vertex labels have been deliberately hidden from the network for clarity.

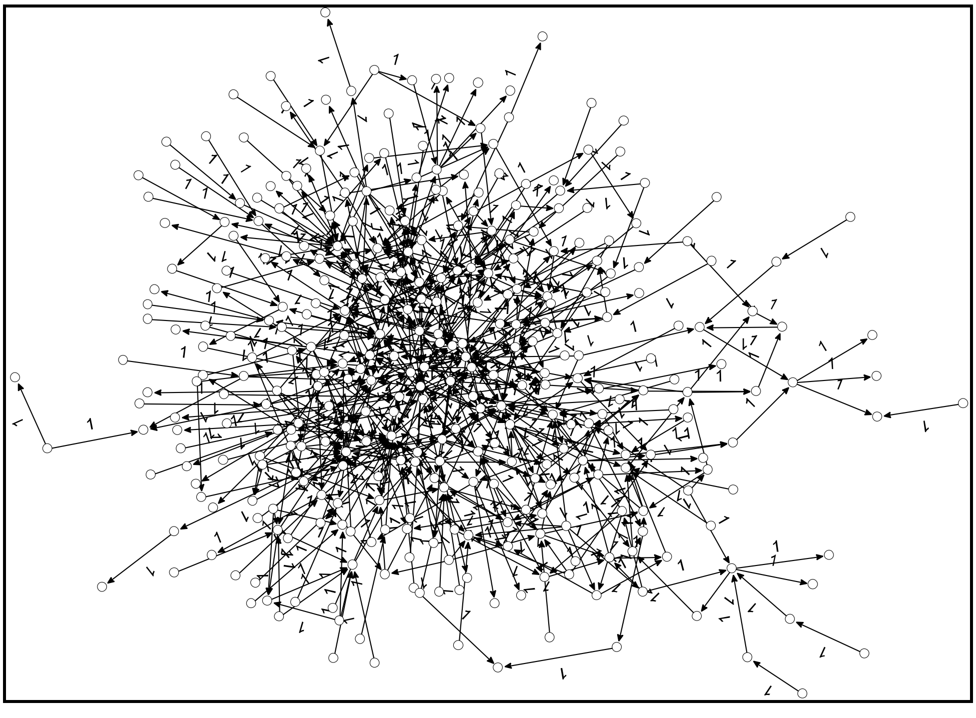


Figure 6.1 A generic cause-and-effect network for integrated sugarcane supply and processing systems at a mill area scale

It can be deduced from the network that it may be difficult to analyse a complex system without the aid of suitable analytical tools. The arcs in the network have a weight of one, which is the default value. The basic statistical properties of the generic network are summarised in Table 6.1. The numbers of source and sink vertices in the network are 103 and 43, respectively.

Table 6.1 Basic statistical properties of the generic network

Name of network property	Value of network property
Number of vertices	340
Number of arcs	643
Degree	1286
Average degree	4
Maximum degree	22
Minimum degree	1
Out-degree	643
Average out-degree	2
Maximum out-degree	18
Minimum out-degree	0
In-degree	643
Average in-degree	2
Maximum in-degree	15
Minimum in-degree	0

6.2 Populating Data for the Sugarcane Milling Areas' Networks

Interviews were conducted in 2010 and 2011 with representative stakeholders at the Eston, Felixton, Komati and Umfolozi sugarcane milling areas. These interviews were not conducted by the author as was explained in Section 1.2. It is acknowledged that other techniques, such as stakeholder workshops could also have been appropriate for eliciting information from stakeholders. However, information gathering techniques fall outside the scope of this study and the expertise of the author. Future research should address the issues involving information gathering techniques. It must be mentioned here that the four mills were studied individually, one at a time. The stakeholders who were interviewed included a representative range of sugarcane growers, hauliers, millers and service providers, such as extension and grower support services personnel. The generic network (see Section 6.1) was used as a blueprint during the interviews. Interviewees were prompted to name a few problematic factors in the milling area from their perspective and to weigh-up the cause-and-effect relationships between the factors depending on the severity of the relationships between the factors. A scale of 1 to 10 was used to weigh-up the cause-and-effect relationships. Table 6.2 contains a qualitative description of the scale. It is acknowledged that the method of assigning weights to the cause-and-effect relationships is subjective and that the values probably need further validation. Empirical values, such as correlation coefficients between measured parts of the system may provide more objective weights of the relationships among the factors. However, the aim of this study was to develop the diagnostic network analyses techniques and not necessarily to come up with the most descriptive network or data gathering method for each milling area. It is hoped that future research will address these issues in more detail.

Table 6.2 The scale that was used for assigning weights to arcs in sugarcane milling areas' networks

Arc weight	Meaning of weight
1	Default
2	Small impact
3	Identifiable impact
4	Mild impact
5	Established
6	Significant
7	Quite significant
8	Severe impact
9	Very severe
10	Critical/most severe

Custom written software was used to automatically incorporate the weights that were provided by the different stakeholders into the generic network culminating in the production of a specific milling area network. If more than one stakeholder assigned a weight to a specific arc, then the highest weight assigned to an arc among all the stakeholders was used in the final milling area network. The author acknowledges that other methods, such as average or weighted average, could also have been used for assigning the weights to the arcs. However, it was found out that this method was the most practical way to come up with weighted cause-and-effect networks for the milling areas. The method allowed for the modelling of the worst possible cause-and-effect relationships between factors. To assist with further explanations of the methodology, the Umfolozi sugarcane milling area network is shown in Figure 6.2 after the weights of the stakeholders were incorporated. The names of the factors have been deliberately hidden for the clarity of the network. Unlike the generic network in Figure 6.1, where all the arcs had a weight of one, the Umfolozi sugarcane milling area network has some arcs with weights of more than one. The weights of the arcs are reflected by their respective thicknesses.

The factors that were provided by the stakeholders during the interviews (see Section 6.2) can be viewed from the TOC perspective as the UDEs in the sugarcane milling areas. Similarly, the cause-and-effect relationships that were weighed-up by the stakeholders can be considered as the initial causal connections between UDEs (see Section 3.2.2). Thus, stakeholder interviews effectively mimic the first two steps that are followed when constructing a CRT; *viz*. (a) coming up with a list of UDEs, and (b) establishing cause-and-effect connections between the UDEs. However, this method has two advantages over the traditional method of constructing a CRT; *viz*. (1) it is computerised and (2) no further stakeholders involvement in CRT construction is required.

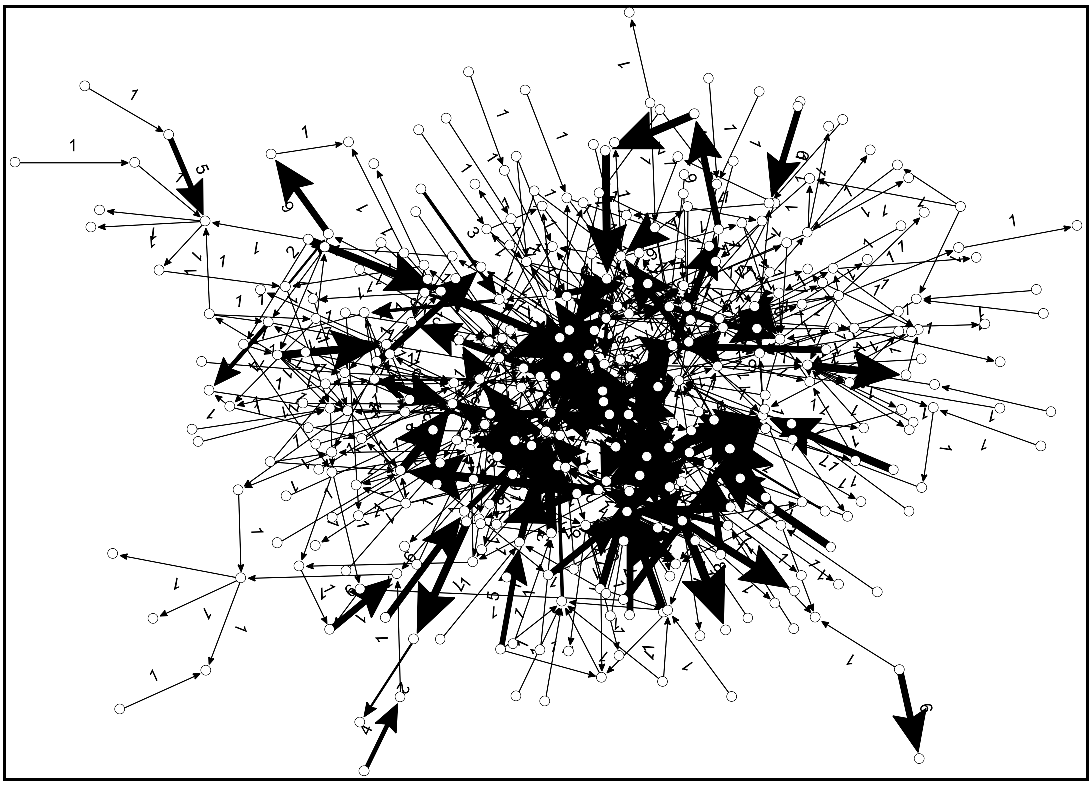


Figure 6.2 The Kamada-Kawai energised Umfolozi sugarcane milling area network after weights of arcs were adjusted based on stakeholder inputs

6.3 Identification of the Factors Perceived to Negatively Affect the Performance of the Sugarcane Milling Areas

The factors that were perceived by stakeholders to negatively affect the performance of the four sugarcane milling areas and their cause-and effect relationships were isolated from the milling areas' networks using the following two steps. Firstly, all the arcs that had a weight of one were removed from the milling areas' networks. This resulted in the creation of milling areas' sub networks whose arcs had a weight of at least two. Secondly, all the vertices that had a degree of zero were removed from the sub networks. The final sub networks consisted of only those factors that were provided by the stakeholders during the interviews and the cause-and-effect relationships that the stakeholders weighed-up.

6.3 Primary Influence Vertices

Primary influence *PI* is a statistical property of a vertex that was specifically devised for this study to measure the power or authority that a vertex has over other vertices in a weighted directed network. It is acknowledged that there are other statistics that are used to measure the power of vertices in networks, such as degree centrality, as explained in Section 2.1.4. Primary influence counts the number of vertices in a network over which a given vertex v_i has power, or authority. A vertex v_i has a power over other vertices, $v \in [\boldsymbol{G}(v)]$, if and only if all the highest weighted incoming arcs of v originate from v_i, or from another vertex over which v_i has power. Alternatively, it can be said that a vertex has power over other vertices when the following four criteria are met: The four criteria are illustrated using Figure 6.3. The numbers inside the vertices and on the arcs are vertex numbers and arc weights, respectively.

1. If there is only one arc that terminates into a receiver vertex, the sender vertex has primary influence over the receiver vertex. For example (see Figure 6.3), one arc (v_5v_{12}) terminates into v_{12}. Therefore v_5 has primary influence over v_{12}.
2. If there are more than one arcs that terminate into a receiver vertex, then the sender vertex of the arc with the highest weight has primary influence over the receiver vertex. Arcs from v_1, v_2 and v_3 in Figure 6.3 terminate into v_4. The respective weights of the arcs are five, three and seven. In this case v_3 has primary influence over v_4.
3. If v_i and v_j are among the sender vertices of arcs that terminate into v_k where $w(v_iv_k) = w(v_jv_k)$, and v_iv_k and v_jv_k have highest weights than the rest of the arcs that terminate into v_k, then neither v_i nor v_j has primary influence over v_k. However, if v_i has primary influence over v_j, then v_i will inherit primary influence over v_k as well. For example (see Figure 6.3), vertex v_{10} receives arcs from v_8 and v_9. The two arcs have the same weight and, hence, neither v_8 nor v_9 has primary influence over v_{10}. However, vertex v_7 receives arcs from v_6 and v_{11} with similar weights. Vertex v_{11} has a primary influence

over v_6, and hence v_{11} has primary influence over v_7 as well, while v_6 has no primary influence over vertex v_7.

4. If v_i has primary influence over v_j and v_j has primary influence over v_k, then v_i has primary influence over v_k. For example (see Figure 6.3) v_3 has primary influence over v_4 and v_4 has primary influence over v_5. Vertex v_5 in turn has primary influence over v_{12}. Therefore v_3 has primary influence over v_4, v_5 and v_{12}.

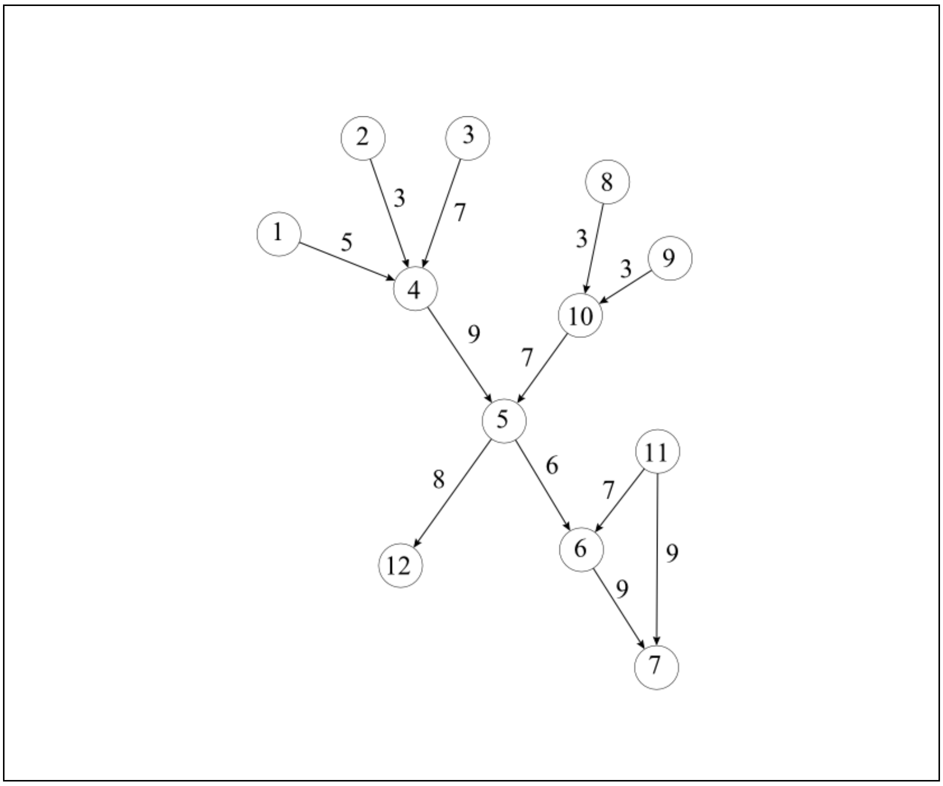


Figure 6.3 A network for illustrating the primary influence criteria

The primary influence vertex concept has its basis in the TOC and network theory. The Theory of Constraints indicates that a constraint is the lowest performing component in a system (see Chapter 3). If the TOC philosophy is extended to an individual vertex v_i in a weighted cause-and-effect network, then the vertex that is sending the highest weighted arc to v_i would be the constraint to the performance of v_i. Also, according to the TOC philosophy, if two vertices v_i and v_j are among the sender vertices of arcs that terminate into v_k, where $w(v_iv_k) = w(v_jv_k)$, and v_iv_k and v_jv_k have the highest weights compared to the other arcs that terminate into v_k, then neither v_i nor v_j would be the constraint to the performance of v_k. This would be so because by solving either v_i or v_j, the performance of v_k would still remain the same. Criterion number 4 is based on the concept of "reach" (see Section 4.1.5), which allows a vertex to extend its primary influence beyond its first out-neighbour via heavily weighted pathways.

The number of vertices over which a vertex v_i has a primary influence is called its primary influence index, $I_{PI}(v_i)$. The primary influence indices of the vertices in the network in Figure 6.3 are shown in Table 6.3. Custom written software was used to compute the primary influence indices of the vertices.

Table 6.3 Primary influence indices for the network in Figure 6.3

Name of vertex	**Primary influence index**
v_1	0
v_2	0
v_3	3
v_4	2
v_5	1
v_6	0
v_7	0
v_8	0
v_9	0
v_{10}	0
v_{11}	2
v_{12}	0

Four vertices v_3, v_4, v_5 and v_{11} have primary influence indices of at least one, while the remainder have primary influence indices of zero. The vertices that have primary influence indices of at least one are called primary influence vertices. Conversely, the vertices that have primary influence indices of zero are called non-primary influence vertices. Primary influence vertices of a network represent the driver factors in the system that the network represents. The average primary influence $\overline{I_{PI}}$ for a network is calculated in this study as the quotient of the sum of all the $I_{PI}(v_i)$ in a network and the number of primary influence factors in the network. It must be mentioned that $\overline{I_{PI}}$ is calculated like this for practical reasons. The number of non-primary influence vertices (*i.e.* the vertices whose $I_{PI} = 0$) in a network can be large. Thus, a $\overline{I_{PI}}$ that is calculated as the quotient of the sum of all the $I_{PI}(v_i)$ in a network and the number of factors in the network could be too small to be of significance for further analyses (see Equation 6.1 in Section 6.5) The $\overline{I_{PI}}$ value for the network in Figure 6.3 is two.

The primary influence concept can be used for diagnosing problems in complex systems and for devising strategies for improving the performance of such systems. The primary influence was specifically devised to address two phenomena that generally occur in complex systems. The first phenomenon is multiple causalities. This phenomenon occurs when a factor has more than one cause. Examples of multiple causalities can readily be found in ISSPSs. For example, under loading, aged equipment and less preventative maintenance may be some of the causes of low transport efficiency. However, it may be difficult to determine which of the factors drives low transport efficiency.

The second phenomenon that can be addressed by the *PI* concept is the knock-on effect (or ripple effect) of a causal factor. A vertex directly affects its 1^{st} out-neighbours. Additionally, a vertex may indirectly affect higher order out-neighbours (*e.g.* 2^{nd}, 3^{rd}, ..., n^{th}) through a series of paths (P_n). Some vertices affect large parts of a network via heavily weighted pathways. An example of knock-on effect in ISSPSs is a flood. Floods may directly or indirectly cause many problems in an ISSPS, such as the lodging of sugarcane, an increase in the percentage of soil in sugarcane, road damage, low transport efficiency, low availability of sugarcane at mills and low sugarcane quality.

The primary influence concept can be used to identify the factors on which interventions aimed at improving the performance of the system should be targeted. The primary influence concept may offer a method for identifying important factors in complex systems and a way for developing techniques that can be used to identify the factors on which interventions aimed at improving the performance of systems must be targeted. This is well aligned with the TOC philosophy.

6.4 Primary Influence Vertex Analysis

Primary influence vertex analysis was carried out on the four sugarcane milling areas' networks to calculate the relative importance of factors as the drivers of poor performance in the respective areas. The analysis was carried out using the following procedure:

Step 1: The arcs with weights of one (default value) were removed from a milling area network. This resulted in a sub network with arcs' weights ranging from two to ten. This was done to prevent non weighted arcs from having an influence on the results of the analyses. It should be noted that this step only applies to networks that have been developed from a generic perspective.

Step 2: Primary influence indices were calculated for all the vertices in the sub network based on the criteria outlined in Section 6.3. Custom written software (see Section 6.3) was used to calculate the primary influence indices of the vertices.

Step 3: The results from the calculations were used to generate a primary influence network and a primary influence report for a milling area.

As an illustration, the Felixton primary influence report is shown in Table 6.4. The primary influence factors have been arranged in a descending order of magnitude based on their I_{PI} values. Figure 6.4 is a Kamada-Kawai energised primary influence network for the Felixton sugarcane milling area. The names of the primary influence factors and their respective I_{PI} have been deliberately hidden for the clarity of the network. The sizes of the vertices in the network (also known as the vector of the graph ***G***) reflect on the I_{PI} of the factors.

Table 6.4 Primary influence report for the Felixton sugarcane milling area

```
------------------------------------------------------------------------------
1. C:\pajek\primary influence.vec (340)
------------------------------------------------------------------------------
Dimension: 340
The lowest value:                    0.0000
The highest value:                  14.0000

Highest values:
```

Rank	Vertex	Value	Id
1	53	14.0000	Drought
2	9	13.0000	Yield decrease
3	109	8.0000	More foreign material
4	242	7.0000	Mill throughput Reduction
5	103	6.0000	Lower sucrose %
6	42	5.0000	Lower cane quality
7	4	5.0000	Longer queue
8	159	4.0000	Longer cycle time
9	258	4.0000	Low stacking efficiency
10	7	3.0000	Harvest efficiency reduction
11	246	3.0000	Poor communication infrastructure
12	48	3.0000	Transport efficiency reduction
13	253	2.0000	Phosphate shortage
14	247	2.0000	Behind allocation
15	106	2.0000	More lodging
16	96	2.0000	Poor communication
17	46	2.0000	Cane excess at end of season
18	86	2.0000	Heat
19	259	2.0000	More diffuser residence time
20	250	1.0000	Increase in weekly crush rate
21	120	1.0000	More grower/miller conflict
22	22	1.0000	More underloading
23	45	1.0000	Cane depletion end of season
24	172	1.0000	More inversion in diffuser
25	80	1.0000	More deterioration
26	153	1.0000	Poor clarification
27	280	1.0000	More pests and diseases
28	65	1.0000	Extended length of milling season

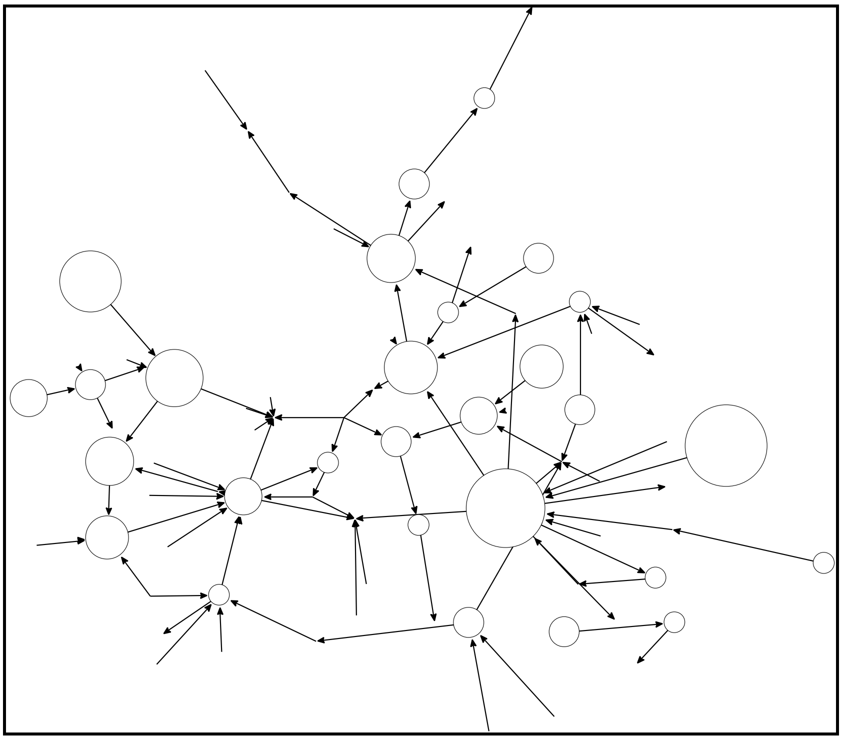


Figure 6.4 Primary influence network for the Felixton sugarcane milling area

6.5 Indicator Vertices

The concept of an indicator vertex was specifically devised in this study to identify vertices that can provide information about the performance of a system represented by a weighted cause-and-effect network or that can be used to predict the performance of the system. It is acknowledged that there are other methods that are used to identify indicators in systems, such as the Balanced Score Cards, as explained in Section 4.1. Indicator vertex measures the ability of a vertex to provide information about the performance of a system represented by a weighted cause-and-effect network or to predict the performance of the system. This study considers the most significant indicator vertex in a network to be the one that is reachable at short distances by many primary influence vertices with higher than average I_{PI} values, while simultaneously not reachable by many non-primary influence vertices at short distances. An indicator index (I_I) was devised in this study for quantifying the strength of a vertex's ability to act as an indicator or proxy of a system represented by a weighted cause-and-effect network. Consider a vertex v_i that is reachable by m vertices, where $m \leq n = |V(\boldsymbol{G})|$. The indicator Index for v_i $I_I(v_i)$ is calculated using Equation 6.1. Three observations can be made from Equation 6.1; *viz*. (1) a vertex has a high I_I value if it is reached by a primary influence vertex with a higher than average I_{PI} value at a short distance, (2) a vertex is penalised if it is reached by a non-primary influence vertex at a short distance, and (3) a vertex is penalised if it located at a longer distance from primary influence vertices.

$$I_I(v_i) = \frac{I_{PI(v_1)} - \overline{I_{PI}}}{l(v_1 v_i)} + \frac{I_{PI(v_2)} - \overline{I_{PI}}}{l(v_2 v_i)} + \cdots + \frac{I_{PI(v_n)} - \overline{I_{PI}}}{l(v_n v_i)} \quad (6.1)$$

Figure 6.5 is used to illustrate how the I_I of vertices are calculated. Three sub networks of a hypothetical network with an assumed $\overline{I_{PI}}$ of two are shown in Figure 6.5. The values inside the vertices represent vertex numbers, while those in the square brackets represent I_{PI} of the primary influence vertices.

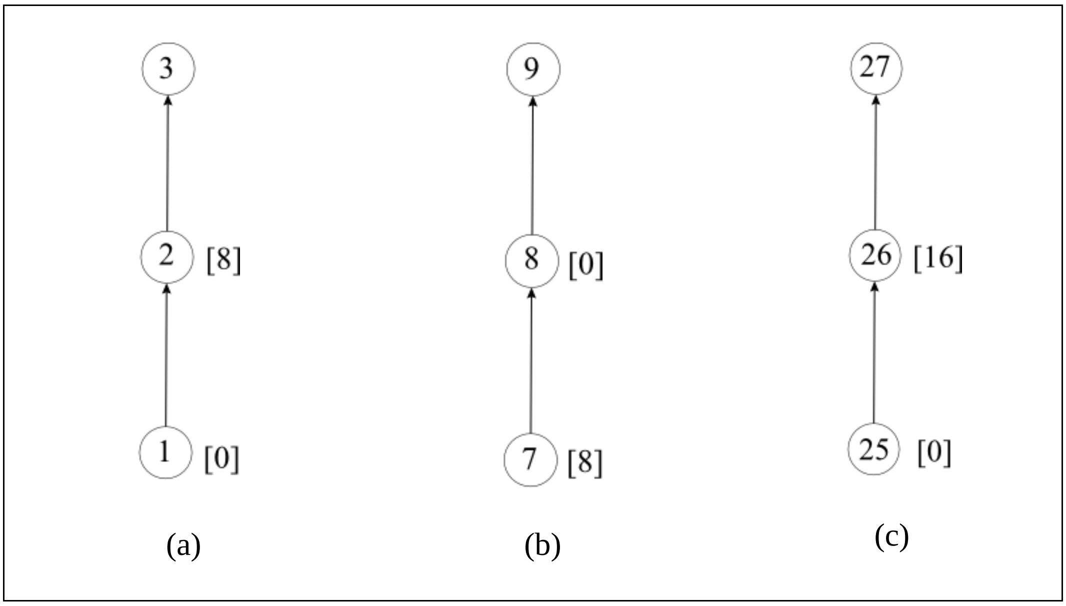


Figure 6.5 Sub networks from a hypothetical network for illustrating indicator index calculations

Consider vertices v_3 and v_9 in Figures 6.5(a) and 6.5(b), respectively. Vertex v_3 is reached by one primary influence vertex and one non-primary influence vertex, and so does v_9. Each primary influence vertex in the two sub networks has a I_{PI} that equals eight (see the numbers in square brackets). Vertex v_3 is reached by the primary influence vertex and the non-primary influence vertex at distances of one and two, respectively. Conversely, v_9 is reached by the primary influence vertex and the non-primary influence vertex at distances of two and one, respectively. Vertex v_3 has an $I_I(v_3) = 5$, while $I_I(v_9) = 1$. Vertex v_3 has six index points for being reached by the primary influence vertex and is penalised by one index point for being reached by a non-primary influence vertex. Conversely, v_9 has only three index points for being reached by the primary influence vertex and is penalised two points for being reached by the non-primary influence vertex. Vertices v_3 and v_{27} are both reached by one primary influence vertex and one non-primary influence vertex. The primary influence vertices are all located at distances of one from v_3 and v_{27}. The primary influence vertex that reaches v_3 has a I_{PI} = 8, while the one that reaches v_{27} has a I_{PI} = 16. Consequently, $I_I(v_3) = 5$, while $I_I(v_{27}) = 13$. Other statistics that are used to measure the importance of vertices, such as degree and centrality, could also be used in Equation 6.1 instead of I_{PI}, but this falls outside the scope of this study.

The technique of rewarding and penalising vertices based on the relative distances of the primary and non-primary influence vertices that reach them is consistent with an important assumption on which the analyses of the shortest distances between vertices in networks is based (Opsal *et al*., 2010). The assumption has its roots in the philosophy of Simmel (1950). The assumption states that information can be distorted by intermediary vertices, such that the higher the numbers of intermediary vertices (*i.e*. the longer the distance between vertices), then the higher are the chances that information would be distorted before it reaches the target vertex. Thus, a vertex is more likely to readily and correctly respond to signals from a vertex that is located near it compared to a vertex that is located far away. A vertex that is reachable by many non-primary influence vertices at relatively short distances may give a false signal that something drastic may be taking place or may take place in a system represented by the network. Thus, non-primary influence vertices may be considered as being synonymous to sources of *noise* in communication systems.

6.6 Indicator Vertex Analysis

Indicator vertex analysis was carried on the four sugarcane milling area networks to identify the factors that could provide information about, or predict the overall performance of the sugarcane milling areas represented by the networks. The analysis was carried out using the following procedure:

Step 1: Using the in-neighbour facility in the Pajek software, the in-neighbours of every vertex in a milling area network and the respective distances of the in-neighbours from the target vertex were identified.

Step 2: The I_{PI} of the in-neighbours, the $\overline{I_{PI}}$ for the network and the distances l of the in-neighbours from a target vertex were used to calculate the I_I values for each vertex using Equation 6.1 in Section 6.5. Microsoft Excel spread sheets were used to facilitate the calculations.
Step 3: The vertices were ranked in a descending order of magnitude according to their I_I values. The vertices that had higher I_I values were considered to be stronger indicator vertices.

6.7 Root Cause Vertices

A root cause (RC) vertex is a vertex that is an initiator of a causal chain of events that affects the performance of a system or component(s) of the system represented by a network. A hypothetical cause-and-effect set of problematic events in a sugarcane hauling truck is illustrated in Figure 6.6.

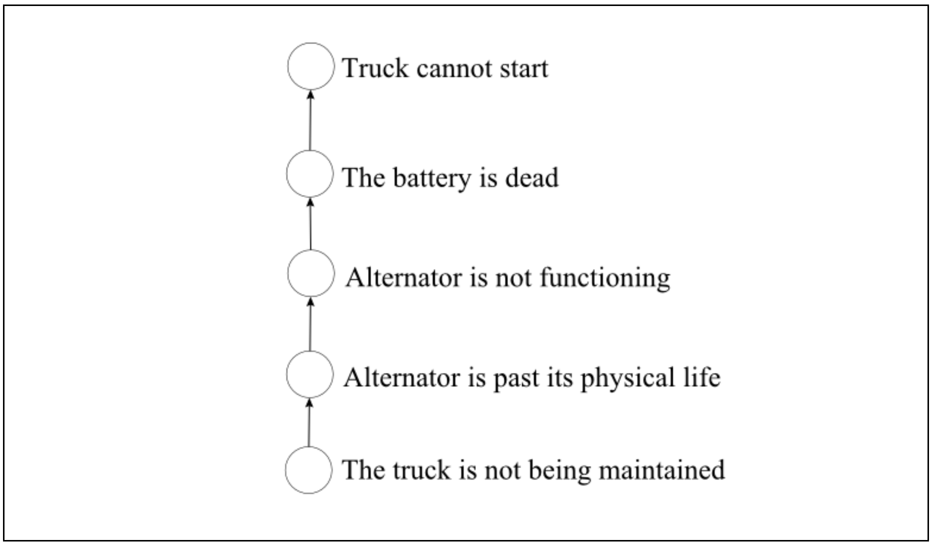


Figure 6.6 A network depicting the causal pathway of the failure of a sugarcane haulage truck to start

In this illustration the lack of truck maintenance causes the failure of the truck to start through three intermediary problems. The failure can be prevented by addressing any of the intermediary problems, such as replacing the dead battery or the alternator. However, those solutions are less likely to provide a long term solution. It is apparent that the failure of the truck to start and the three intermediary problems are all caused by the lack of truck maintenance. Truck maintenance is therefore the root cause of the problem. Although this example may appear simple, these problems are complex when many vertices are connected via many arcs. This simple analysis bears one important resemblance to the CRT technique for identifying root causes of problems in systems. The root cause of problems in a system is typically located at the bottom of the CRT (see Section 3.2.2), just like is the case in this simple analysis. It may therefore be argued that the source vertices of a cause-and-effect network are the root causes of problems in the system that the network represents. It can also be argued that the source vertices of a generic-cause-and-effect network represent all the possible root causes of problems that may exist in the system that the network represents.

It is hypothesized in this study that a strong RC vertex in a weighted cause-and-effect network is a source vertex that reaches most primary influence vertices with high I_{PI} within relatively short distances. A statistic called the root cause index I_{RC} was devised in this study for quantifying the root cause characteristics for source vertices in a weighted cause-and-effect network. For this study, the root cause index of vertex v_i $I_{RC}(v_i)$ is calculated as the sum of the quotients of the primary influence index of each primary influence vertex reachable from v_i and the distance of the respective primary influence vertex from v_i (see Equation 6.2). Other statistics that are used to measure the importance of vertices, such as degree and centrality can also be used instead of I_{PI}, but this falls outside the scope of this study.

$$I_{RC}(v_i) = \frac{I_{PI}(v_1)}{l(v_i v_1)} + \frac{I_{PI}(v_2)}{l(v_i v_2)} + \cdots + \frac{I_{PI}(v_n)}{l(v_i v_n)} \tag{6.2}$$

Figure 6.7 is used to provide an illustration on how the I_{RC} calculated, while Table 6.5 shows the respective I_{RC} for the source vertices in Figure 6.7. The sub network in Figure 6.7(a) has three source vertices v_1, v_2 and v_3. Additionally, the sub network has one *PI* vertex (v_5) with a I_{PI} of 10 (depicted by the number in square bracket). Vertices v_1, v_2 and v_3 reach the *PI* vertex at distances of one, one and two, respectively. Vertices v_1, and v_2 have equal I_{RC} values because they are located at the same distance from the *PI* vertex. In contrast, v_3 has a lower I_{RC} value than either v_1 or v_2 (see Table 6.5) because it is located further away from the *PI* vertex. Vertex v_7 is a source vertex in the sub network in Figure 6.7(b). Vertex v_7 reaches one primary influence vertex (v_{25}) at a distance of one – similar to v_1 or v_2. However, v_7 has a higher I_{RC} value than either v_1 or v_2. This is because v_{25} has a higher I_{PI} value than v_5. Vertex v_6 reaches two *PI* vertices v_{45} and v_{83}, each of which has a I_{PI} value of 10. Vertex v_6 in Figure 6.7(c) has a I_{RC} value of 20. This is because v_6 reaches more *PI* vertices than either v_1 or v_2.

This technique of calculating I_{RC} for source vertices also takes into account the assumption that information can be distorted by intermediary vertices as was explained in Section 6.5.

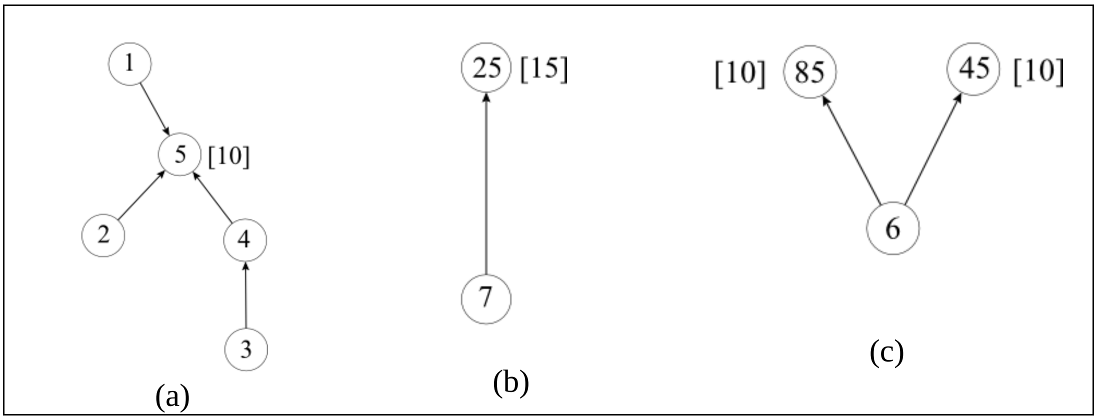


Figure 6.7 Hypothetical sub networks for illustrating root cause indices' calculations

Table 6.5 Root cause indices of the source vertices depicted in Figure 6.7

Name of source vertex	**Root cause indicator index**
v_1	10
v_2	10
v_3	5
v_6	20
v_7	15

6.8 Root Cause Vertex Analysis

Root cause vertex analysis was carried out on the four sugarcane milling area networks to identify the factors that were possibly the root causes of the problems in the sugarcane milling areas represented by the networks. The root cause vertex analyses of the sugarcane milling areas networks were carried out using the following procedures:

Step 1: The source vertices in a milling area network were identified using a facility in the Pajek software called in-neighbour analysis (*i.e.* vertices with zero in-neighbours are the source vertices). Microsoft Excel spread sheets were used to facilitate the calculations.

Step 2: The primary influence vertices that were reachable by every source vertex and their respective distances from the source vertex were identified using a facility in the Pajek software called out-neighbour analysis.

Step 3: The I_{PI} of primary influence vertices and the distances of the primary influence vertices from a source vertex *l* were used in Equation 6.2 (see Section 6.7) to calculate the I_{RC} values for the source vertices.

Step 4: The source vertices that had I_{RC} values of more than zero were identified as the possible root causes of the problems in the sugarcane milling areas represented by the networks.

Step 5: The possible source vertices were ranked in a descending order of magnitude of their respective I_{RC} values. The source vertices with higher I_{RC} values were considered to be stronger root causes of the problems in the sugarcane milling area represented by the network.

6.9 Summary

This chapter has discussed the processes that were followed to develop network theory approaches for analysing complex systems. The chapter has also discussed the steps to be followed when analysing systems using the approaches. The approaches provide a suite of analytical tools with the capability to identify the following in a system as part of one data set; *viz*. (a) the driver factors of poor performance in a system, (b) the factors that can provide information about the performance of a system and (c) the root causes of poor performance in a system. A combination of these tools provides a solid basis from which complex systems can be approached. The approaches also provide mechanisms that address some of the limitations associated with some of the well known and established systems analyses tools. These approaches do not require systems' stakeholders to undergo long periods of training in order to master their use. Most of the steps that the approaches use are computerised. This effectively eliminates the long and arduous task of manually constructing cause-and-effect diagrams as is the case with most systems analyses tools, such as the TOC. The time required to identify and solve of problems in systems is significantly reduced. The application of the approaches is less reliant on group work. This potentially reduces human bias in problem identification and solving processes. Additionally, the approaches provide systematic methods for prioritising factors in systems. It should be noted that the types and ranks of the factors obtained from the analyses reflect on the performance of a system at the time of the study. Such being the case, the tools are designed to be used in the fashion of the TOC's FFS for the continuous improvement of systems performance.

7. RESULTS AND DISCUSSIONS

7.1 Basic Properties of the SA Sugarcane Milling Areas' Networks

The basic statistical properties of the generic and the four sugarcane milling areas' networks are shown in Table 7.1. Each of the four milling areas' networks has $|V(\boldsymbol{G})| = 340$ and $|A(\boldsymbol{G})| = 643$. The $|V(\boldsymbol{G})|$ and $|A(\boldsymbol{G})|$ values of the networks are equal because they were developed from the same blueprint (*i.e*. the generic network). The weighted degree values for the generic network (Table 7.1) are equivalent to its degree values. This is because all the arcs in the generic network have a default weight of one.

Table 7.1 Basic statistical properties of the South African sugarcane milling areas' networks

Statistical Property	**Network Name**				
	Generic	**Eston**	**Felixton**	**Komati**	**Umfolozi**
Number of vertices	340	340	340	340	340
Number of arcs	643	643	643	643	643
Average weight of arcs	1.00	1.96	1.67	1.51	1.82
Total weighted degree	1286	2526	2152	1936	2336
Maximum weighted degree	22	102	122	74	65
Minimum weighted degree	1	1	1	1	1
Average weighted degree	4	7	6	6	7
Total weighted out-degree	643	1263	1076	968	1168
Maximum weighted out-degree	18	54	64	36	38
Minimum weighted out-degree	0	0	0	0	0
Average weighted out-degree	2	4	3	3	3
Total weighted in-degree	643	1263	1076	968	1168
Maximum weighted in-degree	15	70	58	55	50
Minimum weighted in-degree	0	0	0	0	0
Average weighted in-degree	2	4	3	3	3

The average weighted degrees are seven for the Eston and Umfolozi networks and six for the Felixton and Komati (see Table 7.1). Figure 7.1 shows that about 60 % of the vertices in the networks have weighted degrees of five or less as depicted by the dotted line. It appears as if the weighted degrees' distributions in the networks exhibit *scale-free* behaviours. Albert and Barabasi (2002) indicate that *scale-free* networks have few vertices with high degrees, while the rest have low degrees. This behaviour is consistent with the findings from several other studies of complex networks (*e.g*. Barrat *et al*., 2004; Barthélemy *et al*., 2005; Jeżewski, 2005; Zang *et al*., 2010). The *scale-free* nature of these weighted networks may support the notion that sugarcane production and processing systems are complex systems (*e.g*. Lisson *et al*., 2000).

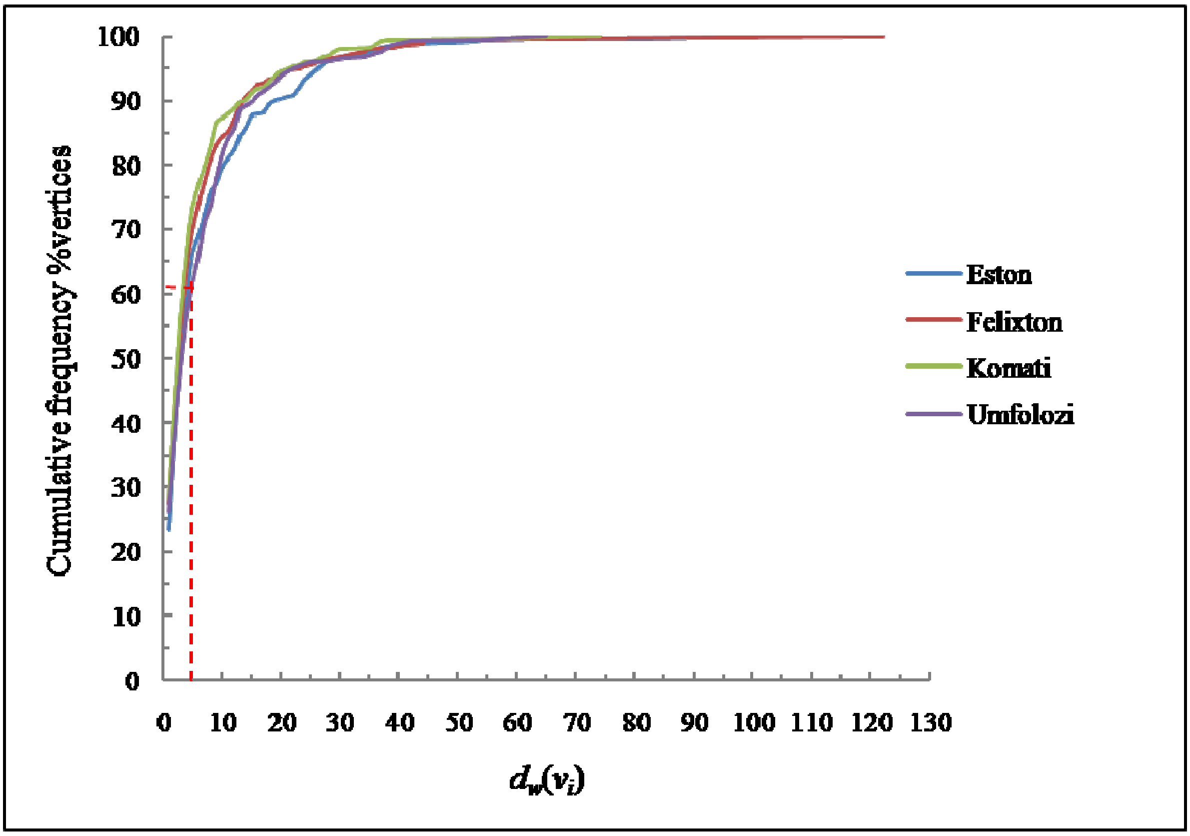
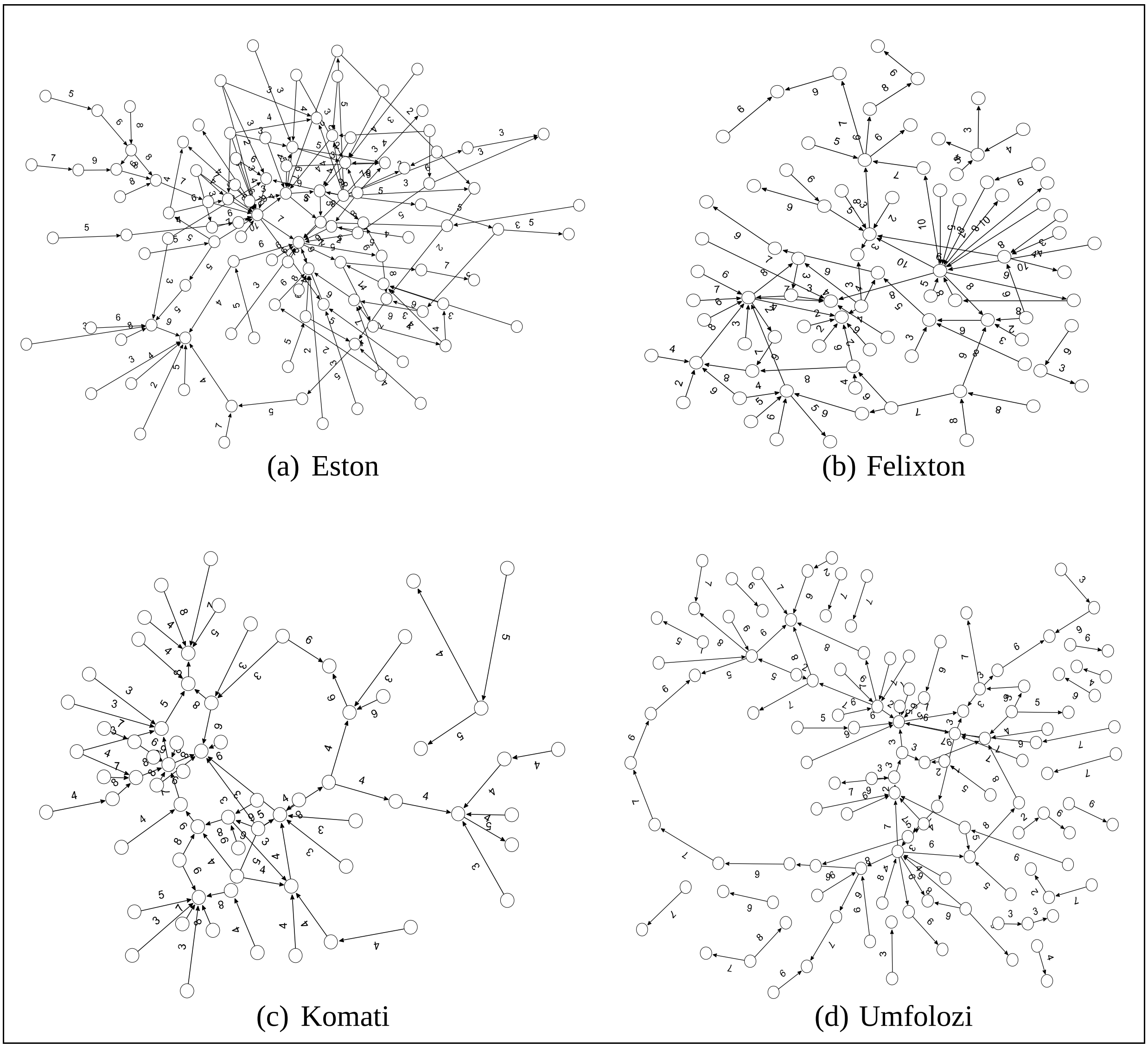


Figure 7.1 The distribution of weighted degrees in South African sugarcane milling areas' networks

7.2 Properties of Mill-specific Sub Networks

Figure 7.2 depicts the sub networks of the four sugarcane milling areas' networks. The vertices in the sub networks represent the factors that were perceived by stakeholders to negatively affect the performance of the four sugarcane milling areas, while the arcs represent the causal relationships between the factors (see Section 6.3). The names of the factors have deliberately been hidden in the sub networks for clarity. The basic statistical properties of the sub networks are shown in Table 7.2.



(a) Eston (b) Felixton

(c) Komati (d) Umfolozi

Figure 7.2 Sub networks of the South African sugarcane milling areas' networks

The numbers of vertices in the sub networks expressed as a percentage of the vertices in the generic network ranged from 20 % to 35%. The numbers of arcs in the sub networks expressed as a percentage of the arcs in the generic network ranged from 12 % to 23 %. This indicates that the generic network incorporates more factors and cause-and-effect relationships than what would be present at an average sugarcane milling area. It can therefore be argued that the generic network is comprehensive enough to be used as a blueprint for developing ISSPSs networks in South Africa and maybe even beyond.

Table 7.2 Basic statistical properties of South African sugarcane milling areas' sub networks

Statistical property	Name of milling area sub network			
	Eston	**Felixton**	**Komati**	**Umfolozi**
Number of vertices	109	82	68	119
Number of arcs	150	91	75	112
Average degree	2.75	2.22	2.21	1.88
Average weight of arcs	5.13	5.76	5.33	5.67
Number of source vertices	40	16	16	26

7.3 Factors that Negatively Affect the Performance of the Sugarcane Milling Areas

This section discusses the factors that were perceived by the stakeholders to negatively affect the performance of four sugarcane milling areas in South Africa.

7.3.1 Type of factors that negatively affect the performance of the milling areas

The number of factors that were perceived by stakeholders to negatively affect the performance of the four milling areas ranged from 68 to 119 (see Table 7.2). Umfolozi had the highest number of factors followed by Eston, while Komati had the lowest. The variations in the number of factors can be attributed to the relatively diverse configurations of the milling areas. For example, Komati mill is new, while the Umfolozi mill is quite old. Based on the ages of the two mills alone, it may be expected that Umfolozi milling area would have more factors that negatively affect its performance than Komati. The foregoing argument does not necessarily imply that the number of factors perceived to negatively affect the performance of a sugarcane milling area corresponds to the age of a mill.

7.3.2 Thematic areas of the factors in the milling areas

The common factors that were perceived by the stakeholders to negatively affect the performance in all the four milling areas can be grouped into eight thematic areas. Table 7.3 depicts the categorisation of the factors into these thematic areas. Additionally, Table 7.3 shows the colour codes that were used to represent the thematic areas. These codes will be used throughout the discussions unless stated otherwise. It is apparent from Table 7.3 that a majority of factors fall under the cane transport and supply themes. This may suggest that a majority of factors that negatively affect sugarcane milling areas relate to transport and supply of cane to mills. It is also apparent that at least 58 % of the factors fall under three thematic areas; *viz*. (1) cane production and harvesting, (2) cane transport and supply and (3) cane milling. Incidentally, the three thematic areas constitute the core operations of a sugarcane production and processing system. It can therefore be argued that a majority of factors that negatively affect the sugarcane milling areas are directly related to sugarcane production and processing. There are yet other factors that fall under thematic areas that are not directly related to sugarcane production and processing. These thematic areas include; cane quality, economics, environment, labour and cross cutting issues. The presence of the other thematic areas suggests that the SA sugarcane milling areas do not operate in isolation. The milling areas are also affected by factors that are not directly related to sugarcane production and processing.

Table 7.3 Thematic areas of the factors that negatively affect the performance of the South African sugarcane milling areas

Thematic area	**Colour code**	**Percentage of factors**			
		Eston	**Felixton**	**Komati**	**Umfolozi**
Cane production and harvesting		19	23	21	22
Cane transport and supply		22	27	25	28
Cane milling		17	15	21	18
Environment		6	5	6	7
Cane quality		8	12	16	12
Economics		12	4	1	7
Labour		10	2	3	4
Cross cutting		6	12	7	3

7.3.3 Common, shared and unique factors across the milling areas

The factors that were perceived to negatively affect the performance of the sugarcane milling areas can be categorised into three; *viz*. (1) the factors that were common to all the four milling areas, (2) the factors that were shared by at least two milling areas (3) the factors that were unique to a milling area. The first, second and third categories are termed common, shared and unique factors, respectively. Figure 7.3 shows the categories of factors in the four milling areas.

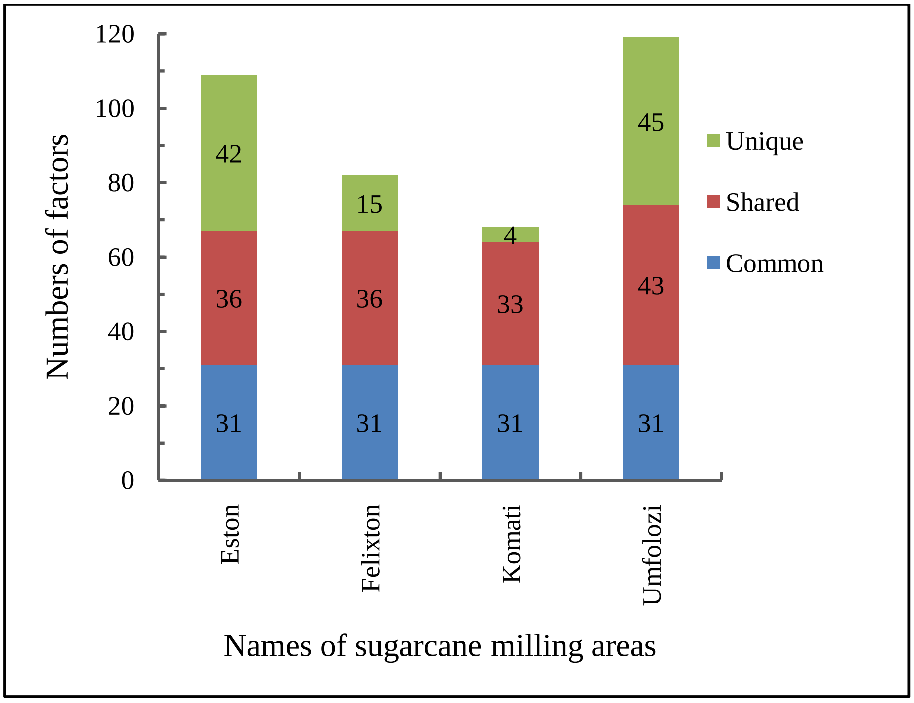


Figure 7.3 Categories of factors that negatively affect the performance of the South African sugarcane milling areas

It is evident from Figure 7.3 that 31 factors were common to all the four milling areas. Common and shared factors constitute more than 60 % of factors in the milling areas. This suggests that a majority of factors that negatively affect the performance of the sugarcane milling areas are similar. This can be attributed to the following; *viz*. (a) most of the processes in sugarcane production and processing are similar and (b) the milling areas under study are located in one country and are therefore subjected to many similar conditions, such as the same laws and cane payment system. Figure 7.3 also shows that there were 42, 15, 4 and 45 unique factors in the Eston, Felixton, Komati and Umfolozi milling areas, respectively. The presence of the unique factors is a manifestation of the relatively diverse configurations of the four milling areas.

Common factors across milling areas

Table 7.4 depicts the factors that were common across the four sugarcane milling areas. The factors are grouped into eight thematic areas using colour codes; *viz*. (1) cane production and harvesting (2) transport and supply of cane to mills, (3) cane milling, (4) environment, (5) cane quality, (6) economics, (7) labour, and (8) cross cutting factors.

Table 7.4 Common factors that negatively affect the performance of South African sugarcane milling areas

Behind allocation	Harvest efficiency reduction	Higher non sucrose %
Less logistics transparency	Lower cutter productivity	Lower cane density
Longer cycle time	More field damage	Lower cane quality
Longer queue	More lodging	Lower sucrose %
Lower cane supply reliability	Poor variety	More deterioration
More times no-cane at zone on arrival	Shorter crop cycles	More foreign material
More under loading	Yield decrease	Aged equipment
Not meeting daily rateable delivery	Yield increase	More mechanical breakdowns
Transport efficiency reduction	More mechanical mill stops	Less spending on inputs
Drought	Mill throughput reduction	
Wind	Fewer cutters	

Cane production and harvesting; Cane transport and supply; Cane milling; Environment; Cane quality; Economics; Labour; Cross cutting

It is evident from Table 7.4 that most of the factors that were common across the four milling areas fall under three thematic areas; *viz*. (a) cane transport and supply to sugarcane mills (≈29 %), (b) cane production and harvesting (≈26 %) and (c) cane quality (≈19 %).

Shared factors across milling areas

Table 7.5 contains a list of shared factors in the four milling areas. The factors have been grouped into eight thematic areas using colour codes (see Table 7.3). It is apparent from Table 7.5 that approximately 65 % of the shared factors fall under three thematic areas; *viz*. (1) cane production and harvesting, (2) cane transport and supply and (3) cane milling. This finding reinforces the argument that a majority of factors that negatively affect the performance of the SA sugarcane milling areas are directly related to sugarcane production and processing.

Table 7.5 Shared factors that negatively affect the performance of South African sugarcane milling areas

No.	Vertex label	Eston	Felixton	Komati	Umfolozi
1	Extended LOMS	✓	✓		✓
2	Higher harvest rate variability	✓		✓	
3	Higher topping	✓	✓		✓
4	Less replanting	✓		✓	
5	More carry-over		✓		✓
6	More mechanical harvesting		✓		✓
7	More trashing		✓	✓	✓
8	Over irrigation			✓	✓
9	Reduced LOMS		✓		✓
10	Poor burn efficiency	✓		✓	✓
11	Low stacking efficiency		✓	✓	
12	More in-field loading	✓		✓	
13	Few load sensors	✓	✓		
14	Fewer trucks			✓	✓
15	Less knowledge of stock at loading point	✓	✓		
16	Less stock stored at loading point	✓	✓	✓	
17	Less stockpile	✓			✓
18	Longer BHTCD)	✓	✓		✓
19	Low loading efficiency	✓		✓	
20	More no cane stops	✓		✓	✓
21	Ahead of estimate	✓	✓		✓
22	Cane depletion end of season		✓		✓
23	More road damage		✓	✓	✓
24	More stock stored at loading point		✓		✓
25	More trucks		✓	✓	✓
26	RTMS implemented	✓	✓		
27	A-pan saturation			✓	✓
28	High viscosity		✓		✓
29	Higher crush rate variability	✓		✓	✓
30	Higher energy requirements			✓	✓
31	Incomplete crystallisation			✓	✓
32	Low factory capital utilisation		✓		✓
33	Lower diffuser percolation			✓	✓
34	Lower exhaustion		✓	✓	
35	Lower extraction		✓	✓	✓
36	Lower sugar recovery		✓		✓
37	More diffuser flooding	✓		✓	✓
38	More diffuser residence time	✓	✓		
39	More inversion in diffuser	✓	✓		
40	More mill chokes	✓		✓	✓
41	Poor clarification		✓		✓
42	Heat		✓	✓	✓
43	High moisture content			✓	✓
44	More pests and disease	✓	✓		
45	Rain	✓		✓	✓
46	Higher fibre %	✓	✓	✓	
47	More silica % cane			✓	✓
48	More soil % cane			✓	✓
49	More ash % cane	✓		✓	✓
50	Cane supply area shrinkage	✓	✓		✓
51	Less income	✓	✓		
52	More spending on input costs	✓			✓
53	Operating cost increase	✓			✓
54	HIV/Aids	✓			✓
55	Lower Cutter availability	✓			✓
56	Pay days	✓			✓
57	Poor Nutrition	✓			✓
58	Strikes	✓	✓	✓	
59	Lack of skills		✓	✓	
60	Less preventative maintenance	✓	✓	✓	
61	Poor communication	✓	✓		
62	Poor stakeholder trust		✓		✓
63	Breakdowns and accidents	✓	✓	✓	

Cane production and harvesting; Cane transport and supply; Cane milling; Environment
Quality; Economics; Labour; Cross cutting

Unique factors across milling areas

Table 7.6 shows the unique factors in the four milling areas. The numbers of unique factors correspond with the numbers of factors that were perceived to negatively affect the performance of the milling areas (*i.e.* the higher the number of factors in a milling area, the higher is the number of unique factors). Some of the unique factors suggest that the analyses that were done in this study can bring forth accurate results.

Table 7.6 Unique factors that negatively affect the performance of South African sugarcane milling areas

Eston	28. Less profit	13. Poor communication infrastructure	20. Less cane volume
1. Harvesting of immature cane	29. More expenses	14. Unsynchronisation of operations	21. Vehicle schedule implemented
2. Less land use plans	30. Higher fixed cost component	15. More grower/miller conflict	22. Transport efficiency increase
3. Less seed cane	31. High labour cost	Komati	23. Longer hauls
4. Incorrect time for applying inputs	32. Less farmers	1. Bullwhip in transport	24. Fewer times no-cane at zone on arrival
5. More runaway fires	33. Land bond repayments	2. More evaporator scaling	25. Shorter BHTCD
6. Inability to burn	34. Alternative industries/crops	3. More mud recycling	26. Lower heat transfer coefficient
7. Stool death	35. Other industries	4. More pulping	27. More heater scaling
8. Lower cane supply	36. Labour problems	**Umfolozi**	28. Higher evaporation requirements
9. More trash included in load	37. Absenteeism	1. Crop damage	29. More coal utilisation
10. Cane supply variability	38. Social grants	2. More reluctance to burn/harvest	30. High evaporation rate
11. Overestimates	39. Legal cutters	3. Less burning	31. More encrustation in crystalliser
12. Cane diversions	40. Poor knowledge	4. Less ripening	32. More imbibition water
13. Standing trucks	41. Skills shortage	5. Harvest efficiency increase	33. Higher sugar recovery
14. Low milling efficiency	42. Poor training and management	6. More harvest scheduling	34. Increased environmental impacts
15. Slower diffuser throughput	**Felixton**	7. Lower topping	35. High rainfall
16. Lower front-end efficiency	1. Less carry-over	8. Incorrect harvesting time	36. More upstream floods
17. Low crush rate (not stops)	2. Cane excess at end of season	9. More cane rolling	37. Lower environmental priority
18. More operational mill stops	3. Higher above ground cutting	10. Poor ratoonability	38. Lower non sucrose %
19. More wear on hammers and shredders	4. More burning	11. Shorter queue	39. Low quality syrup
20. Lower dewater milling efficiency	5. Impact on haulage capacity	12. Shorter cycle time	40. Higher sugar quality
21. Low boiler efficiency	6. More consignments	13. Slow response	41. More silt on leaves
22. More undetermined losses	7. Phosphate shortage	14. Fewer consignments	42. Less willingness to invest
23. Lower back-end efficiency	8. Increase in weekly crush rate	15. Low infield transport efficiency	43. More income
24. Lower boiler capacity	9. High humidity	16. Less vehicle maintenance needed	44. More land claims
25. Frost	10. Poor VHP	17. Increase logistics transparency	45. Higher sugar price
26. Hail	11. Low juice purity	18. Poor road maintenance	
27. Cold	12. Lower pol factor	19. Less in-field loading	

Cane production and harvesting; Cane transport and supply; Cane milling; Environment
Cane quality; Economics; Labour; Cross cutting

For example, Table 7.6 shows that frost and high humidity are some of the unique factors that negatively affect the performance of the Eston and Felixton milling areas, respectively. These findings match the milling areas' descriptions in Chapter 5. The factors in Table 7.6 have been grouped into thematic areas using colour codes (see Table 7.3). It is evident that the unique factors in the Eston, Felixton, Komati and Umfolozi milling areas fall under seven, six, two and six thematic areas, respectively.

7.4 Cause-and-Effect Relationships between the Factors that Negatively Affect the Performance of Sugarcane Milling Areas

This section discusses the cause-and-effect relationships between the factors that were perceived by the stakeholders to negatively affect the performance of four sugarcane milling areas in South Africa.

7.4.1 Number of cause-and-effect relationships in the milling areas

The numbers of cause-and-effect relationships in the milling areas' sub networks ranged from 75 to 150 (see Table 7.2). Apparently, the number of cause-and-effect relationships does not necessarily correspond with the number of factors that were perceived to negatively affect the performance of a milling area. For example, the Umfolozi area has a higher number of factors than Eston. However, the Eston area has a higher number of cause-and-effect relationships than Umfolozi. This indicates that there are variations in the connectivity of factors between milling areas.

The connectivity of factors in the milling areas can be explained by the average degrees of vertices in their sub networks. The average degrees of vertices (see Table 7.2) range from 1.88 in the Umfolozi sub network to 2.75 in the Eston. Apparently, the Eston milling area has the highest connectivity among its factors followed by Felixton and then Komati, while Umfolozi has the lowest. The differences in connectivity of factors between the milling areas are also reflected in Figure 7.2. The Eston sub network has all its vertices connected as one unit. Conversely, the Umfolozi sub network consists of 18 sub units that are detached from each other. A high number of detached sub units reflects low connectivity of factors.

7.4.2 Strength of cause-and-effect relationships in the milling areas

There are variations in the strengths of the cause-and-effect relationships between factors in the four sugarcane milling areas. The strengths of the relationships in the milling areas are reflected in the average weights of arcs in their sub networks. Table 7.2 shows the average weights of arcs in the four milling areas' sub networks. The Felixton milling area has the strongest cause-and-effect relationships among its factors, while Eston has the weakest.

7.5 Primary Influence Factors in the Sugarcane Milling Areas

It was explained in Section 6.3 that primary influence is a measure of the potential knock-on effect of a vertex in a weighted network. It was also explained that a vertex with a primary influence index of at least one is termed a primary influence vertex. A factor that is represented by a primary influence vertex is called a primary influence factor. The primary influence factors are the drivers of systems.

7.5.1 Number of primary influence factors in the milling areas

Figures 7.4 to 7.7 show the primary influence factors in the four sugarcane milling areas. It is evident that there are variations in the numbers of primary influence factors between the milling areas. The Umfolozi milling area has the highest number of primary influence factors, while Komati has the lowest. It is also apparent from Figure 7.8 that the number of primary influence factors tend to correspond with the number of factors that were perceived to negatively affect the performance of a milling area *i.e.* the higher the number of factors that affect a milling area, the higher is the number of primary influence factors and *vice versa*. The number of primary influence factors expressed as percentages of factors that were perceived to negatively affect the performance of the milling areas were 34 %, 34 %, 26 % and 45 % in the Eston, Felixton, Komati and Umfolozi milling areas, respectively. This indicates that the number of factors that drive sugarcane milling areas can be high.

7.5.2 Strengths of primary influence factors in the milling areas

It evident from Figures 7.4 to 7.7 that there are variations in the strengths of primary influence factors between the milling areas. These variations are reflected in the primary influence indices of the factors. For example, the primary influence indices of rain in the Eston, Komati and Umfolozi milling areas are eight, three and two, respectively. The average primary influence indices for the Eston, Felixton, Komati and Umfolozi milling areas' networks are 2.2, 3.5, 1.4 and 1.9, respectively. This indicates that the primary influence factors in the Felixton milling area are on average stronger than those in the other milling areas. An intervention targeted at one primary influence factor in the Felixton milling area would therefore affect more other factors than would be the case in the rest of the milling areas.

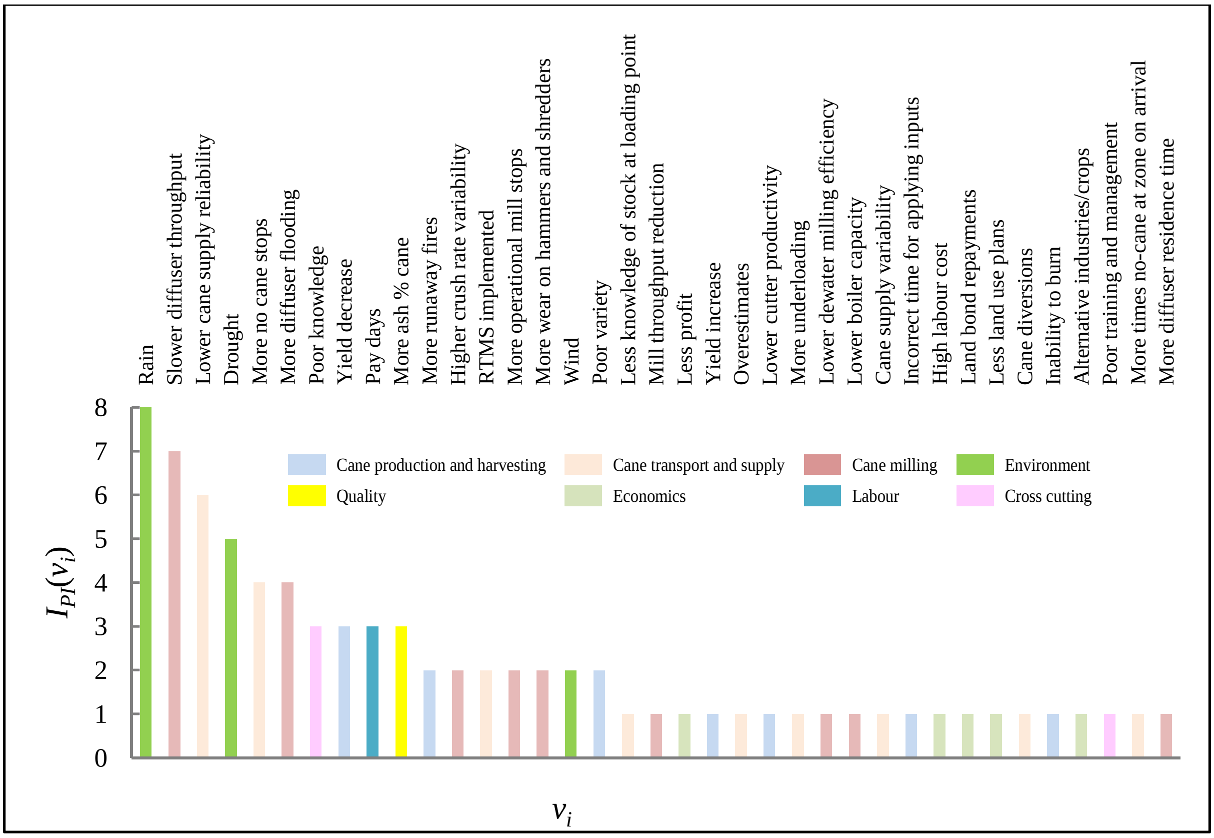


Figure 7.4 Primary influence factors in the Eston sugarcane milling area

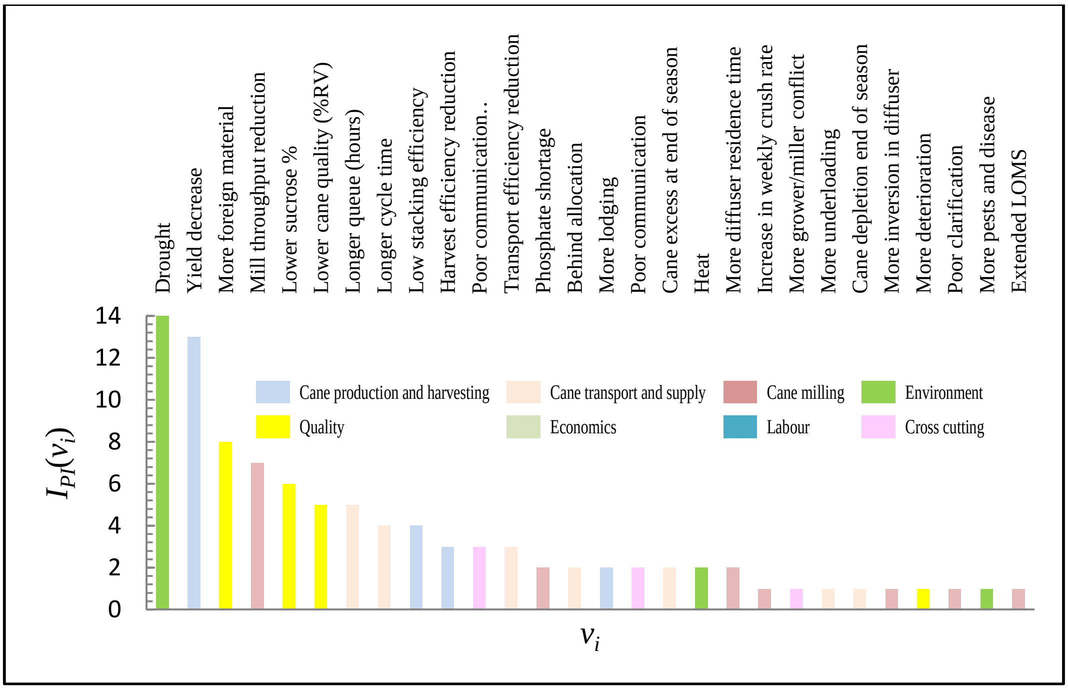


Figure 7.5 Primary influence factors in the Felixton sugarcane milling area

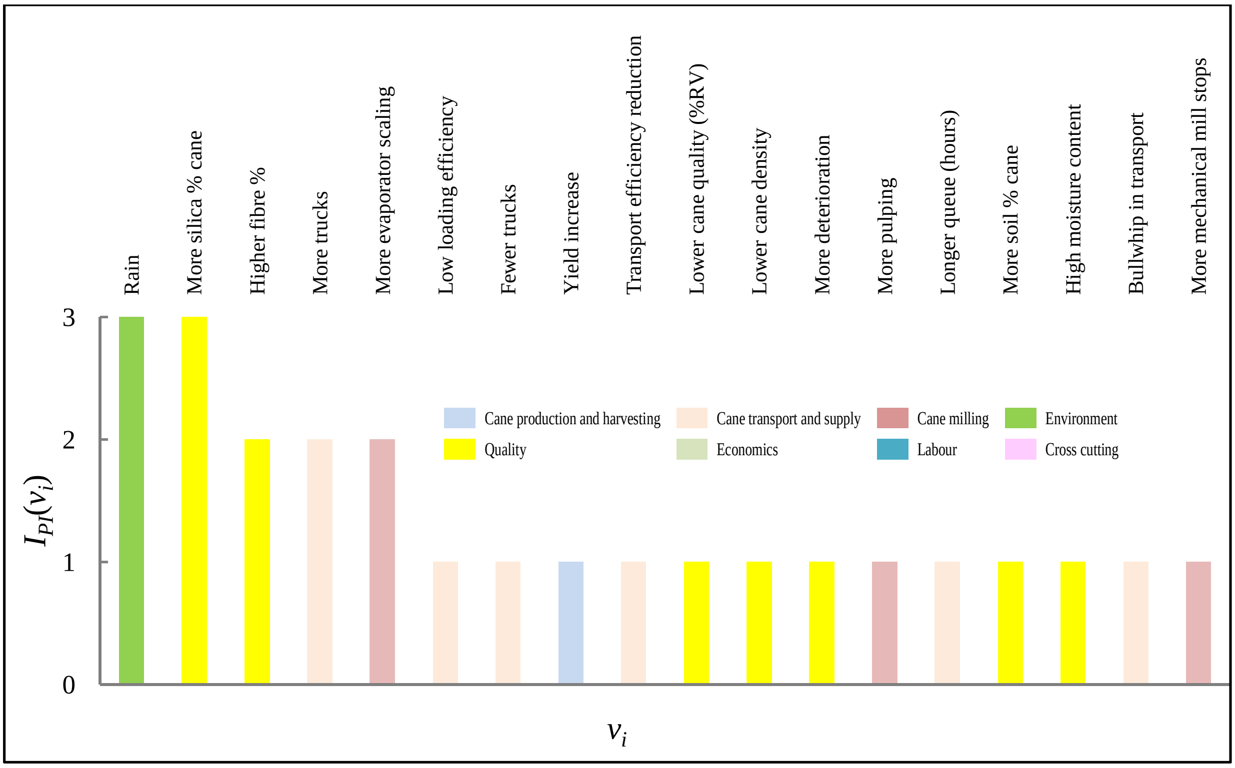


Figure 7.6 Primary influence factors in the Komati sugarcane milling area

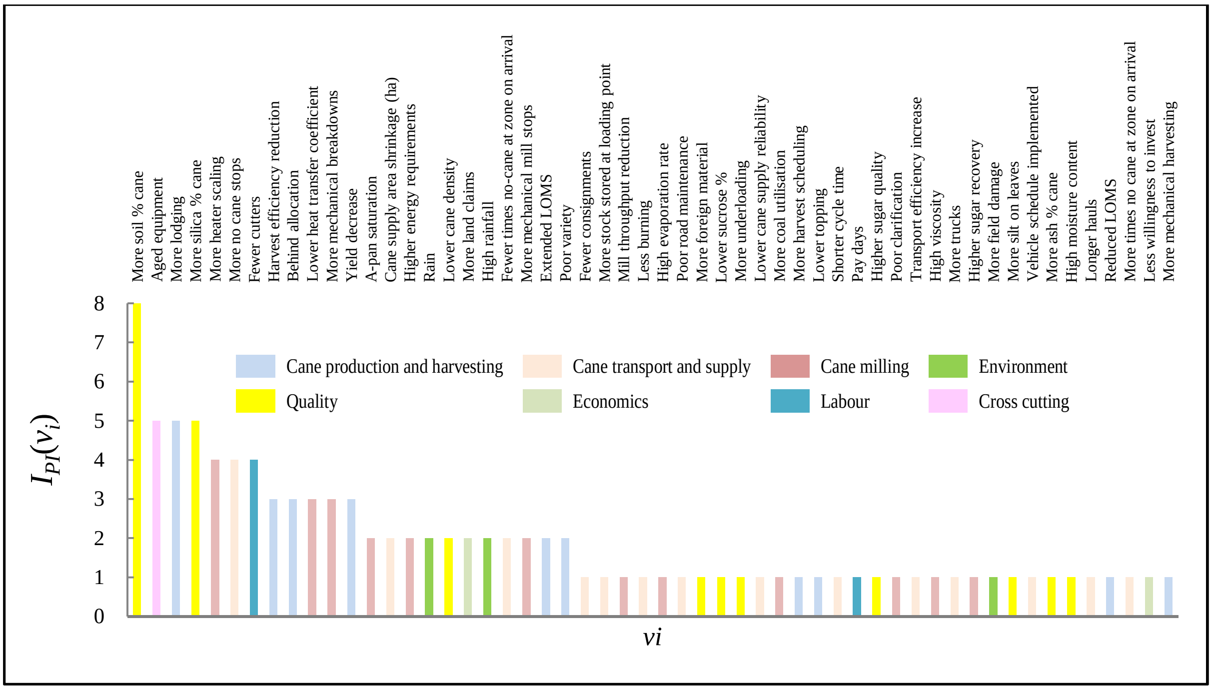


Figure 7.7 Primary influence factors in the Umfolozi sugarcane milling area

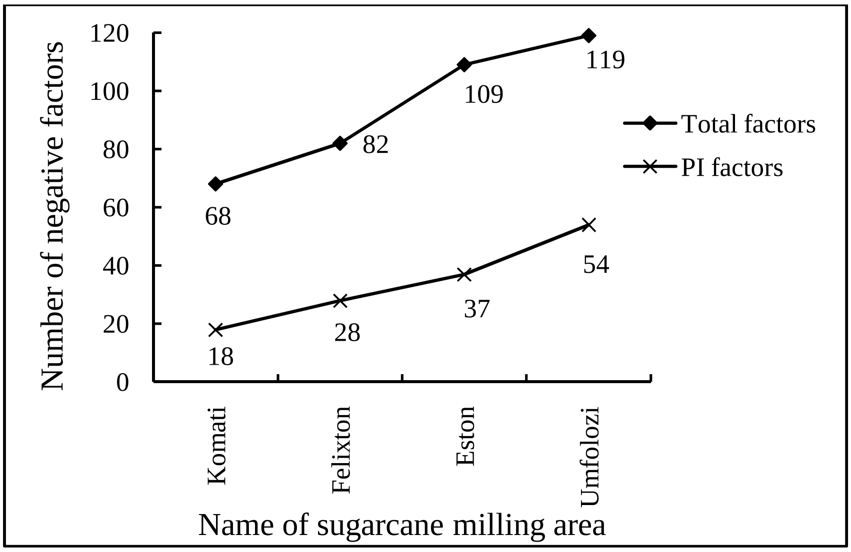


Figure 7.8 Comparison of the primary influence (PI) factors to the total number of factors that were perceived to negatively affect the performance of four South African sugarcane milling areas

7.5.4 Thematic areas of primary influence factors in the milling areas

The primary influence factors in the four sugarcane milling areas can be categorised into the eight thematic areas outlined in Table 7.3. Table 7.7 shows the percentages of primary influence factors that fall under each of the thematic areas. It is apparent that at least 56 % of the primary influence factors fall under three thematic areas; *viz*. (1) cane production and harvesting, (2) cane transport and supply and (3) cane milling. This may be because at least 58 % of the factors that were perceived to negatively affect the performance of the milling areas fall under the three thematic areas (see Section 7.3.2). It can therefore be assumed that a majority of factors that have a knock-on effect in the SA sugar industry may be directly related to the core operations of sugarcane production and processing. It can also be seen from Table 7.7 that a substantial percentage of primary influence factors in the Felixton (14 %), Komati (39 %) and Umfolozi (17 %) milling areas fall under the quality thematic area. On the other hand, only 3 % of the primary influence factors in the Eston milling area fall under the quality thematic area. This is in agreement with studies (*e.g*. Davis and Achary, 2008; Davis *et al*., 2009, Smith *et al*., 2010) that indicate that the Eston milling area has better cane quality than the rest of the SA milling areas.

Table 7.7 Thematic areas of primary influence factors in South African sugarcane milling areas

Thematic area	**Primary influence factors in a sugarcane milling areas (%)**			
	Eston	**Felixton**	**Komati**	**Umfolozi**
Cane production and harvesting	22	18	6	20
Cane transport and supply	24	29	33	26
Cane milling	24	21	17	20
Environment	8	7	6	4
Quality	3	14	39	17
Economics	14	0	0	7
Labour	0	0	0	2
Cross cutting	5	11	0	4

7.5.5 Common, shared and unique primary influence factors in the milling areas

The primary influence factors in the four sugarcane milling areas can be grouped into three; *viz*. (1) the factors that are common to all the four milling areas, (2) the factors that are shared by at least two milling areas and (3) the factors that are unique to a specific milling area.

Figure 7.9 is a categorisation of the primary influence factors based on whether they are common, shared or unique.

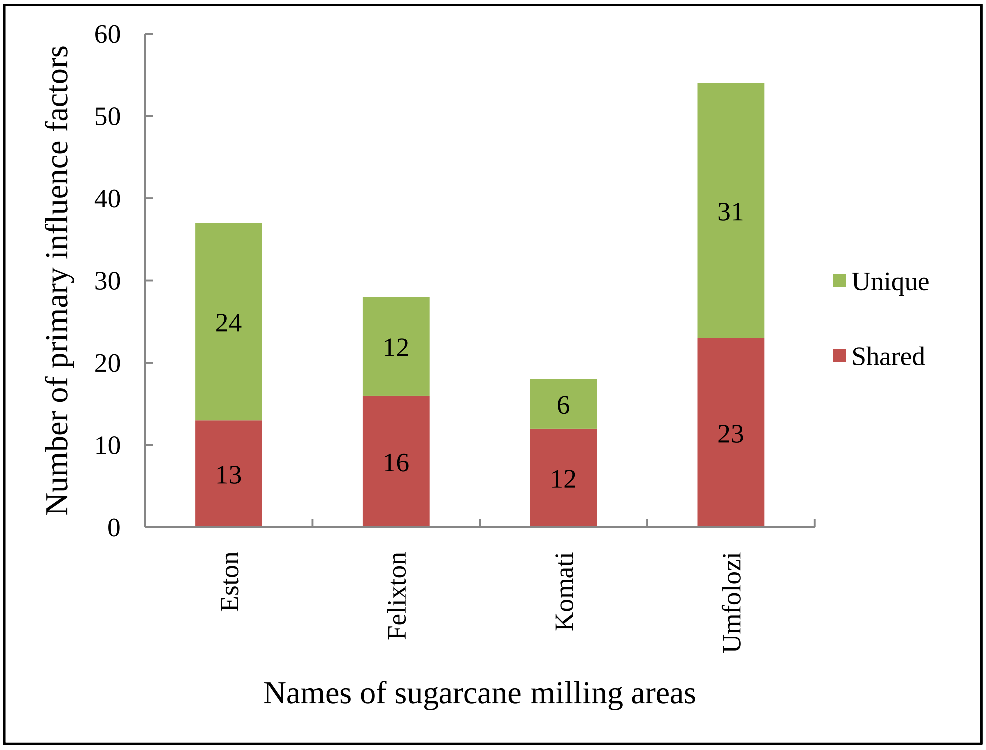


Figure 7.9 Categories of primary influence factors in South African sugarcane milling areas

Common primary influence factors in the milling areas

It is evident from Figure 7.9 that no primary influence factor is common to the four milling areas. This is despite the fact that 26 to 46 % of the factors that were perceived to negatively affect the performance of the milling areas are common (see Figure 7.3). This result indicates that the commonality of factors among systems does not necessarily imply that the systems would have common primary influence factors (*i.e.* the factors that drive the performance of the systems may vary).

Shared primary influence factors in the milling areas

The shared primary influence factors in the four sugarcane milling areas are shown in Table 7.8. It can be seen that 60 % of the shared primary influence factors fall under three thematic areas that represent the core operations of a sugarcane production and processing system. This may be because at least 60 % of primary influence factors at the four milling areas fall under the thematic areas of cane production and harvesting, cane transport and supply and cane milling. It can also be seen that 30 % of the shared primary influence factors fall under the quality thematic area. This may be because a substantial percentage of primary influence factors at three of the four milling areas fall under the quality thematic area (see Section 7.5.4).

Table 7.8 Shared primary influence factors in South African sugarcane milling areas

No.	Common	Eston	Felixton	Komati	Umfolozi
1	More lodging		✓		✓
2	Extended length of milling season		✓		✓
3	Harvest efficiency reduction		✓		✓
4	Poor variety	✓			✓
5	Yield decrease	✓	✓		✓
6	Yield increase	✓		✓	
7	Behind allocation		✓		✓
8	Lower cane supply reliability	✓			✓
9	Longer queue		✓	✓	
10	More times no-cane at zone on arrival	✓			✓
11	More trucks			✓	✓
12	More under loading	✓	✓		✓
13	Transport efficiency reduction		✓	✓	
14	Mill throughput reduction	✓	✓		✓
15	More diffuser residence time	✓	✓		
16	More mechanical mill stops			✓	✓
17	More no cane stops	✓			✓
18	Poor clarification		✓		✓
19	Drought	✓	✓		
20	Rain	✓		✓	✓
21	High moisture content			✓	✓
22	More ash % cane	✓			✓
23	More silica % cane			✓	✓
24	More soil % cane			✓	✓
25	More foreign material		✓		✓
26	Lower cane density			✓	✓
27	Lower cane quality		✓	✓	
28	Lower sucrose %		✓		✓
39	More deterioration		✓	✓	
30	Pay days	✓			✓

Cane production and harvesting | Cane transport and supply | Cane milling | Environment
Quality | Economics | Labour | Cross cutting

Unique primary influence factors in the milling areas

The primary influence factors that were unique to specific milling areas are listed in Table 7.9. Apparently the number of unique primary influence factors tends to correspond with the number of primary influence factors in a milling area. The Umfolozi milling area has the highest number of unique primary influence factors followed by the Eston, while Komati has the lowest.

Table 7.9 Unique primary influence factors in South African sugarcane milling areas

Eston	Felixton	Umfolozi	Umfolozi (Continued)
1. Inability to burn	1. More pests and diseases	1. Less burning	25. Higher sugar quality
2. More runaway fires	2. Low stacking efficiency	2. Lower topping	26. Cane supply area shrinkage
3. Incorrect time for applying inputs	3. Longer cycle time	3. More field damage	27. Less willingness to invest
4. Less land use plans	4. Cane depletion end of season	4. More harvest scheduling	28. More land claims
5. Lower cutter productivity	5. Cane excess at end of season	5. More mechanical harvesting	29. Fewer cutters
6. Cane diversions	6. Increase in weekly crush rate	6. Reduced LOMS	30. Aged equipment
7. Cane supply variability	7. More inversion in diffuser	7. Fewer consignments	31. More mechanical breakdowns
8. Overestimates	8. Phosphate shortage	8. Fewer times no-cane at zone on arrival	
9. Less knowledge of stock at loading point	9. Heat	9. Longer hauls	
10. RTMS implemented	10. More grower/miller conflict	10. More stock stored at loading point	
11. Higher crush rate variability	11. Poor communication	11. Poor road maintenance	
12. Lower boiler capacity	12. Poor communication infrastructure	12. Shorter cycle time	
13. Lower dewater milling efficiency	**Komati**	13. Transport efficiency increase	
14. More diffuser flooding	1. Bullwhip in transport	14. Vehicle schedule implemented	
15. More operational mill stops	2. Fewer trucks	15. A-pan saturation	
16. More wear on hammers and shredders	3. Low loading efficiency	16. High evaporation rate	
17. Slower diffuser throughput	4. More evaporator scaling	17. High viscosity	
18. Wind	5. More pulping	18. Higher energy requirements	
19. Alternative industries/crops	6. Higher fibre %	19. Higher sugar recovery	
20. Land bond repayments		20. Lower heat transfer coefficient	
21. Less profit		21. More coal utilisation	
22. High labour cost		22. More heater scaling	
23. Poor knowledge		23. High rainfall	
24. Poor training and management		24. More silt on leaves	

Cane production and harvesting; Cane transport and supply; Cane milling; Environment; Quality; Economics; Labour; Cross cutting

7.6 Indicator Factors in the Sugarcane Milling Areas

This section provides and discusses the results from the indicator vertex analyses that were carried out on the four sugarcane milling areas.

7.6.1 Type and strength of indicator factors in the milling areas

Tables 7.10 to 7.13 show the factors that were identified as indicators in the four sugarcane milling areas. The factors are ranked in a descending order of their indicator indices. The number of indicator factors range from 148 in the Felixton milling area to 165 in Eston milling area. This result suggests that there are many factors that can possibly be used as performance indicators in sugarcane milling areas.

There are variations in the strengths of the indicator factor between the four milling areas. The variations are reflected in the rankings of the indicator factors (see Tables 7.10 to 7.13). For example, crush rate variability is ranked 1^{st}, 35^{th}, 57^{th} and 13^{th} in the Eston, Felixton, Komati and Umfolozi milling areas, respectively. Furthermore, crush rate variability, cutter productivity, deviation from allocation and operating costs are the strongest indicator factors in the Eston, Felixton, Komati and Umfolozi milling areas, respectively. This indicates that what may be a strong indicator in one milling area may not necessarily be strong in another milling area. Hence, it may not always be appropriate to use the same set of indicators for all milling areas.

Some of the factors that were identified in this study are already used as indicators in the SA sugar industry. Information about some of the indicators that are already in use can be obtained from literature (*e.g*. Davis and Achary, 2008; Davis *et al*., 2009; Smith *et al*., 2010). It is acknowledged that the author is unaware of the methods that were used to select the indicators that are already in use. The factors that are not highlighted in Tables 7.10 to 7.13 are directly or indirectly used as indicators in the industry. It is evident that a majority of indicators that are used by the industry relate to cane milling and quality issues. It is also evident that there is a substantial number of additional factors that the industry can use as indicators. The factors relate mainly to in-field cane condition, cane harvesting, cane transport, economics, environment, stakeholders' relations and labour issues. It is also evident from Tables 7.10 to 7.13 that some of the factors that the industry does not currently use as indicators are ranked as important. For example, the highest ranking factors that were identified in the Felixton, Komati and Umfolozi milling areas are not currently used as indicators. It is hoped that future research may provide answers to the foregoing.

Table 7.10 Indicator factors in the Eston sugarcane milling area

1. Crush rate variability	43. Leuconostoc infections	85. Sugar quality	127. Washing
2. Cane lodging	44. Exhaustion efficiency	86. Problems with mixing drives	128. Poor communication
3. Deviation from allocation	45. Income	87. Sugar colour	129. Crystalliser maintenance
4. Length of milling season	46. Cane supply area shrinkage	88. Crystallisation efficiency	130. Boiling rates
5. Sucrose %	47. Weekly crush rate	89. Reluctance to burn/harvest	131. Drying efficiency of raw sugar
6. BHTCD	48. Cane excess/depletion at end of season	90. Transport efficiency	132. Heat transfer in massucuites
7. Diffuser residence time	49. Foreign material in cane	91. Dextran	133. Bagasse combustion
8. Milling efficiency	50. Deviation from estimates	92. Mannitol	134. Scheduled mill stops
9. Juice purity	51. Cycle time	93. Boiler efficiency	135. Wash water requirements
10. Cane deterioration	52. Heat	94. Diffuser percolation	136. Amount of burning
11. Harvest efficiency	53. Cane supply variability	95. Mill mechanical wear	137. Mill crash stops
12. Crush rate	54. Cane carry-over	96. Encrustation in crystalliser	138. Stool death
13. Cane supply reliability	55. Length of crop cycles	97. Amount of starch	139. Pulping
14. Cane quality	56. Road maintenance	98. Impact on haulage capacity	140. Cost of enzyme in boiler house
15. Inversion in diffuser	57. Diffuser flooding	99. Mill mechanical damage	141. Crystal colour
16. Cutter productivity	58. Energy requirements	100. Preparation efficiency	142. Environmental impacts
17. Fibre %	59. Fixed cost component	101. Boiler corrosion	143. Synchronisation of operations
18. Diffuser throughput	60. Evaporator scaling	102. Amount of ash in syrup & molasses	144. Heat transfer coefficient
19. Over cooling of cooling crystallisers	61. Blinding of centrifugal screen	103. Syrup quality	145. Packaging quality
20. Non sucrose %	62. Wear on hammers and shredders	104. Bagacillo in clear juice	146. Trashing
21. Extraction efficiency	63. Clarification	105. VHP	147. Knowledge of stock at loading point
22. Burn efficiency	64. pH	106. Mill maintenance	148. Evaporation requirements
23. Front-end efficiency	65. Amount of misshapen crystals	107. Corrosion	149. Ratoonability
24. Soil % cane	66. Pol factor	108. Lime requirements	150. Pests and diseases
25. Factory capital utilisation	67. Phosphate shortage	109. Juice colour	151. Fertilizer efficiency
26. Mechanical mill stops	68. Dehydration of sugarcane	110. Crystal loss through centrifuge	152. Aluminium tolerance
27. Juice spillage	69. Evaporation rates	111. Number of consignments	153. Turbidity
28. Physical losses	70. Number of times no-cane at zone on arrival	112. Vehicle maintenance	154. Pesticide & fertiliser efficiency
29. Operational mill stops	71. Field damage	113. Profit	155. Variety
30. No-cane stops	72. In-field loading	114. Silica in clear juice	156. Cutter availability
31. Sucrose loss in mollasses	73. Length of queues	115. Expenses	157. Absenteeism
32. Yield	74. Mechanical breakdowns	116. Loss in sugarcane mass	158. Availability of PBS vehicles
33. Amount of trash in load	75. Over/under loading	117. Operating costs	159. Inability to burn
34. Road damage	76. Harvest rate variability	118. Logistics transparency	160. Cane supply
35. Coal utilisation	77. Grower/miller conflicts	119. Mill yard double handling	161. Land ownership stability
36. Viscosity	78. Mill chokes	120. Cane replanting	162. Shortage of cutters
37. Mill throughput	79. Stakeholder trust	121. Return on investment	163. Topping height
38. Cane density	80. Silica % cane	122. Cash flow	164. Cane harvesting age
39. Ash % cane	81. Ash % bagasse	123. In-field transport efficiency	165. Number of load sensors
40. Suspended solids in juice	82. Permeability	124. Heater scaling	
41. Deviation from DRD	83. Sugar recovery	125. Sugar price	
42. Spending on inputs	84. Filterability	126. Number of trucks	

Not used in SA sugar industry   Unique indicator factor

Table 7.11 Indicator factors in the Felixton sugarcane milling area

1. Cutter productivity	38. Yield	75. Leuconostoc infections	112. Foreign material in cane
2. Cane quality	39. Problems with mixing drives	76. Energy requirements	113. Scheduled mill stops
3. Cane supply reliability	40. Weekly crush rate	77. Crystalliser maintenance	114. Stakeholder trust
4. Non sucrose %	41. Length of crop cycles	78. Reluctance to burn/harvest	115. Corrosion
5. Length of milling season	42. Mill mechanical wear	79. Diffuser residence time	116. Lime requirements
6. Sucrose %	43. Number of trucks	80. Crush rate	117. Crystal loss through centrifuge
7. Cane excess/depletion at end of season	44. Encrustation in crystalliser	81. Pol factor	118. Diffuser percolation
8. Cane supply area shrinkage	45. Mill chokes	82. Blinding of centrifugal screen	119. Extraction efficiency
9. Income	46. Fibre %	83. Sucrose loss in mollasses	120. Silica in clear juice
10. Viscosity	47. Crystallisation efficiency	84. Mechanical mill stops	121. Cane supply variability
11. Phosphate shortage	48. Spending on inputs	85. pH	122. Silica % cane
12. Exhaustion efficiency	49. Grower/miller conflicts	86. Environmental impacts	123. Ash % bagasse
13. BHTCD	50. Juice purity	87. Amount of misshapen crystals	124. Permeability
14. Deviation from DRD	51. Amount of ash in syrup & molasses	88. Cane lodging	125. Road damage
15. Factory capital utilisation	52. Syrup quality	89. Mill crash stops	126. Amount of trash in load
16. Harvest efficiency	53. Bagacillo in clear juice	90. Crystal colour	127. Boiling rates
17. Stool death	54. VHP	91. Synchronisation of operations	128. Drying efficiency of raw sugar
18. Length of queues	55. Fixed cost component	92. Washing	129. Suspended solids in juice
19. Deviation from allocation	56. Deviation from estimates	93. Poor communication	130. Heat transfer in massucuites
20. Number of times no-cane at zone on arrival	57. Juice colour	94. Sugar price	131. Trashing
21. Mill yard double handling	58. Mechanical breakdowns	95. Cane density	132. Evaporation requirements
22. No-cane stops	59. Sugar quality	96. Knowledge of stock at loading point	133. Ash % cane
23. Operating costs	60. Sugar colour	97. Burn efficiency	134. Number of consignments
24. Milling efficiency	61. Expenses	98. Soil % cane	135. Heater scaling
25. Mill mechanical damage	62. Filterability	99. In-field transport efficiency	136. Amount of starch
26. Preparation efficiency	63. Impact on haulage capacity	100. Pulping	137. Turbidity
27. Clarification	64. Dehydration of sugarcane	101. Operational mill stops	138. Packaging quality
28. Diffuser throughput	65. Over cooling of cooling crystallisers	102. Wash water requirements	139. Pesticide & fertiliser efficiency
29. Mill throughput	66. Inversion in diffuser	103. Juice spillage	140. Vehicle maintenance
30. Boiler corrosion	67. Road maintenance	104. Loss in sugarcane mass	141. Bagasse combustion
31. Mill maintenance	68. Diffuser flooding	105. Physical losses	142. Over/under loading
32. Profit	69. Logistics transparency	106. Evaporation rates	143. Wear on hammers and shredders
33. Cane deterioration	70. Cane replanting	107. Dextran	144. Evaporator scaling
34. Boiler efficiency	71. Return on investment	108. Mannitol	145. Heat transfer coefficient
35. Crush rate variability	72. Cash flow	109. Front-end efficiency	146. Cost of enzyme in boiler house
36. Cane carry-over	73. Heat	110. Amount of burning	147. Cycle time
37. Transport efficiency	74. Sugar recovery	111. Coal utilisation	148. Land ownership stability

Not used in SA sugar industry

Table 7.12 Indicator factors in the Komati sugarcane milling area

1. Deviation from allocation	1. Clarification	77. Front-end efficiency	115. Washing
2. BHTCD	2. Coal utilisation	78. Wear on hammers and shredders	116. Mill throughput
3. Crystallisation efficiency	3. Dehydration of sugarcane	79. Encrustation in crystalliser	117. Income
4. Length of milling season	4. Length of queues	80. Mill chokes	118. Crystalliser maintenance
5. Crush rate	5. Inversion in diffuser	81. Over cooling of cooling crystallisers	119. Boiler corrosion
6. Extraction efficiency	6. Sugar recovery	82. Over/under loading	120. Mill maintenance
7. Cane lodging	7. Mechanical breakdowns	83. Amount of starch	121. Evaporation requirements
8. Burn efficiency	8. Ash % bagasse	84. Number of times no-cane at zone on arrival	122. Boiler efficiency
9. Ash % cane	9. Permeability	85. Dextran	123. Pulping
10. Evaporator scaling	10. Cutter productivity	86. Transport efficiency	124. Mechanical mill stops
11. Heater scaling	11. Sugar quality	87. Mannitol	125. Boiling rates
12. Scheduled mill stops	12. In-field loading	88. Stakeholder trust	126. Drying efficiency of raw sugar
13. Viscosity	13. Sucrose loss in mollasses	89. Cane density	127. Heat transfer in massucuites
14. Cane quality	14. Cane carry-over	90. Number of trucks	128. Cost of enzyme in boiler house
15. Fixed cost component	15. Weekly crush rate	91. Reluctance to burn/harvest	129. Cane supply variability
16. Factory capital utilisation	16. Harvest rate variability	92. Amount of ash in syrup & molasses	130. Amount of burning
17. Amount of trash in load	17. Evaporation rates	93. Syrup quality	131. Crystal colour
18. Fibre %	18. Suspended solids in juice	94. Bagacillo in clear juice	132. Cane replanting
19. Sucrose %	19. Crush rate variability	95. VHP	133. Return on investment
20. Cane deterioration	20. Heat	96. Deviation from estimates	134. Cash flow
21. Harvest efficiency	21. Mill yard double handling	97. Operational mill stops	135. Number of consignments
22. Energy requirements	22. Vehicle maintenance	98. Juice spillage	136. Poor communication
23. Yield	23. Diffuser residence time	99. Physical losses	137. Corrosion
24. Operating costs	24. Expenses	100. Pol factor	138. Lime requirements
25. Road damage	25. Mill mechanical wear	101. Juice colour	139. Crystal loss through centrifuge
26. Leuconostoc infections	26. Length of crop cycles	102. Loss in sugarcane mass	140. Silica in clear juice
27. Diffuser percolation	27. Road maintenance	103. Profit	141. Wash water requirements
28. Soil % cane	28. Diffuser flooding	104. Milling efficiency	142. Mill crash stops
29. Exhaustion efficiency	29. No-cane stops	105. Blinding of centrifugal screen	143. Trashing
30. Cycle time	30. Spending on inputs	106. In-field transport efficiency	144. Packaging quality
31. Grower/miller conflicts	31. Non sucrose %	107. Impact on haulage capacity	145. Synchronisation of operations
32. Cane excess/depletion at end of season	32. Field damage	108. Sugar price	146. Knowledge of stock at loading point
33. Cane supply reliability	33. Logistics transparency	109. pH	147. Turbidity
34. Juice purity	34. Foreign material in cane	110. Amount of misshapen crystals	148. Pesticide & fertiliser efficiency
35. Phosphate shortage	35. Problems with mixing drives	111. Bagasse combustion	149. Cane supply area shrinkage
36. Environmental impacts	36. Sugar colour	112. Mill mechanical damage	150. Land ownership stability
37. Diffuser throughput	37. Heat transfer coefficient	113. Deviation from DRD	
38. Filterability	38. Silica % cane	114. Preparation efficiency	

Not used in SA sugar industry

Table 7.13 Indicator factors in the Umfolozi sugarcane milling area

1. Operating costs	42. Diffuser flooding	83. pH	124. Maintenance costs
2. Deviation from allocation	43. Milling efficiency	84. Diffuser throughput	125. Loading efficiency
3. Coal utilisation	44. Fibre %	85. No-cane stops	126. Sugar price
4. Cutter productivity	45. Expenses	86. Amount of misshapen crystals	127. Silica in clear juice
5. Ash % cane	46. Leuconostoc infections	87. Problems with mixing drives	128. Logistics transparency
6. Energy requirements	47. Cane lodging	88. Sugar quality	129. Boiling rates
7. Cane deterioration	48. Cycle time	89. Boiler efficiency	130. Drying efficiency of raw sugar
8. Mill throughput	49. Length of queues	90. Cane supply area shrinkage	131. Heat transfer in massecuites
9. Ash % bagasse	50. Soil % cane	91. Fixed cost component	132. Mill crash stops
10. Permeability	51. Sucrose loss in mollasses	92. Dextran	133. Evaporation rates
11. Mill mechanical wear	52. Heat	93. Cane excess/depletion at end of season	134. Washing
12. Burn efficiency	53. Inversion in diffuser	94. Mannitol	135. Cane supply variability
13. BHTCD	54. Wear on hammers and shredders	95. Mill yard double handling	136. Cost of enzyme in boiler house
14. Number of times no-cane at zone on arrival	55. Stakeholder trust	96. Vehicle maintenance	137. Wash water requirements
15. Suspended solids in juice	56. Scheduled mill stops	97. Number of trucks	138. Crystal colour
16. Filterability	57. Length of crop cycles	98. Clarification	139. Trashing
17. In-field transport efficiency	58. Profit	99. Cane replanting	140. Evaporation requirements
18. Evaporator scaling	59. Road damage	100. Return on investment	141. Synchronisation of operations
19. Diffuser percolation	60. Crystallisation efficiency	101. Cash flow	142. Knowledge of stock at loading point
20. Silica % cane	61. Exhaustion efficiency	102. Income	143. Amount of burning
21. Spending on inputs	62. Amount of starch	103. Sugar recovery	144. Environmental impacts
22. Juice purity	63. Cane carry-over	104. Sugar colour	145. Packaging quality
23. Mechanical breakdowns	64. Viscosity	105. Amount of ash in syrup & molasses	146. Turbidity
24. Crush rate variability	65. Yield	106. Syrup quality	147. Pesticide & fertiliser efficiency
25. Length of milling season	66. Mechanical mill stops	107. Bagacillo in clear juice	148. In-field loading
26. Weekly crush rate	67. Deviation from estimates	108. VHP	149. Willingness to invest
27. Heater scaling	68. Grower/miller conflicts	109. Operational mill stops	150. Ratoonability
28. Cane quality	69. Front-end efficiency	110. Pol factor	151. Pests and diseases
29. Over cooling of cooling crystallisers	70. Dehydration of sugarcane	111. Juice spillage	152. Cane harvesting age
30. Harvest efficiency	71. Mill chokes	112. Physical losses	153. Fertilizer efficiency
31. Sucrose %	72. Impact on haulage capacity	113. Juice colour	154. Aluminium tolerance
32. Heat transfer coefficient	73. Mill mechanical damage	114. Number of consignments	155. Environmental priority
33. Non sucrose %	74. Bagasse combustion	115. Poor communication	156. Field damage
34. Cane density	75. Preparation efficiency	116. Loss in sugarcane mass	157. Land ownership stability
35. Cane supply reliability	76. Blinding of centrifugal screen	117. Crush rate	158. Harvest rate variability
36. Deviation from DRD	77. Pulping	118. Reluctance to burn/harvest	159. Cane moisture content
37. Foreign material in cane	78. Phosphate shortage	119. Diffuser residence time	160. Cane volume
38. Extraction efficiency	79. Over/under loading	120. Crystalliser maintenance	161. Vehicle response time
39. Transport efficiency	80. Boiler corrosion	121. Corrosion	162. Cutter availability
40. Factory capital utilisation	81. Mill maintenance	122. Lime requirements	163. Amount of trash in load
41. Road maintenance	82. Encrustation in crystalliser	123. Crystal loss through centrifuge	

Not used in SA sugar industry Unique indicator factor

7.6.2 Thematic areas of indicator factors in the milling areas

Because of the wide range and large number of indicators, this section approaches the indicator vertex analyses results from a thematic perspective to attempt to make more sense of the results. Table 7.14 depicts the categorisation of indicator factors in the four milling areas into thematic areas. It is evident that at least 35 % of indicator factors in each milling area fall under the cane milling thematic area. Indicators that fall under cane milling and quality thematic areas constitute at least 57 % of the indicator factors in each milling area. This may explain why most of the indicator factors that are used in the SA sugar industry relate to cane milling and quality as was earlier explained. Assuming that objective methods were used for selecting the indicators that are used in the SA sugar industry, it can be argued that indicator vertex analysis is a credible technique for identifying indicator factors in complex systems.

Table 7.14 Thematic areas of indicator factors in South African sugarcane milling areas

Thematic area	**Percentage of indicator factors**			
	Eston	**Felixton**	**Komati**	**Umfolozi**
Cane production and harvesting	16	10	11	13
Cane transport and supply	15	14	15	15
Cane milling	35	39	38	35
Environment	1	1	1	2
Quality	22	25	25	24
Economics	6	7	7	7
Labour	2	0	0	1
Cross-cutting	4	4	4	4

7.6.3 Common, shared and unique indicator factors in the milling areas

Some of the indicator factors were common to all four milling areas. Others were shared among some milling areas, while the rest were unique to specific milling areas. Figure 7.10 shows the percentages of common, shared and unique indicator factors in the four milling areas. It is evident that at least 90 % of indicator factors in each milling area are common to all the milling areas. Common and shared indicator factors constitute at least 95 % of the indicator factors in each milling area. The foregoing results indicate that the factors that can be used as indicators in SA sugarcane milling areas are generally the same. It was stated in Section 4.1 that at most ten indicators would be sufficient to monitor the performance of most companies. Hence, the top ten factors in the four milling areas were compared for similarities. It was found out that no indicator factor was common to the four milling areas. This further reinforces the argument against the use of the same set of indicators for all milling areas.

The Eston and Umfolozi milling areas have some unique indicator factors, while Felixton and Komati have none. It can, however, be seen in Tables 7.10 and 7.13 that the unique indicator factors are generally weak. The highest ranking unique factors at the Eston and Umfolozi milling areas fall outside of the top 93 % and 76 % of indicators, respectively.

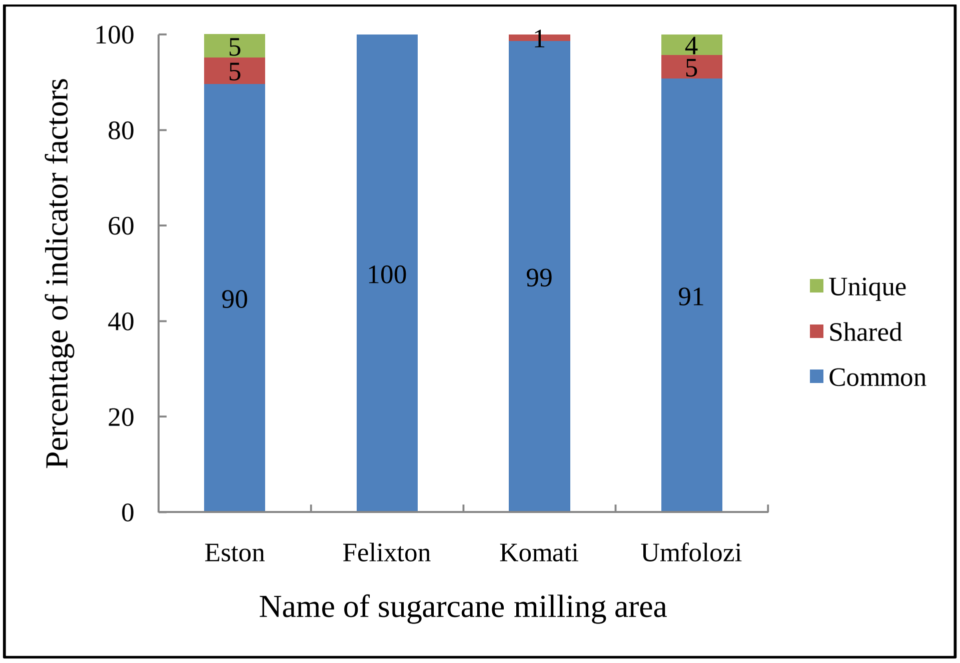


Figure 7.10 Categories of indicator factors in South African sugarcane milling areas

7.7 Root Causes of Problems in the Sugarcane Milling Areas

It was explained in Section 6.7 that a root cause of a problem is a factor that initiates a causal chain of events that leads to the poor performance of a system. It was also explained that the source vertices of a cause-and-effect network are the possible root causes of problems in the system that the network represents.

7.7.1 Preliminary root problems in the milling areas

Some of the factors that were perceived by the stakeholders to negatively affect the performance of the four sugarcane milling areas are source vertices in the milling areas' networks. These factors may be considered as the preliminary root problems in the milling areas. These factors may provide an idea of how many root problems can be identified from stakeholders' interviews alone. The percentages of the preliminary root problems to the factors that were perceived by the stakeholders to negatively affect the performance of the four milling areas are 37%, 20 %, 24 % and 22 % for the Eston, Felixton, Komati and Umfolozi, respectively. This indicates that a majority of factors that were perceived as problems by the stakeholders were not root problems. This finding is in agreement with the assertion by Goldratt and Fox (1986) that most of what people perceive as problems are merely symptoms of problems.

Table 7.15 Preliminary root problems in South African sugarcane milling areas

Eston	26. Frost	11. More mechanical harvesting	3. Higher sugar quality
1. Poor knowledge	27. Wind	12. More stock stored at loading point	4. Over irrigation
2. Less farmers	28. HIV/Aids	13. Poor communication infrastructure	5. HIV/Aids
3. Less seed cane	29. Legal cutters	14. Less preventative maintenance	6. Vehicle schedule implemented
4. Alternative industries/crops	30. More undetermined losses	15. Breakdowns and accidents	7. More cane rolling
5. Social grants	31. Less spending on input costs	16. Drought	8. Less ripening
6. Less stock stored at loading point	32. Aged equipment	**Komati**	9. More silt on leaves
7. Rain	33. Drought	1. A-pan saturation	10. Drought
8. Lower boiler capacity	34. Lower back-end efficiency	2. Wind	11. Poor nutrition
9. Standing trucks	35. More in-field loading	3. Lack of skills	12. Less stockpile
10. Less land use plans	36. Breakdowns and accidents	4. Rain	13. Less spending on input costs
11. More runaway fires	37. Less preventative maintenance	5. Less stock stored at loading point	14. Pay days
12. Cane diversions	38. High labour cost	6. More in-field loading	15. Wind
13. Lower dewater milling efficiency	39. Strikes	7. Bullwhip in transport	16. More stock stored at loading point
14. RTMS implemented	40. Hail	8. Breakdowns and accidents	17. A-pan saturation
15. Incorrect time for applying inputs	**Felixton**	9. Strikes	18. More upstream floods
16. Land bond repayments	1. Wind	10. Less spending on input costs	19. Aged equipment
17. Cold	2. Strikes	11. Drought	20. More land claims
18. Pay days	3. Aged equipment	12. Over irrigation	21. High rainfall
19. Poor training and management	4. Lack of skills	13. Low stacking efficiency	22. High evaporation rate
20. Less stockpile	5. Less stock stored at loading point	14. Aged equipment	23. Lower topping
21. Few load sensors	6. High humidity	15. Less preventative maintenance	24. More mechanical harvesting
22. Other industries	7. RTMS implemented	16. More mud recycling	25. Longer hauls
23. Poor nutrition	8. Less spending on input costs	**Umfolozi**	26. Crop damage
24. Skills shortage	9. Low stacking efficiency	1. Rain	
25. Overestimates	10. Few load sensors	2. More imbibition water	

Cane production and harvesting | Cane transport and supply | Cane milling | Environment
Quality | Economics | Labour | Cross cutting

The percentage of factors that were perceived to negatively affect the performance of the four milling areas that were not reachable by the preliminary root problems were 13 %, 42 %, 63

% and 42 % for Eston, Felixton, Komati and Umfolozi, respectively. This indicates that the stakeholders' interviews did not reveal all the root problems in the milling areas. It can therefore be argued that stakeholders' interviews may not always reveal all the root causes of problems in a system unless the interviews are very detailed. The foregoing argument justifies the use of a generic network for developing networks for systems. Subsequent sections will show that more root problems can be identified from a network that has been developed from a generic perspective compared to the one that has been developed from stakeholders' interviews alone.

Categories of preliminary root problems in SA milling areas

The preliminary root problems in the four milling areas can be grouped into three; *viz.* (1) those that were common to all the four milling areas, (2) those that were shared by at least two milling areas and (3) those that were unique to a milling area. Figure 7.11 shows a categorisation of the preliminary root problems in the four milling areas.

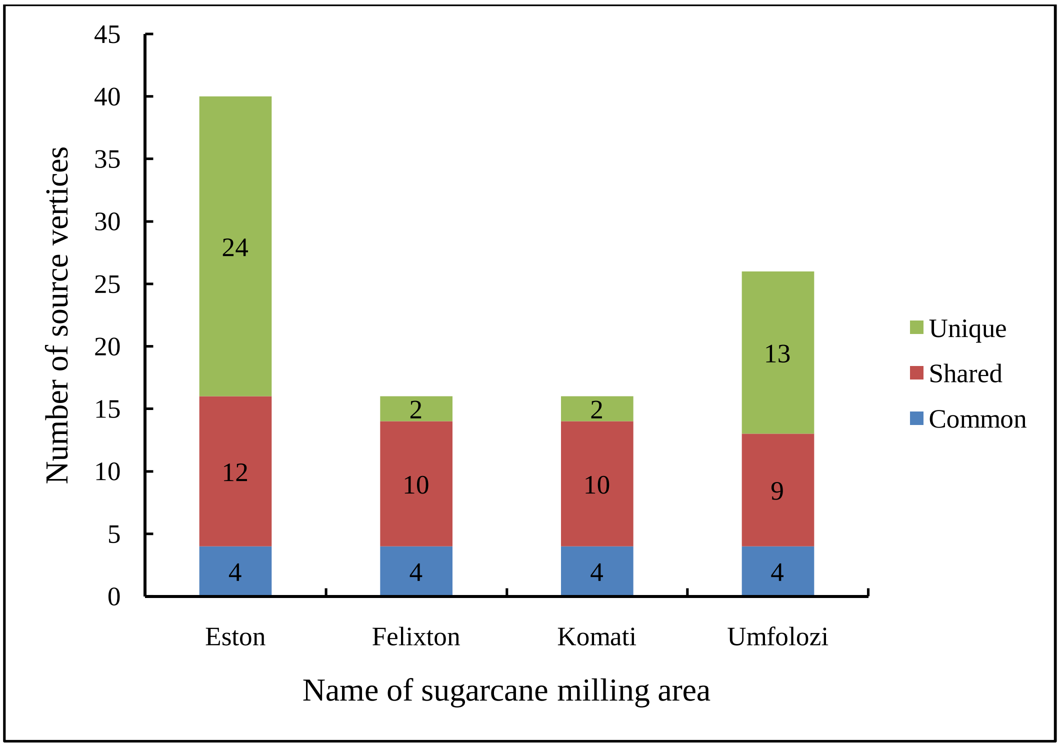


Figure 7.11 Categories of preliminary root problems in South African sugarcane milling areas

Common preliminary root problems in the milling areas

Four preliminary root problems were common to the milling areas; *viz.* (1) drought, (2) wind, (3) aged equipment and (4) less spending on agricultural inputs. Apparently, drought and wind are environmental factors that mainly affect cane production. On the other hand, aged equipment and less spending on agricultural inputs may be indicative of a high degree of uncertainty concerning the future of the sugar industry. Businesses are less willing to invest in equipment and production inputs when there is a high degree of uncertainty in an industry.

Shared preliminary root problems in the milling areas

Table 7.16 shows the shared preliminary root problems in the four milling areas. It is evident that most of the shared preliminary root problems fall under cane transport and supply thematic area. This may suggest that transport and cane supply factors may be some of the major root causes of poor performance in the SA sugar industry. However, these results must be treated with caution because the preliminary root problems are not yet ranked.

Table 7.16 Shared preliminary root problems in South African sugarcane milling areas

No.	Name of vertex	Eston	Felixton	Komati	Umfolozi
1	Over irrigation			✓	✓
2	More mechanical harvesting		✓		✓
3	Low stacking efficiency		✓	✓	
4	Few load sensors	✓	✓		
5	Less stock stored at loading point	✓	✓	✓	
6	More stock stored at loading point		✓		✓
7	More in-field loading	✓		✓	
8	RTMS implemented	✓	✓		
9	Less stockpile	✓			✓
10	A-pan saturation			✓	✓
11	Rain	✓		✓	✓
12	Strikes	✓	✓	✓	
13	Poor nutrition	✓			✓
14	HIV/Aids	✓			✓
15	Pay days	✓			✓
16	Lack of skills		✓	✓	
17	Breakdowns and accidents	✓	✓	✓	
18	Less preventative maintenance	✓	✓	✓	

Cane production and harvesting; Cane transport and supply; Cane milling; Environment; Quality; Economics; Labour; Cross cutting

Unique preliminary root problems in SA milling areas

Table 7.17 shows the unique preliminary root problems in the four milling areas. In general, these results tend to agree with the milling areas' descriptions in Chapter 6. For example, frost, high humidity, bullwhip in transport and upstream floods are some of the unique preliminary root problems at the Eston, Felixton, Komati and Umfolozi milling areas, respectively.

Table 7.17 Unique preliminary root problems in South African sugarcane milling areas

Eston	Eston (Continued)	Felixton	Umfolozi
1. Less seed cane	14. Hail	1. High humidity	1. Crop damage
2. Less land use plans	15. Other industries	2. Poor communication infrastructure	2. More cane rolling
3. Incorrect time for applying inputs	16. Less farmers	**Komati**	3. Less ripening
4. More runaway fires	17. Alternative industries/crops	1. Bullwhip in transport	4. Lower topping
5. Overestimates	18. Land bond repayments	2. More mud recycling	5. Vehicle schedule implemented
6. Cane diversions	19. High labour cost		6. Longer hauls
7. Standing trucks	20. Social grants		7. More imbibition water
8. Lower boiler capacity	21. Legal cutters		8. High evaporation rate
9. Lower dewater milling efficiency	22. Poor knowledge		9. More upstream floods
10. More undetermined losses	23. Poor training and management		10. High rainfall
11. Lower back-end efficiency	24. Skills shortage		11. More silt on leaves
12. Cold			12. Higher sugar quality
13. Frost			13. More land claims

Cane production and harvesting; Cane transport and supply; Cane milling; Environment; Quality; Economics; Labour; Cross cutting

7.7.2 Possible root causes of problems in the milling areas

Preliminary root problems in SA sugarcane milling areas were identified in Section 7.7.1. Though useful, the analytical technique has two weaknesses; *viz*. (1) the technique does not always identify all the root problems in a system and (2) the technique does not provide a means of determining the relative strengths of the identified root problems. Such being the case, *RC* vertex analysis was used to identify all the possible root problems in the sugarcane milling areas. Additionally, the analysis was used to determine the strengths of the identified root problems. It must be stated that the term "possible" root problem is deliberately used here because not all the factors that are identified from *RC* vertex analysis may qualify as root problems. There are two reasons for this. The first reason is that the milling areas' networks that were analysed in this study were developed from a generic perspective. Such being the case, some of the root causes identified may not be the true root causes of the problems in the milling areas represented by the networks. For example, over-irrigation may be highlighted as a possible root cause in an area where no irrigation is applied. The second reason is that management may not have control to fix some of the factors (see the definition of root cause in Section 4.3). Examples of such factors may include rain and drought. Caution must therefore be exercised when interpreting the I_{RC} results. Consultations with the stakeholders and experts of the systems represented by the networks are required when interpreting the results. Once again this is outside the scope of the study.

The number of possible root problems in the four sugarcane milling areas were 94 for the Eston, Felixton and Komati. The Umfolozi milling area had 96 possible root problems. These results indicate that the number of factors that can possibly be the root causes of poor performance in SA sugarcane milling areas is high. The possible root problems in the four milling areas are listed in Tables 7.18 to 7.21. The possible root problems have been arranged in the descending order of their I_{RC} values. It can be observed that a majority of the preliminary root problems that were identified in Section 7.7.1 are ranked highly. For example, rain is ranked first among the possible root problems in the Eston, Komati and Umfolozi milling areas, while wind is ranked third in the Felixton milling areas. The foregoing observation further reinforces the argument that the approaches that were developed in this study can bring forth accurate results.

Figure 7.12 indicates that the Eston, Felixton and Komati milling areas have 100 % of their possible root problems common to all the four milling areas. The Umfolozi milling area has 98 % of its possible root problems common to all the four milling areas. This observation suggests that the factors that can possibly be the root causes of problems in SA sugarcane milling areas are generally the same. However, the rankings would determine which factors are the major root causes of problems in specific milling areas. The TOC philosophy (see Section 3.1) asserts that there are only a few constraints in any given system; usually just one. Going by the philosophy, it can be said that rain is the root problem in the four milling areas. However, rain may not qualify as a root cause of problems because, to the author’s knowledge, it cannot be fixed. Mechanisms can, however, be put in place to deal with the deleterious effects of rain. A comparison of the top five root cause factors in Tables 7.18 to 7.21 indicates that only rain is common across the four milling areas. This indicates that root problems may vary across milling areas even when some of the symptoms of poor performance in the milling areas are similar. The foregoing discussions indicate that RC vertex analysis provides a relatively fast and systematic way for identifying and ranking the possible root problems in systems. However, results from RC vertex analysis need to be validated by the stakeholders or experts of the systems being analysed.

Table 7.18 Possible root causes of problems in the Eston sugarcane milling area

1. Rain	25. Strikes	49. More sucrose in boiler water	73. Vehicle schedule implemented
2. More in-field loading	26. Breakdowns and accidents	50. Overestimates	74. Lower lime quality
3. Aged equipment	27. RTMS implemented	51. More sand % bagasse	75. Wrong yield estimates
4. More mechanical harvesting	28. More alternative products	52. Longer hauls	76. More Consignments from small growers
5. Poor communication infrastructure	29. High humidity	53. Less farmers	77. High labour cost
6. Lower boiler capacity	30. More sugarcane injury	54. Alternative industries/crops	78. Lower dewater milling efficiency
7. More land claims	31. Poor nutrition	55. More water % bagasse	79. Poor training and management
8. More upstream floods	32. Lack of skills	56. Diversion from cane growing operation	80. Lower diffuser temperature
9. Hail	33. More cane shortage	57. Less ripening	81. High colour variety
10. Less land use plans	34. Standing trucks	58. Poor pan boiling	82. Higher milling capacity
11. Drought	35. Cane diversions	59. Incorrect time for applying inputs	83. Poor labour practices
12. Pay days	36. High pith to fibre ratio	60. More mud recycling	84. Land bond repayments
13. HIV/Aids	37. Less stock stored at loading point	61. More air quality pressure	85. Poor flashing
14. More runaway fires	38. Bullwhip in transport	62. High rainfall	86. Poor determination of phosphate levels
15. Low stacking efficiency	39. More cane rolling	63. Cold	87. Reduction in purity
16. Less spending on input costs	40. More silt on leaves	64. Less coal	88. Lower imbibition water
17. Over irrigation	41. Legal cutters	65. Less bagasse	89. More lime preparation problems
18. Less stockpile	42. Other industries	66. Low mill hygiene	90. More lime dosing pump problems
19. Frost	43. Skills shortage	67. Shorter fibre length	91. More imbibition water
20. Less seed cane	44. Poor knowledge	68. A-pan saturation	92. Higher diffuser temperature
21. Few load sensors	45. RTMS not implemented	69. High juice purity	93. More stakeholder trust
22. Little harvest scheduling	46. Social grants	70. High evaporation rate	94. Fewer harvest groups
23. Wind	47. More stock stored at loading point	71. High super saturated syrup	
24. Less preventative maintenance	48. More manual harvesting	72. Crop damage	

Preliminary root cause

Table 7.19 Possible root causes of problems in the Felixton sugarcane milling area

1. Rain	25. Strikes	49. Poor Nutrition	73. More stock stored at loading point
2. Poor knowledge	26. Breakdowns and accidents	50. Poor communication infrastructure	74. Cold
3. Wind	27. Low stacking efficiency	51. Bullwhip in transport	75. RTMS not implemented
4. More alternative products	28. Less land use plans	52. Longer hauls	76. High juice purity
5. More cane shortage	29. Less coal	53. Poor training and management	77. High evaporation rate
6. Cane diversions	30. Less bagasse	54. More silt on leaves	78. High super saturated syrup
7. Standing trucks	31. Wrong yield estimates	55. Less farmers	79. More air quality pressure
8. Aged equipment	32. More mechanical harvesting	56. Alternative industries/crops	80. Poor flashing
9. More in-field loading	33. Frost	57. Lower boiler capacity	81. Poor determination of phosphate levels
10. Little harvest scheduling	34. Vehicle schedule implemented	58. More cane rolling	82. A-pan saturation
11. Poor pan boiling	35. Less spending on inputs	59. Lower dewater milling efficiency	83. More consignments from small growers
12. Overestimates	36. Drought	60. Legal cutters	84. Lower imbibition water
13. Diversion from cane growing	37. HIV/Aids	61. Other industries	85. More lime preparation problems
14. Less stockpile	38. More mud recycling	62. Skills shortage	86. More lime dosing pump problems
15. More upstream floods	39. More runaway fires	63. Lower diffuser temperature	87. High labour cost
16. Lack of skills	40. Over irrigation	64. More sucrose in boiler water	88. Higher milling capacity
17. High pith to fibre ratio	41. Less ripening	65. High humidity	89. Land bond repayments
18. Hail	42. Crop damage	66. More sugarcane injury	90. Reduction in purity
19. Incorrect time for applying inputs	43. Less seed cane	67. More sand % bagasse	91. More imbibition water
20. RTMS implemented	44. Pay days	68. Shorter fibre length	92. More stakeholder trust
21. Few load sensors	45. More land claims	69. Low mill hygiene	93. Fewer harvest groups
22. Less stock stored at loading point	46. Social grants	70. Poor labour practices	94. Higher diffuser temperature
23. More water % bagasse	47. More manual harvesting	71. High rainfall	
24. Less preventative maintenance	48. Lower lime quality	72. High colour variety	

Preliminary root cause (highlighted: 3, 8, 16, 20, 21, 22, 24, 25, 26, 27, 32, 35, 36, 50, 65, 73)

Table 7.20 Possible root causes of problems in the Komati sugarcane milling area

1. Rain	25. Over irrigation	49. Less coal	73. High super saturated syrup
2. Aged equipment	26. More stock stored at loading point	50. Less bagasse	74. More air quality pressure
3. More alternative products	27. Low stacking efficiency	51. High rainfall	75. Crop damage
4. More in-field loading	28. Incorrect time for applying inputs	52. More mud recycling	76. Lower lime quality
5. Wind	29. Vehicle schedule implemented	53. Wrong yield estimates	77. Lower diffuser temperature
6. Cane diversions	30. Less stockpile	54. Poor nutrition	78. Cold
7. Less preventative maintenance	31. More runaway fires	55. Lower dewater milling efficiency	79. More consignments from small growers
8. Strikes	32. Less ripening	56. Less spending on input costs	80. Poor labour practices
9. Breakdowns and accidents	33. RTMS not implemented	57. A-pan saturation	81. High colour variety
10. Lack of skills	34. More sucrose in boiler water	58. Poor training & management	82. Poor flashing
11. Few load sensors	35. More sand % bagasse	59. More silt on leaves	83. Poor determination of phosphate levels
12. More mechanical harvesting	36. Hail	60. Frost	84. High labour cost
13. More upstream floods	37. Less land use plans	61. Less seed cane	85. Lower imbibition water
14. RTMS implemented	38. More land claims	62. Legal cutters	86. More lime preparation problems
15. Little harvest scheduling	39. Shorter fibre length	63. Other industries	87. More lime dosing pump problems
16. More cane shortage	40. High humidity	64. Skills shortage	88. Higher milling capacity
17. Poor knowledge	41. More sugarcane injury	65. Social grants	89. Land bond repayments
18. Diversion from cane growing operation	42. Poor communication infrastructure	66. More manual harvesting	90. More stakeholder trust
19. Standing trucks	43. Pay days	67. Longer hauls	91. Fewer harvest groups
20. Lower boiler capacity	44. Drought	68. Less farmers	92. Reduction in purity
21. Less stock stored at loading point	45. HIV/Aids	69. Alternative industries/crops	93. More imbibition water
22. Bullwhip in transport	46. More water % bagasse	70. High juice purity	94. Higher diffuser temperature
23. More cane rolling	47. Overestimates	71. Low mill hygiene	
24. High pith to fibre ratio	48. Poor pan boiling	72. High evaporation rate	

*Rank, [highlighted] Preliminary root cause

Table 7.21 Possible root causes of problems in the Umfolozi sugarcane milling area

1. Rain	25. More cane shortage	49. Less farmers	73. High juice purity
2. More mechanical harvesting	26. More upstream floods	50. Alternative industries/crops	74. Shorter fibre length
3. More in-field loading	27. Lower boiler capacity	51. A-pan saturation	75. High evaporation rate
4. Hail	28. RTMS not implemented	52. More silt on leaves	76. High super saturated syrup
5. Poor knowledge	29. Pay days	53. Poor communication infrastructure	77. Lower diffuser temperature
6. Less land use plans	30. More land claims	54. Poor nutrition	78. Lower lime quality
7. More runaway fires	31. HIV/Aids	55. More sucrose in boiler water	79. More consignments from small growers
8. Frost	32. Lack of skills	56. Overestimates	80. High labour cost
9. Little harvest scheduling	33. Low stacking efficiency	57. More sand % bagasse	81. Poor labour practices
10. Drought	34. High humidity	58. Cold	82. Poor flashing
11. Aged equipment	35. More sugarcane injury	59. More water % bagasse	83. Poor determination of phosphate levels
12. RTMS implemented	36. Less stockpile	60. Poor pan boiling	84. High colour variety
13. Over irrigation	37. Legal cutters	61. Low mill hygiene	85. Fewer harvest groups
14. Few load sensors	38. Other industries	62. Social grants	86. Higher milling capacity
15. Less spending on input costs	39. Skills shortage	63. More manual harvesting	87. Land bond repayments
16. Wind	40. Less stock stored at loading point	64. More mud recycling	88. Lower imbibition water
17. Less seed cane	41. Diversion from cane growing operation	65. More air quality pressure	89. More lime preparation problems
18. Vehicle schedule implemented	42. Standing trucks	66. Longer hauls	90. More lime dosing pump problems
19. More stock stored at loading point	43. Bullwhip in transport	67. Less coal	91. Reduction in purity
20. More alternative products	44. More cane rolling	68. Less bagasse	92. More stakeholder trust
21. Cane diversions	45. Less ripening	69. Wrong yield estimates	93. More imbibition water
22. Less preventative maintenance	46. Incorrect time for applying inputs	70. Lower dewater milling efficiency	94. Higher diffuser temperature
23. Strikes	47. High pith to fibre ratio	71. Crop damage	95. Higher labour availability
24. Breakdowns and accidents	48. High rainfall	72. Poor training & management	96. Cane supply area expansion

Preliminary cause.

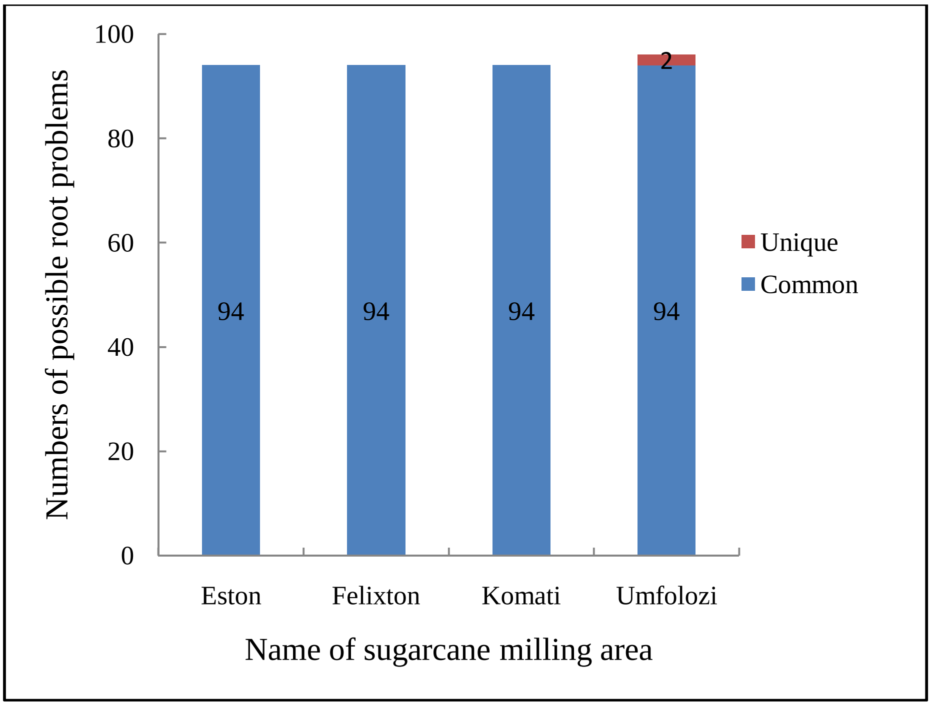


Figure 7.12 Categories of possible root causes of problems in South African sugarcane milling areas

7.8 Summary of Milling Areas' Results

This section provides a brief summary of the results that were obtained after analysing the four sugarcane milling areas.

7.8.1 The Eston milling area results

One hundred and nine factors were perceived by the stakeholders to negatively affect the performance of the Eston sugarcane milling area. The factors fell under eight thematic areas. Figure 7.13 is a graphic representation of the percentage of factors that fell under the thematic areas. About fifty eight percent of the factors fell under three thematic areas; *viz*. (a) transport and supply of cane to mills, (b) cane production and harvesting and (c) cane milling.

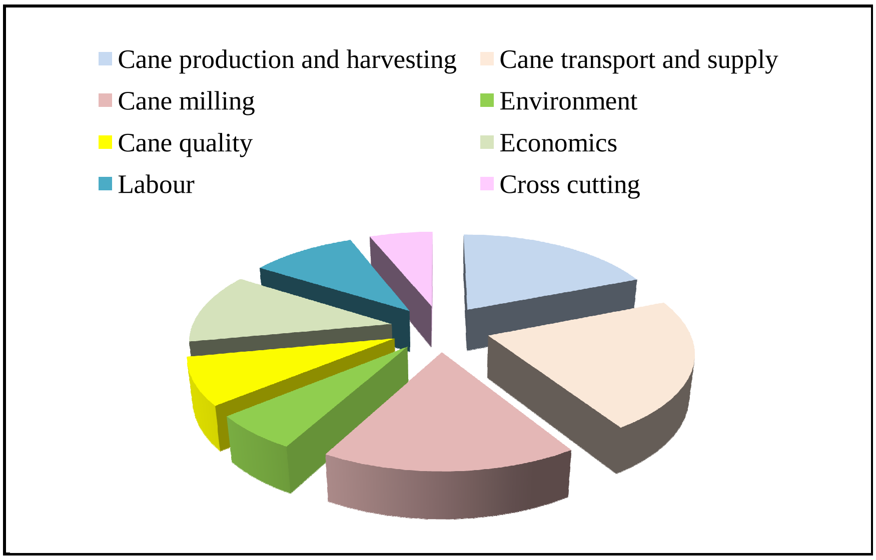


Figure 7.13 Thematic areas of the factors that negatively affect the performance of the Eston sugarcane milling area.

Thirty seven factors were identified as the drivers of poor performance in the Eston milling area. The five top ranked driver factors were rain, low diffuser throughput, unreliable cane supply, drought and no-cane mill stops. One hundred and sixty five factors were identified as possible indicators of poor performance in the Eston milling area. The top ten ranked indicator factors were crush rate variability, lodging of cane, deviation from allocation, LOMS, sucrose percentage in cane, BHTCD, diffuser residence time, milling efficiency, juice purity and cane deterioration. Ninety four factors were identified as the possible root causes of poor performance in the Eston milling area. Rain, in-field loading of cane, aged equipment, mechanical harvesting and poor communication infrastructure were the five top ranked possible root causes of poor performance in the Eston milling area.

7.8.2 The Felixton milling area results

Eighty two factors were perceived by the stakeholders to negatively affect the performance of the Felixton sugarcane milling area. The factors fell under eight thematic areas. Figure 7.14 is a graphic representation of the percentage of factors that fell under the thematic areas. About sixty five percent of the factors fell under three thematic areas; *viz*. (a) transport and supply of cane to mills, (b) cane production and harvesting and (c) cane milling.

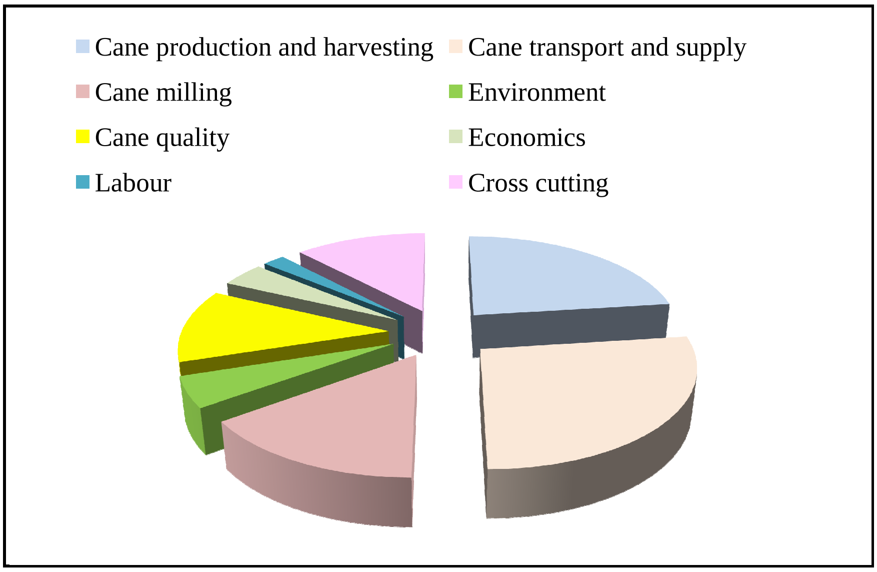


Figure 7.14 Thematic areas of the factors that negatively affect the performance of the Felixton sugarcane milling area.

Twenty eight factors were identified as the drivers of poor performance in the Felixton milling area. The five top ranked driver factors were drought, low yield, foreign material in cane, a reduction in mill throughput and low percentage of sucrose in cane. One hundred and forty eight factors were identified as possible indicators of poor performance in the Felixton milling area. The top ten ranked indicator factors were cutter productivity, cane quality, reliability of cane supply, non-sucrose percentage in cane, LOMS, sucrose % in cane, cane excess/depletion at end of season, cane supply area shrinkage, income and viscosity. Ninety four factors were identified as the possible root causes of poor performance in the Felixton milling area. Rain, poor knowledge, wind, more alternative products and cane shortage were the five top ranked possible root causes of poor performance in the Felixton milling area.

7.8.3 The Komati milling area results

Sixty eight factors were perceived by the stakeholders to negatively affect the performance of the Komati sugarcane milling area. The factors fell under eight thematic areas. Figure 7.15 is a graphic representation of the percentage of factors that fell under the thematic areas. Sixty seven percent of the factors fell under three thematic areas; *viz*. (a) transport and supply of cane to mills, (b) cane production and harvesting and (c) cane milling.

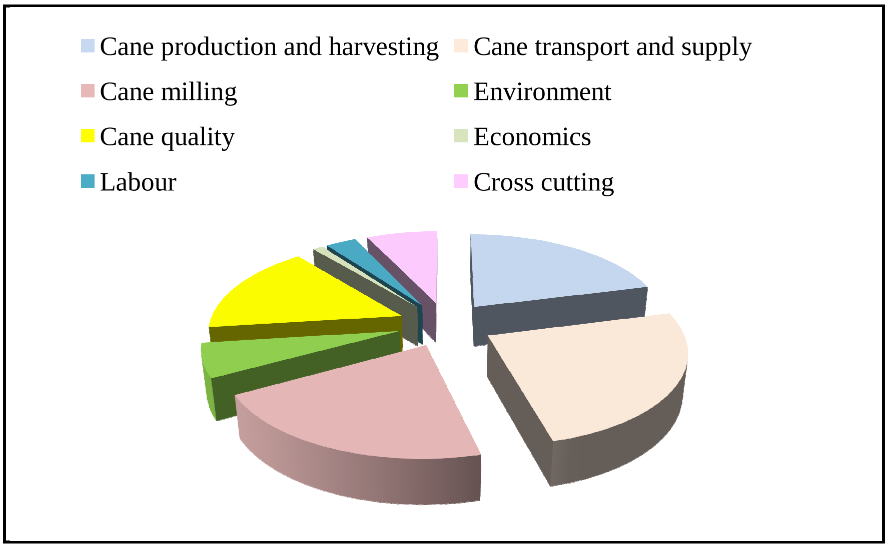


Figure 7.15 Thematic areas of the factors that negatively affect the performance of the Komati sugarcane milling area.

Eighteen factors were identified as the drivers of poor performance in the Komati milling area. The five top ranked driver factors were rain, high percentage of silica in cane, high percentage of fibre in cane, a large number of cane hauling trucks and evaporator scaling. One hundred and fifty factors were identified as possible indicators of poor performance in the Komati milling area. The top ten ranked indicator factors were deviation from allocation, BHTCD, crystallisation efficiency, LOMS, mill crush rate, extraction efficiency, cane lodging, burn efficiency, percentage of ash in cane and evaporator scaling. Ninety four factors were identified as the possible root causes of poor performance in the Komati milling area. Rain, aged equipment, more alternative products, in-field loading of cane and wind were the five to ranked possible root causes of poor performance in the Komati milling area.

7.8.4 The Umfolozi milling area results

One hundred and nineteen factors were perceived by the stakeholders to negatively affect the performance of the Umfolozi sugarcane milling area. The factors fell under eight thematic areas. Figure 7.16 is a graphic representation of the percentage of factors that fell under the thematic areas. About Sixty eight percent of the factors fell under three thematic areas; *viz*. (a) transport and supply of cane to mills, (b) cane production and harvesting and (c) cane milling.

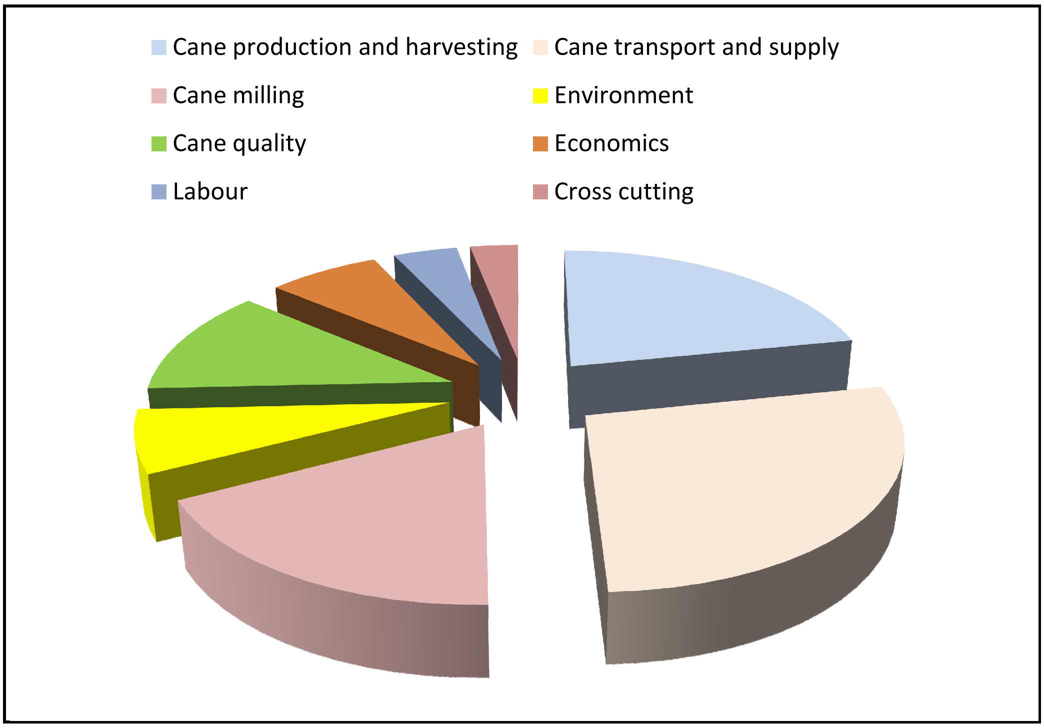


Figure 7.16 Thematic areas of the factors that negatively affect the performance of the Umfolozi sugarcane milling area.

Fifty four factors were identified as the drivers of poor performance in the Umfolozi milling area. The five top ranked driver factors were high soil content in cane, aged equipment, lodging of cane, high silica content in cane and more scaling of heaters. One hundred and sixty three factors were identified as possible indicators of poor performance in the Umfolozi milling area. The ten top ranked indicator factors were operating costs, deviation from allocation, coal utilisation, cutter productivity, percentage of ash in cane, energy requirements, cane deterioration, mill throughput, percentage of ash in bagasse and permeability. Ninety six factors were identified as the possible root causes of poor performance in the Umfolozi milling area. Rain, mechanical harvesting, in-field loading, hail and poor knowledge were the five top ranked possible root causes of poor performance in the Umfolozi milling area.

7.9 Synthesis of Results and Discussions

There are variations in the number of factors that were perceived by stakeholders to negatively affect the performance of the four sugarcane milling areas. These variations can be attributed to the relatively diverse configurations of the milling areas. It was observed that a majority of the factors were either common to all the milling areas or shared among some milling areas. However, there were other factors that were unique to specific milling areas. Most of the factors that were perceived to negatively affect the performance of the milling areas relate to cane production, harvesting, transportation and milling.

There are variations in the number of factors that drive the performance of sugarcane milling areas. The number of driver factors in a milling area tends to correspond with the number of factors that were perceived to negatively affect its performance. A majority of the driver factors relate to cane production, harvesting, transport and milling. It was revealed that there are differences in the type of factors that drive the performance of different milling areas. Furthermore, it was revealed that the strength of a driver factors varied across milling areas.

The study revealed that the factors that can be used to monitor the performance of the sugarcane milling areas are generally the same. It was also found out that the number of factors that can possibly be used as indicators in sugarcane milling areas is high. It was further found out that the number of factors that can practically and economically be used as indicators varied across milling areas. Some indicator factors that were identified in this study are already used in the SA sugar industry. However, there are other factors that were ranked highly in this study that are not yet used in the SA sugar industry.

It was revealed that the factors that can possibly be the root causes of problems in sugarcane milling areas are generally the same. It was also revealed that the number of factors that can possibly be the root causes of poor performance in sugarcane milling areas is high. However, the strength of the factors as root problems varied across milling areas. It was further revealed that a majority of factors that were perceived by stakeholders as problems in the milling areas were symptoms of deeper root problems. Additionally, it was revealed that the information that was obtained from stakeholders' interviews did not show all the root causes of poor performance in the milling areas. Furthermore, it was revealed that some of the root problems that were identified were not relevant to the milling areas.

Although it was not the objective to provide accurate systems analyses of the milling areas, the results generally agree with the issues that were perceived by stakeholders on the ground. This may suggest that the approaches seem to work well.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter contains a discussion of the conclusions from the study. Recommendations for future research have also been made.

8.1 Conclusions

This study has developed comprehensive approaches for analysing complex systems. The approaches comprise a suite of three analytical tools; *viz*. (1) primary influence vertex analysis for identifying the key factors that drive the performance of systems (2) indicator vertex analysis for identifying the factors that can be used to provide information about the performance of systems (3) root cause vertex analysis for identifying the deeper factors that often cause poor performance in systems. A combination of these tools provides a solid basis from which complex systems can be analysed. These approaches conform to the TOC philosophy for the continuous improvement of systems performance in that they allow their users to continuously identify the root causes of problems in the systems, come up with interventions to solve the problems, monitor the performance of the systems and repeat the process. A unique attribute with the approaches is that unlike the CRT and other tools that can do either the RCA or indicator analysis, the approaches can do both as part of one data structure. This attribute is, to the author's knowledge, not available in the existing and well established systems analysis methods. The analytical tools are equipped with computational capabilities to automatically measure the relative strengths of the factors and rank them. These capabilities provide a more objective method for prioritising factors. Most of the well established systems analysis methods are not, to the author's knowledge, equipped with such capabilities. The approaches provide a way for visualising the results of the analyses. This attribute, to the author's knowledge, is also not present in most of the existing systems analysis tools.

This study has demonstrated the various roles that network theory can play in the analysis of complex systems. A generic network provides a method to model all the factors and the cause-and-effect relationships that may possibly exist in a complex system. Similarly, a generic network can be viewed as incorporating all the cause-and-effect diagrams, the root causes of problems and indicator factors that may possibly exist in a system at any given time. Thus, network theory effectively eliminates the long and arduous task of constructing cause-and-effect diagrams in a manual fashion. This reduces (a) the time that is required to analyse a system and (b) the problems that are associated with bringing people together to construct cause-and-effect diagrams, such as human bias and the *recency effect* phenomenon (*cf*. Glenberg *et al*., 1983; Baddeley and Hitch, 1993; Logan and Fischman, 2011). Network theory also provides a way to reduce subjectivity in the analysis of systems. For example, the development of a generic network is done separately from the analysis of specific systems. The people involved in the development of the generic network may not be aware of what the network would be used for and hence human bias may be reduced. Furthermore, a generic network acts as a central repository of knowledge where new finding of scientists could be captured and maintained. Additionally, a generic network is computerised and can therefore be easily updated. Thus, researchers do not have to start from a scratch every time they want to analyse a system.

The study has demonstrated several advantages of the network approaches over the existing and well established systems analysis tools, such as the TOC. The approaches can either fast track or eliminate some of the steps that are followed when analysing systems using the existing systems analysis tools. For example, once a generic network has been developed, the approaches only require the stakeholders to name a few problematic factors in their systems and weigh-up the cause-and-effect relationships between the factors. The stakeholders are not required to carry out the whole process of constructing cause-and-effect diagrams, such as the CRTs, CEDs and IDs. This reduces the time that researchers have to engage with stakeholders. A generic network is computerised and hence can be interfaced with data entry and analysis software. This makes it possible to streamline data collection and analysis and thereby reduce the time required to analyse a system.

The approaches provide mechanisms for addressing some of the limitations associated with the TOC and other well established systems analyses tools. The approaches do not require systems' stakeholders to undergo long periods of training in order to master their use. Most of the steps that the approaches use are computerised and are therefore fast. This may make stakeholders in systems, especially top level managers, more willing to use the approaches. The application of the approaches is less reliant on group work. This can potentially reduce human bias in the analysis of systems.

The aim of this study was not to provide an accurate and comprehensive mapping of the four sugarcane milling areas. Rather, the aim was to develop comprehensive network theory approaches for analysing complex systems. Nevertheless the results from the analyses of the milling areas show that rain, crush rate variability and rain were the highest ranked driver, indicator and root cause factors of poor performance in the Eston sugarcane milling area, respectively (Figure 7.4, Tables 7.10 and 7.18) . The highest ranked driver, indicator and root cause factors of poor performance at the Felixton milling area were drought, cutter productivity and rain, respectively (Figure 7.5, Tables 7.11 and 7.19). Rain, deviation from allocation and rain were the highest ranked driver, indicator and root cause factors of poor performance in the Komati milling area (Figure 7.6, Tables 7.12 and 7.20). Finally, high soil content in cane, operating costs and rain were identified as the highest ranked driver, indicator and root cause factors of poor performance in the Umfolozi sugarcane milling area, respectively (Figure 7.7, Tables 7.13 and 7.21). The results of the analyses were found to be generally consistent with the description of the four sugarcane milling areas. This may suggest that the approaches are effective for analysing complex systems. Since ISSPSs are complex systems as was explained in Chapter 1, it is likely that the approaches can successfully be used to analyse other complex systems. The approaches have never, to the author's knowledge, been used in any agro-industrial application before.

There are, however, some factors that may limit the effectiveness of the approaches. A network model of a system to be analysed is always required in order to use the approaches. This makes the approaches susceptible to the two problems that are encountered when developing models for complex systems; *viz*. (a) how to accurately define the boundaries of a system and (b) how to determine the factors that must be included and excluded in the models. Some important factors, such as the root causes of problems, may therefore be omitted from the network. A network that has been developed from a generic perspective may incorporate factors that are not relevant to a specific system. The results from the analyses must therefore be verified by the stakeholders in a specific system to ensure that they really apply to the system. The approaches are not equipped with an intelligence system to determine whether the factors identified as indicators or root causes are realistic or not. For example, some of the factors that may be identified as the best indicators of the performance of a system may not be easily or economically measurable. Similarly, some of the factors that may be identified as the root causes of problems may not be directly solvable. For example drought may be identified as a root cause of problems in an ISSPS. Drought can only be solved by bringing in capabilities that address its effects.

8.2 Recommendations for Future Research

The network theory approaches were tested on four sugarcane milling areas in South Africa. The tests may not be enough for assessing the effectiveness of the approaches. It is therefore recommended that the approaches be tested on other complex systems other than ISSPSs to further validate their effectiveness and perhaps that more advanced or sophisticated data collection techniques are considered. This study did not compare the accuracy of the approaches with those of the existing and well established systems analysis tools as was explained in Section 1.2. It is therefore recommended that the accuracy of the approaches that were developed in this study be compared with those of existing and established methods that are currently used for analysing complex systems. The analyses used networks that were weighed-up in somewhat a subjective way. It is recommended that these approaches should be tested on networks where the weights of arcs represent empirical values. Primary influence vertex analysis must be compared with the methods that are used for measuring the importance of factors in complex systems. Indicator vertex analysis must be compared with established indicator analysis tools, while root cause vertex analysis needs to be compared with well-established root cause analysis tools. It is recommended that a systematic method for determining the factors that should be included in networks should be developed. It is also recommended that a systematic method for weighing-up the cause-and-effect relationships in networks be developed.

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