

AN OVERVIEW OF THE THEORY OF CONSTRAINTS AND RELATED LITERATURE

TM Sanjika

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Supervisor: Prof C.N. Bezuidenhout

ABSTRACT

Organisations must continuously improve the performance of their systems if they are to survive and flourish. Systems improvement requires the use of suitable techniques to ensure success. Due to the complexity of most modern organisations, it is important that such techniques must be capable of accommodating systems complexity issues.

The South African sugarcane supply chains need to be improved if the South African sugar industry is to minimise its production costs and hence favourably compete on the global market. In pursuit of finding and/or developing a suitable technique for improving the performance of South African sugarcane supply chains, a Systems Thinking based management philosophy called the Theory of Constraints was reviewed.

The review has shown that the Theory of Constraints is effective for improving the performance of systems, regardless of their complexity. Many examples of successful applications of the Theory of Constraints to a wide range of organisations attest to its effectiveness. On the other hand, the review also highlights the various limitations of the Theory of Constraints, some of which are; (1) its inability to fully represent the dynamic complexity inherent in modern systems, (2) the considerable length of time required to identify and solve problems, and (3) its excessive dependence on group work. Nonetheless, it is concluded from the review that the Theory of Constraints could be useful for improving the performance of South Africa's sugarcane supply chains if its limitations are addressed.

The proposed research project aims to develop an innovative computer based cause-and-effect network analyses technique that can be used to establish the most pertinent constraint in a complex sugarcane production system and also perform a wide range of systems diagnostics. The technique will be developed by coupling the Theory of Constraints and the cause-and-effect analysis techniques.

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1. INTRODUCTION

South Africa's sugar industry must minimise its production costs if it is to compete with world-leading low-cost sugar producing countries, such as Brazil and Australia. Fortunately, there is a potential to minimise the production costs of South Africa's sugar industry by improving the efficiency of its sugarcane supply chains at mill area level (*cf.* Higgins *et al.*, 2007; Le Gal *et al.*, 2008). However, this potential can only be effectively exploited if the characteristics of South Africa's sugarcane supply chains are well understood and taken into account in the formulation of improvement strategies and solutions.

South Africa's sugarcane supply chains are complex, fragmented and continuously evolving systems involving 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). This makes the implementation of changes for improving the overall performance of the supply chains difficult. Hence, any attempt to improve the overall performance of the sugarcane supply chains must employ those approaches that are capable of managing system complexity issues. In addition, the approaches must possess mechanisms for encouraging and facilitating collaboration among stakeholders in the supply chains.

Available literature (*e.g.* Eliashberg and Steinberg, 1987; Hobbs, 1996; Croom *et al.*, 2000) suggests that improvements in supply chain efficiency often arise from improved relations among stakeholders. Previous research aimed at improving the overall performance of sugarcane supply chains proposed a range of solutions (*e.g.* Diaz and Perez, 2000; Milan *et al.*, 2003; Higgins *et al.*, 2004; Le Gal *et al.*, 2004; Perry and Wynne, 2004; Le Gal *et al.*, 2008; Lejars *et al.*, 2008; Le Gal *et al.*, 2009). However, adoption of sugarcane supply chain solutions has traditionally been a problem. Higgins *et al.* (2007) indicated that there has been limited adoption of supply chain research results in sugar industries despite the significant potential gains highlighted in literature such as; 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 duration between harvesting and milling (Hansen *et al.*, 1998). This is because most of the solutions failed to deliver benefits to all the supply chain participants concurrently.

The sharing of benefits resulting from improved chain performance has been a fundamental problem in overall supply chain improvement. Higgins *et al.* (2004) observed that where there are a number of independent role players, supply chain solutions need to provide benefits to each participant for successful adoption. If not, the parties involved must move from individual to collective goals (Le Gal *et al.*, 2008; Lejars *et al.*, 2008) and this is difficult to achieve. Otherwise, only win-win solutions would stand chances of adoption. Higgins *et al.* (2007) strongly argued that the success of sugarcane supply chain improvement requires not only a technical solution but also collective participation of all stakeholders and, generally, evolutionary change management.

Appropriate tools are needed to improve the performance of South African sugarcane supply chains. The tools must possess the capability to (1) capture, study and analyse the complexity in the sugarcane supply chains, (2) identify core problem areas that need improvement, (3) develop solutions that address the core problems, and (4) develop management strategies for implementing the developed solutions. The Theory of Constraints (TOC), among others, can provide such tools. The Theory of Constraints comprises a set of tools and strategies for identifying core problems in systems, developing win-win solutions, and managing the successful implementation of the solutions for improved performance of systems.

This literature review assesses the capability and effectiveness of the Theory of Constraints for identifying and solving problems in complex production systems. The review will also investigate the possibility of using the Theory of Constraints for improving the performance of South African sugarcane supply chains.

2. THEORY OF CONSTRAINTS

2.1 Background to the Theory of Constraints

The Theory of Constraints is a systems based management philosophy that is used to assist in the continuous improvement of a system's performance by focussing on core problems that are preventing the system from achieving its goal (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 Theory of Constraints approach is based on Systems Thinking (Mabin, 1999; Gupta *et al.*, 2002; Mabin and Balderstone, 2003; Scoggin *et al.*, 2003; Taylor and Churchwell, 2004) and as such, considers the overall performance of the system rather than focussing on improving the performance of an individual task or component in the system. The Theory of Constraints recognises that every system has elements that limit its performance, 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). The Theory of Constraints assumes 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). 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. machinery, 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). It is claimed (Rahman, 1998) that most organisations have more policy constraints than physical ones. The Theory of Constraints encourages managers to identify the constraints and find ways to eliminate them (Simatupang *et al.*, 2004).

The Theory of Constraints has been applied to a wide range of commercial and not-for-profit organisations and sectors (Blackstone, 2001; Mabin and Baldestone, 2003; Watson *et al.*, 2007). Mabin and Balderstone (2003) and Watson *et al.* (2007) listed examples of commercial organisations known to have employed the Theory of Constraints techniques such as Boeing, Delta Airlines, General Motors, General Electric, Ford Motor Company, 3M and Lucent Technologies. It was also pointed out (Watson *et al.*, 2007) that there are a number of

companies that have adopted the Theory of Constraints techniques but have chosen to remain anonymous for competitive reasons. Watson *et al.* (2007) further gave examples of not-for-profit organisations and government agencies that have applied the Theory of Constraints techniques to their operations such as Habitat for Humanity, Pretoria Academic Hospital, British National Health Service, United Nations, NASA, United States Department of Defence (Air Force, Marine Corps, and Navy), and the Israeli Air Force.

The Theory of Constraints has also been applied to a wide range of business areas. Blackstone (2001) reported the application of the Theory of Constraints in business areas that included Operations, Finance and Measures, Projects, Distribution and Supply Chains, Marketing, Strategy and Tactics, Sales, and People Management. An analysis by Kim *et al.* (2008) of the Theory of Constraints literature in the public domain peer-reviewed publications spanning a period from 1994 to early 2006 revealed a plethora of applications of the Theory of Constraints. Mabin and Balderstone (2003) in a meta-analysis of over 80 successful Theory of Constraints applications found over 100 descriptions of the Theory of Constraints applications, spanning such areas 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 Theory of Constraints in agriculture (integrated poultry industry).

Available literature (*e.g.* Aggarwal, 1985; Gardner *et al.*, 1994; Gupta *et al.*, 2002; Mabin and Balderstone, 2003; Watson *et al.*, 2007; Inman *et al.*, 2009; Lin *et al.*, 2009) indicates that the application of the Theory of Constraints results in significant improvement in organisational performance. Sale and Inman (2003) determined through a survey that firms that employ the Theory of Constraints techniques perform significantly better than those using traditional manufacturing methods. Rigorous academic testing confirmed that manufacturing systems that employ the Theory of Constraints techniques perform better than those using well known alternatives, such as Manufacturing Resource Planning (MRP), Just-in-Time (JIT), Lean Manufacturing and Agile Manufacturing (Ramsy *et al.*, 1990; Mabin and Baldestone, 2000). Studies have demonstrated that the use of the Theory of Constraints reduces inventory, work in process inventory, lead times, and improves due date delivery performance (Reimer, 1991; Wahlers and Cox, 1994; Darlington, 1995; Mabin and Balderstone, 2003; Watson and Patti, 2008). Inman *et al.* (2009) argued that the adoption of the Theory of Constraints techniques yields observable outcomes, which lead to improved business unit performance. A meta-

analysis of over 80 successful Theory of Constraints applications by Mabin and Baldestone (2003) provided 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. The burgeoning uptake of the Theory of Constraints can thus be attributed to its impressive success rate.

Theory of Constraints is, however, not without criticism. Reid and Koljonen (1999) singled out the inability of the Theory of Constraints to capture the dynamic nature of modern manufacturing environment as one major drawback. They argued that the relationships among systems' components depicted in the Theory of Constraints' logic trees often appear to be linear and relatively static and hence fail to fully represent the dynamic complexity in modern business organisations. They therefore proposed the coupling of the Theory of Constraints' logic trees with System Dynamics modelling techniques as a way of strengthening the Theory of Constraints process. Watson *et al.* (2007) also stated that top-level management support and commitment have more often been insufficient to sustain the Theory of Constraints success. They argued that many top-level managers delegate the implementation of the Theory of Constraints to mid-level managers because of the considerable length of training time that is required to master the subject matter. Furthermore, Goldratt (1990) stated that the Theory of Constraints process cannot succeed in an organisation unless all its members develop as much enthusiasm for the Theory of Constraints as the expert facilitating the process. He argued that such levels of enthusiasm among organisation members can only be achieved if the members come to the same conclusion and regard the conclusions as their own.

Considering the success stories of the Theory of Constraints, it is likely that its application for improving the performance of the South African sugarcane supply chains will be a success. Cases have been reported in literature of the successful application of the Theory of Constraints in areas bearing some resemblance to integrated sugarcane supply and processing systems. For example, Chaudhari and Mukhopadhyay (2003) used the Theory of Constraints to improve the performance of an integrated poultry firm in India. They identified and resolved the policy constraints that were adversely affecting the profitability of the firm. The application of the Theory of Constraints resulted in an overwhelming improvement in the firm's profit without any major investment being made.

2.2 Components and Applications of the Theory of Constraints

Theory of Constraints consists of three components (Rahman, 1998; Chaudhari and Mukhopadhyay, 2003; Mabin and Balderstone, 2003); (1) an operational strategy consisting of five focussing steps for continuous systems improvement, (2) Thinking Process (TP) tools for investigating, analysing and solving complex problems, and (3) a performance measurement system for assessing the performance of a system in achieving its goal. The Theory of Constraints components are shown in Figure 2.1. These components will be discussed in the subsequent sections.

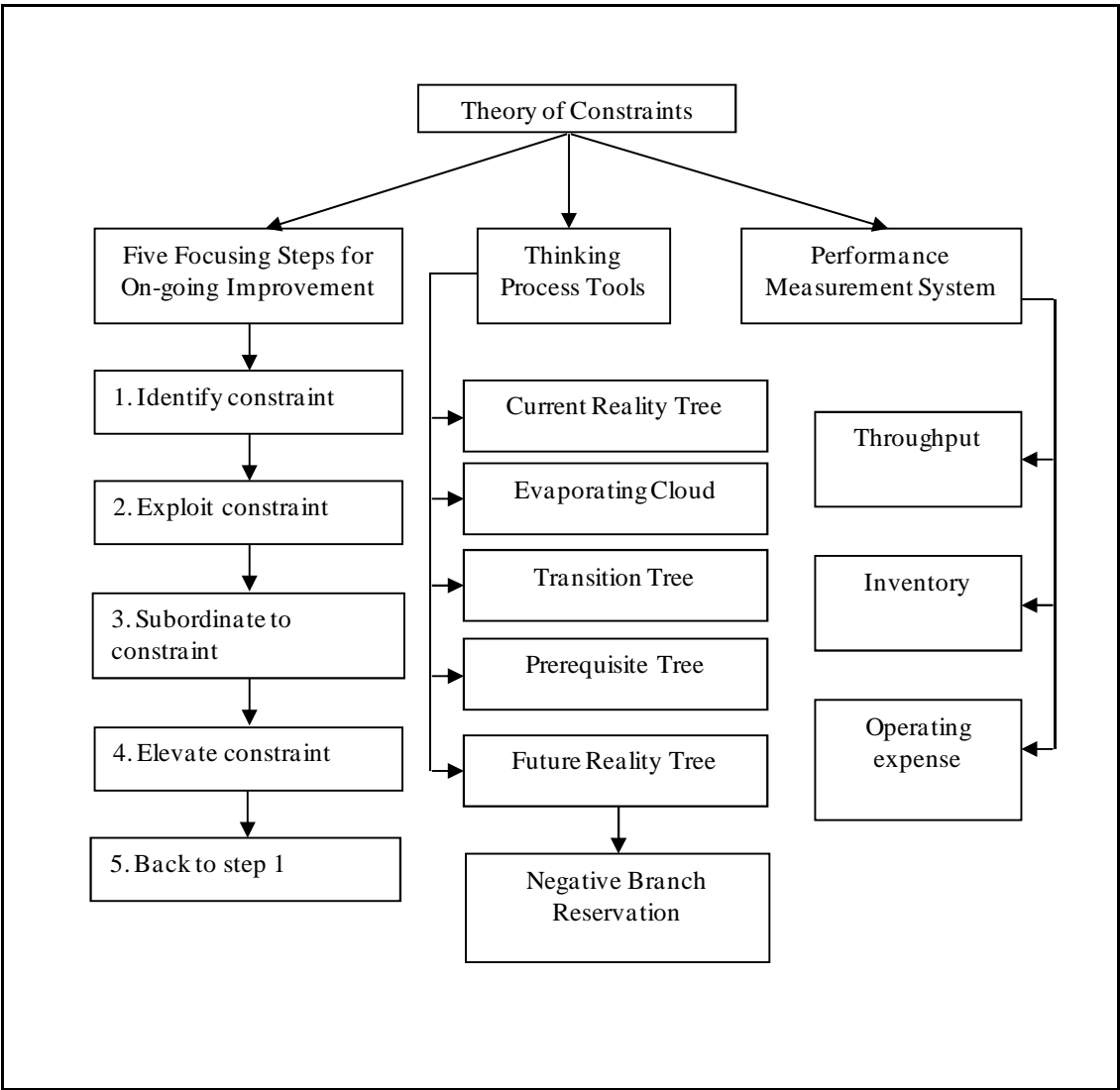


Figure 2.1 Components of the Theory of Constraints

2.2.1 The Theory of Constraints five focussing steps

Dalton (2009) stated that most traditional continuous improvement techniques are based on the premise that the overall performance of a system can be improved by maximising individual efficiencies of the system's components or processes *i.e.* improving local efficiencies or achieving local optima. It is, however, argued (Smith and Pretorius, 2003) that interventions aimed at achieving local optima can negatively affect the overall performance of an organisation or system.

Theory of Constraints, as opposed to the traditional continuous improvement techniques, is based on the premise that the performance of a system is limited by the lowest performing component or process in the system. Hence, in order to improve the overall performance of a system, Theory of Constraints stipulates that any improvement effort must be directed at increasing the performance of the constraint (Goldratt, 1990). It is argued (Dalton, 2009) that improving the performance of a non-constraint is a wasted effort because the constraint will still be determining the overall performance of the system.

Theory of Constraints provides a five-step process, called the five focussing steps (FFS) for achieving continuous improvement of a system's performance (Goldratt and Cox, 1992). The five focussing steps of the Theory of Constraints are outlined in Figure 2.1 and will be discussed in subsequent sections. Goldratt (1990) prescribed two extra steps prior to the FFS that Scheinkopf (1999) described as prerequisite steps for any improvement process. The two steps are; (i) define the system's goal and (ii) determine measures of performance (performance metrics) to use.

The Theory of Constraints on-going improvement process starts by defining the system's goal and identifying the proper, global and simple performance metric to use for measuring the performance of the system relative to its goal. Having identified the system's goal and the performance metric(s) to use, the FFS process begins by first identifying the system's constraint. Goldratt (1990) stated that the process of improving the performance of any system must begin with identifying its constraint. Rahman (1998) emphasised the importance of identifying organisation's constraints and the necessity to prioritise them based on their impact on the goal of the organisation.

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 be eliminated from the system as pointed out by Rahman (1998). Thus, policies that are limiting the performance of a system must be replaced with the ones that support improved performance.

The third step of the FFS process involves subordinating the actions 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). A constraint may be elevated by among other things investing in new equipment and increasing staff numbers.

If a constraint has been addressed 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 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 obviously, another component within the system will become the next constraint according to the Theory of Constraints philosophy *i.e.* every system has at least one constraint.

The five focusing steps of the Theory of Constraints provide an approach to continually solve systems problems and hence improve the performance of organisations. It is stated (Mabin, 1999; Gupta *et al.*, 2002; Davies *et al.*, 2005; Gupta and Kline, 2008; Dalton, 2009) that the FFS provide a means for continuously identifying and managing systems’ constraints. Mabin and Balderstone (2000; 2003) showed from the literature that there have been remarkable gains for organisations who adopted the use of the FFS. Several examples are cited in literature on the successful application of the FFS in improving the performance of organisations (*e.g.* Roybal *et al.*, 1999; Pegels and Watrous, 2005).

Pegels and Watrous (2005) described the successful application of the FFS process to a manufacturing plant operations problem. The manufacturing plant produced tail, marker, interior, auxiliary and head light assemblies for heavy-duty trucks and trailers. Assorted moulded components requiring the use of different moulds were used in the manufacture of the products. Hence, the plant's moulding machines had to be stopped from time to time to change moulds. This resulted in excessive down time for the moulding machines and also affected the production of components required for downstream operations. Consequently, the plant's throughput was sub-optimal and thus productivity and efficiency of the plant were negatively affected. The plant was thus struggling to complete customer orders on time. Using the FFS process, mould set-ups were identified as a plant's constraint. The constraint was exploited while subordinating all the other manufacturing processes to the limitations of the constraint. A new method for prioritising mould changes was executed. This ensured that all orders were completed on time. A mould storage database was created and the routers (detailed process sheets) for each product were modified to include all the necessary auxiliary equipment needed during the moulding stage of each component. These interventions reduced the amount of time spent in locating moulds and auxiliary equipment. Some tasks that the mould set-up crews used to do were transferred to the maintenance department. This allowed the crews to focus more of their time on mould set-ups thereby increasing the throughput for mould set-ups. The constraint was then elevated by finding and implementing a method of completing moulding changeovers at a faster rate. This resulted in the breaking of the constraint, *i.e.* moulding set-ups were no longer the constraint. The application of the FFS process resulted in a 26% reduction in the amount of time required to complete a mould change. Consequently, the plant was able to increase its throughput which culminated in improved productivity and efficiency.

The use of the FFS is not without flaws. Mabin (1999) argued that the FFS provide Theory of Constraints users with a simple and effective method for achieving continuous improvement of organisations or systems only in cases where the constraint is easy to identify *e.g.* a physical constraint in a manufacturing company or low staffing levels. She stipulated that the FFS method is flawed where the constraint is harder to pinpoint. This inherent weakness of the FFS, she added, manifests itself when dealing with policy and behavioural constraints where what should be done to rectify a constraint is not as clear.

The Theory of Constraints' FFS can be very valuable to the South African sugar industry in its efforts to improve the performance of its sugarcane supply chains. Adoption of the FFS may ensure that the South African sugarcane supply chains are improved on a continuous basis. However, using the FFS single-handedly may not bring about any improvements in the performance of the supply chains. The FFS only outline the steps that must be followed when improving the performance of systems but do not provide a methodology for executing the steps. For example, the FFS do not provide a methodology for identifying constraints in systems. Considering the complexity of South Africa's sugarcane supply chains, identifying constraints may pose a big challenge to the successful use of the FFS.

2.2.2 The Theory of Constraints Thinking Processes

Organisations must continuously transform and adapt to their continually 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) pointed out that successful implementation of positive organisational changes requires managers to possess the capability to; (1) measure, assess and analyse the existing situation in line with organisational goals, (2) formulate relevant action plans to effectively address organisational problems, and (3) successfully manage the implementation of the formulated action plans.

The Theory of Constraints approach to change management (Goldratt, 1990) involves finding answers to three basic questions; (1) what to change, (2) what to change to, and (3) how to cause the change. Koljonen and Reid (1999) stressed that the answers to these three questions provide managers with a roadmap on how to successfully implement positive organisational changes. Thinking Processes (TPs) are a set of Theory of Constraints logic-based tools that 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 Thinking Process tools comprise a suite of five cause-and-effect tree diagrams and an ancillary tool (see Figure 2.1) that are constructed following strict logic rules to represent situations (Mabin and Balderstone, 2003; Kim *et al.*, 2008; Inman *et al.*, 2009). The tools use either sufficiency or necessity logic to help managers or Theory of Constraints users to do the

following; (1) to identify problematic symptoms, called undesirable effects (UDEs), which act as indicators of the poor performance of a system relative to its goals, (2) to find the causes of the UDEs, (3) to determine what to do to eliminate the causes, (4) to ascertain the impact of interventions designed to eliminate the causes, and (5) to 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). TP tools thus provide a framework for understanding existing situations in systems, identifying effective strategies to achieve goals and implementing improvements within systems. Mabin (1999) described TP tools as a roadmap that is used through the process of structuring and identifying problems, developing solutions to problems, identifying the barriers likely to be encountered while implementing a solution, and ultimately implementing the solution. Table 2.1 is a summary of the respective roles of Theory of Constraints TP tools in change management while a roadmap for the Theory of Constraints TP is presented in Figure 2.2 - all of which are discussed more fully later in this chapter.

The Theory of Constraints TPs are reputed to be powerful and versatile. Noreen *et al.* (1995) described the TPs as “may be the most important intellectual achievement since the invention of calculus”. Kim *et al.* (2008) argued 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. Mabin and Baldestone (2000) further argued that the broader potential of TP tools application arises from two unique characteristics they possess, *viz*: (1) the ability to solve relatively abstract quality and productivity problems that manifest themselves through paradigm or policy constraints; and (2) the ability to accommodate the interdependent relationships between system components. Rahman (1998) described 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 drivers (Chaudhari and Mukhopadhyay, 2003) and that it is generally difficult to identify non-physical constraints in systems (Rahman, 1998). Davies *et al.* (2005) singled out the ability of the Theory of Constraints TP to provide better understanding of situations as one of its strengths. They explained 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

explained that TP tools allow for different sides to be heard and hence achieving greater enlightenment and empowerment.

Table 2.1 Change sequence, Theory of Constraints tools and managerial utility relationships (after Scoggin *et al.*, 2003)

Change question	sequence	Thinking Process tools	Management purposes
What to change?		<ol style="list-style-type: none"> 1. Evaporating Cloud 2. Current Reality Tree 	<ul style="list-style-type: none"> • 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?		<ol style="list-style-type: none"> 1. Future Reality Tree 2. Negative Branch Analysis 	<ul style="list-style-type: none"> • Validate the effectiveness of the proposed solutions • Identify undesirable side-effects of proposed solutions and their corrections
How to cause the change?		<ol style="list-style-type: none"> 1. Prerequisite Tree 2. Transition Tree 	<ul style="list-style-type: none"> • 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

Current Reality Tree

It is evident from the literature already cited that a successful process of improving the performance of a system must begin with identifying what to change *i.e.* problem(s) to solve. Interestingly, Taylor and Churchwell (2004) pointed out that while most managers are aware of the importance of identifying problems in systems they manage, the major challenge they face is to identify the right problem(s) to solve. Many tools have been developed over the years to help managers in identifying what to change, such as cause-and-effect diagrams (Fredendall *et al.*, 2002).

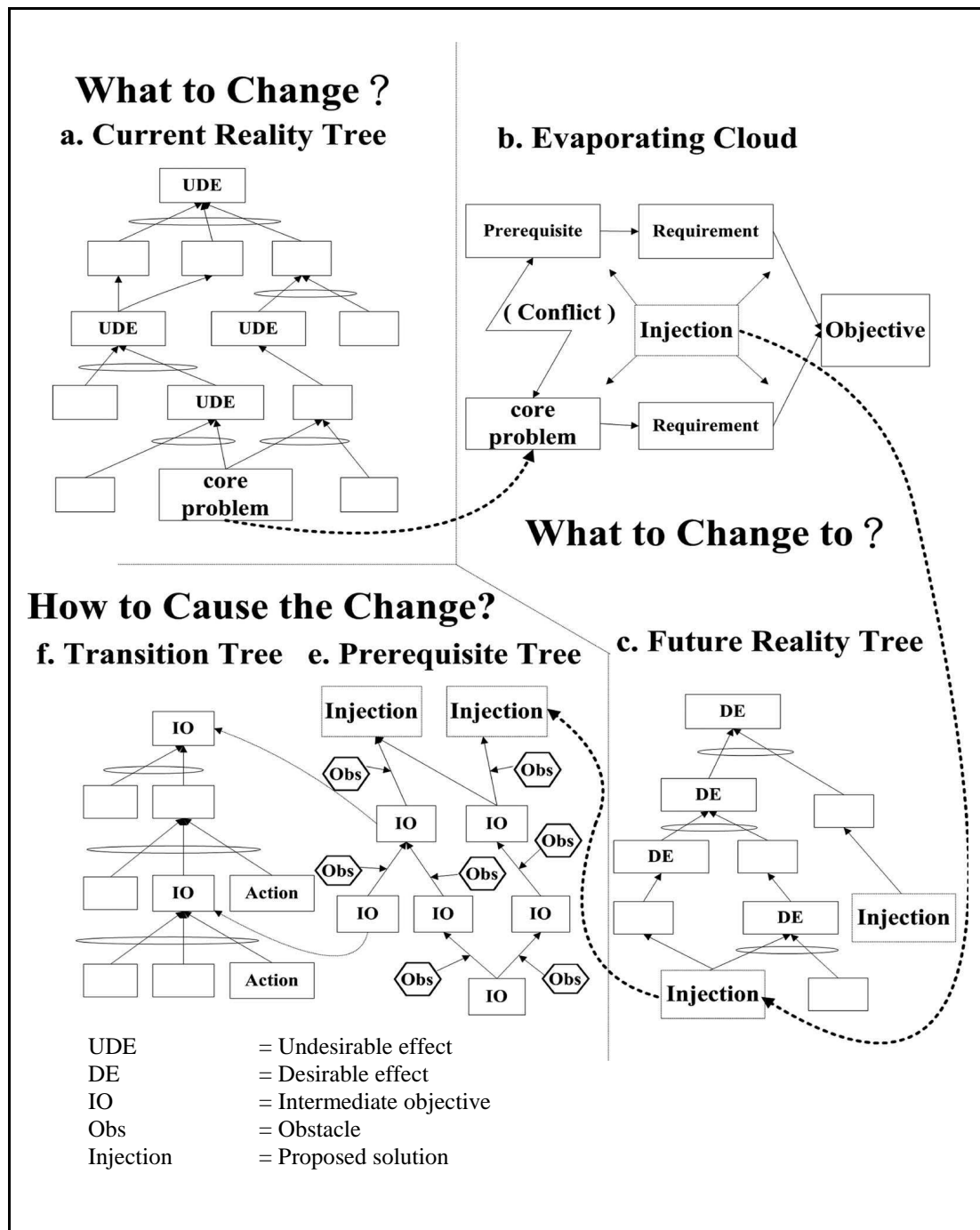


Figure 2.2 Theory of Constraints Thinking Processes roadmap (Lin *et al.*, 2009)

The CRT is a Theory of Constraints TP tool that is used to identify core problems in systems (Cox *et al.*, 2003; Scoggin *et al.*, 2003). The CRT is normally used as the first step in TP-based change management process and is 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). The CRT is a tree diagram that employs cause-and-effect logic to identify core problems in the system under consideration and determine what must be changed (Mabin,

1999; Fredendall *et al.*, 2002). It is argued (Kim *et al.*, 2008) that the CRT is a particularly effective tool when dealing with policy constraints.

There are two major approaches that are used for building the CRT; (1) the “traditional approach” (*cf.* Dettmer, 1997; Cox, *et al.*, 2003) and (2) the “three-cloud approach” (*cf.* Button, 1999; Button, 2000; Cox *et al.*, 2003). Fredendall *et al.* (2002) outlined the five steps that are followed when creating a CRT using the traditional approach as follows; (1) identify the group’s span of control and sphere of influence, (2) list UDEs of the problem *i.e.* symptoms indicating that the system is not performing as desired, (3) develop causal connections between the UDEs, (4) build a cause and effect chain to validate the UDEs, and (5) identify root causes and the core problem. They further used an example of a car failing to start in the morning to give a detailed explanation on how to construct and validate a CRT using the traditional approach (see Figures 2.3, 2.4 and 2.5).

Figure 2.3 contains a set 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 UDEs are carefully examined to ensure that they are real. In addition, each UDE is scrutinised to determine whether it is a problem or just an effect arising from one or more underlying causes.

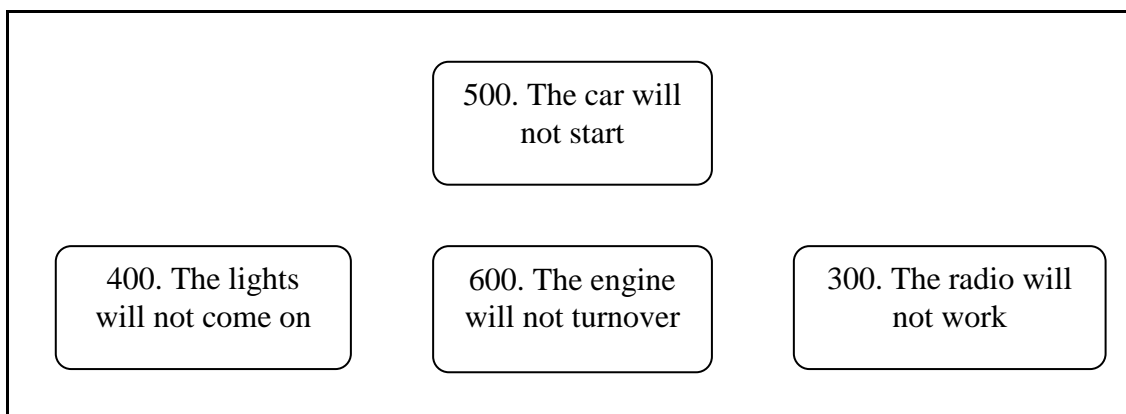


Figure 2.3 Initial undesirable effects (Fredendall *et al.*, 2002)

The next step involves the development of a causal connection between the UDEs. This is done by connecting the UDEs with arrows as shown in Figure 2.4.

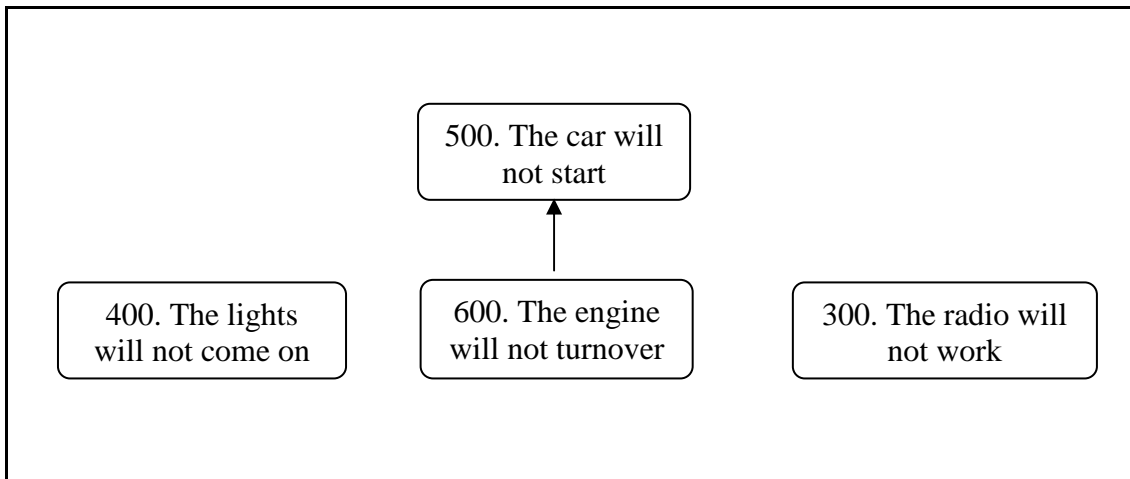


Figure 2.4 Initial connection for the Current Reality Tree (Fredendall *et al.*, 2002)

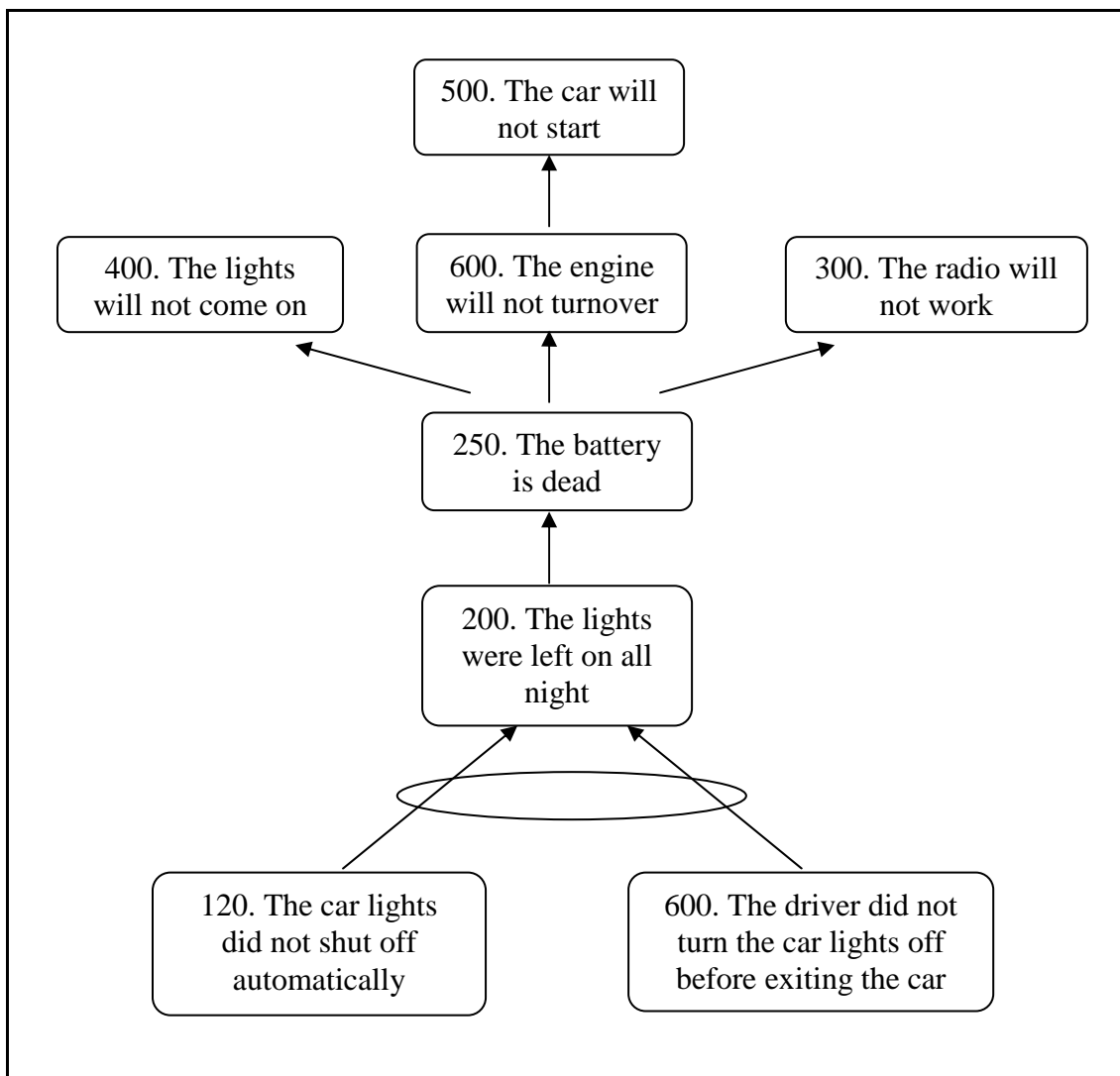


Figure 2.5 Complete Current Reality Tree (Fredendall *et al.*, 2002)

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 2.4 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 2.5, 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. It is said that the root cause is typically at the bottom or near the bottom of the CRT. Thus, in this example, 110 and 120 will be the most likely candidates for root cause (see Figure 2.5).

It is however reported (Kim *et al.*, 2008) that two major problems often arise when building a CRT using the traditional approach. The first problem is 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 (Button, 2000). Secondly, there is a perception that building a CRT is complicated and time consuming (Button, 2000; Cox *et al.*, 2003). This has often resulted in an unfortunate tendency by many top-level managers of delegating the CRT building process and even the entire Theory of Constraints implementation process to mid-level managers (Watson *et al.*, 2007). They further argued that such a tendency deprives the process of the necessary top-level management support and commitment that are always required to sustain Theory of Constraints success.

Many examples on the application of 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). For example, Lin *et al.* (2009) used the CRT to explore the problems and UDEs in the construction development process. It was observed that most small-to medium-sized developers in Taiwan were going bankrupt. An individual case of a small-to medium-sized construction company was used to identify the problems that the small-to medium-sized developers were having with the construction development process. The process comprised five stages, viz. (1) land development, (2) product design and planning, (3) construction project management, (4)

product marketing and sales, and (5) after-sales service. The chairman of the case company was interviewed. Results from the interview were used to identify the UDEs of each construction development process and the reasons for their existence. Current reality Trees were constructed for each construction development process stage. The CRTs were validated by major stakeholders in the Taiwanese construction industry. Using the CRTs, it became possible to identify the root problems of each construction development stage and explore ways to find solutions to the problems.

The South African sugar industry can benefit from the use of the CRT. Any effort by the South African sugar industry to improve the performance of its sugarcane supply chains would require that it first of all identify the core problems of the chains. Identifying core problems in complex systems such as the South African sugarcane supply chains requires suitable techniques. The CRT has proven to be an effective tool for identifying problems in systems, regardless of their complexity. In addition, the CRT is reputed to be effective when dealing with policy constraints which are known to be very difficult to identify. Policy constraints may constitute a substantial proportion of the problems in the South African sugarcane supply chains. Thus, there is a high probability that the application of the CRT for identifying problems in South Africa's sugarcane supply chains may yield good results. However, successful application of the CRT will require the support and commitment of top-level management and the active participation of all stakeholders. Hence, suitable techniques will be needed to address the aforementioned concerns prior to applying the CRT.

Evaporating Cloud

The second step in the Theory of Constraints TPs approach to change management involves answering the question "what to change to?". It is however pointed out that conflicts often underlie many systems' problems (Davies *et al.*, 2005). Taylor and Churchwell (2004) claimed that the CRT would generally generate a conflict. Thus, managers or Theory of Constraints users often find themselves in dilemma or conflicting situations when trying to develop solutions to the problem(s) identified using the CRT. This makes it difficult to find an acceptable solution to a given problem (Choe and Herman, 2004; Taylor and Churchwell, 2004).

Holt and Button (2000) presented a generic conflict which sums up dilemmas often encountered when trying to improve the overall efficiency of a supply chain having several independent business units (see Figure 2.6).

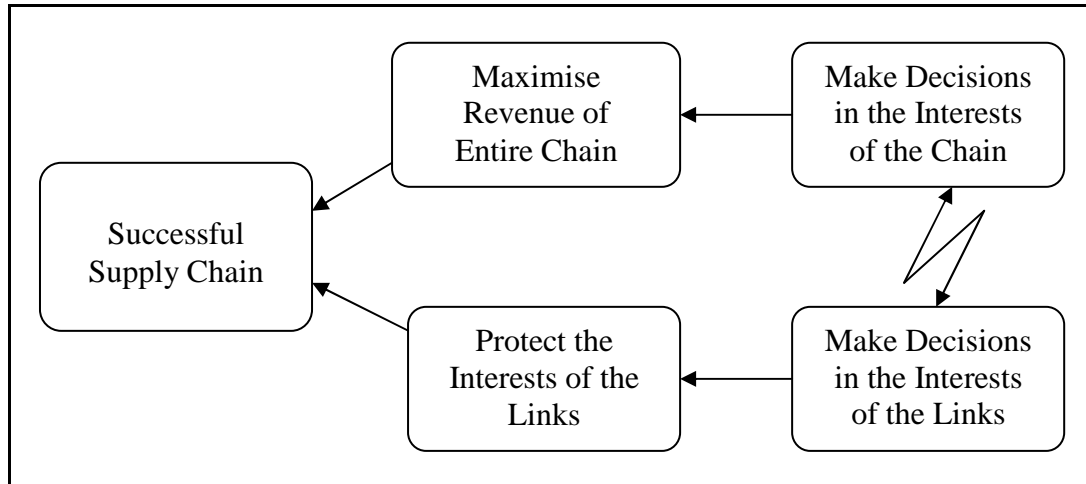


Figure 2.6 Generic conflict diagram of a supply chain (after Holt and Button, 2000)

Referring to Figure 2.6, the following explanation is made. On the one hand, it is argued that to have a successful supply chain, the chain must maximise the revenue of the entire chain. Maximising the revenue of the entire chain requires that supply chain members must make decisions in the interests of the chain. On the other hand, it is also argued that to have a successful supply chain, the chain must protect the interests of individual links. Protecting the interests of individual links requires that the chain must make decisions in the best interests of the links. A conflict therefore arises because decisions in the best interests of the links are often in conflict with those in the best interests of the entire chain.

It is observed that managers have traditionally resorted to compromise solutions when resolving conflicts (Goldratt, 1990; Dettmer, 1999; Taylor and Churchwell, 2004). However, Taylor and Churchwell (2004) criticised the tendency of using compromise solutions when resolving conflicts, arguing that such solutions do not eliminate core problem(s) in a system. Additionally, they argued that sometimes there may not be an acceptable compromise for solving a particular problem, more especially where the conflict involves people or organisations. This argument is corroborated by Cooper and Loe (1998) who explained that traditional compromise solutions for resolving conflicts tend to produce discontent by forcing each side in the conflict to sacrifice what they may consider to be important.

The EC, also known as a Conflict Resolution Diagram, is a TP tool that is used after a core problem has been identified using the CRT. The evaporating cloud was designed by Goldratt (1990) to address conflict or dilemma situations where there is no acceptable compromise. Cooper and Loe (1998) explained that the EC process is aimed at analysing both sides of a conflict and coming up with a win-win solution. Mabin (1999) and Kim *et al.* (2008) stated that the EC is used to find plausible solution(s) to the core problem(s) *i.e.* answers to the question “what to change to?”. Davies *et al.* (2005) described the EC as a tool designed to resolve conflict, dilemma or trade-off situations with the aim of coming up with a win-win solution. It is claimed (Goldratt, 1990) that the EC approach to conflict resolution would most often resolve a conflict completely without resorting to a compromise. Cooper and Loe (1998) explained that one of the strengths of the EC process is its ability to surface ideas and creative solutions that would have otherwise remained dormant.

The EC is usually built from the CRT (*cf.* Goldratt, 1994; Noreen *et al.*, 1995; Mabin *et al.*, 2001). Choe and Herman (2004) explained the process of constructing the EC from the CRT. Referring to Figure 2.7, the construction of the EC starts by identifying the desired objective (A) which is basically the opposite of the core problem identified in the CRT.

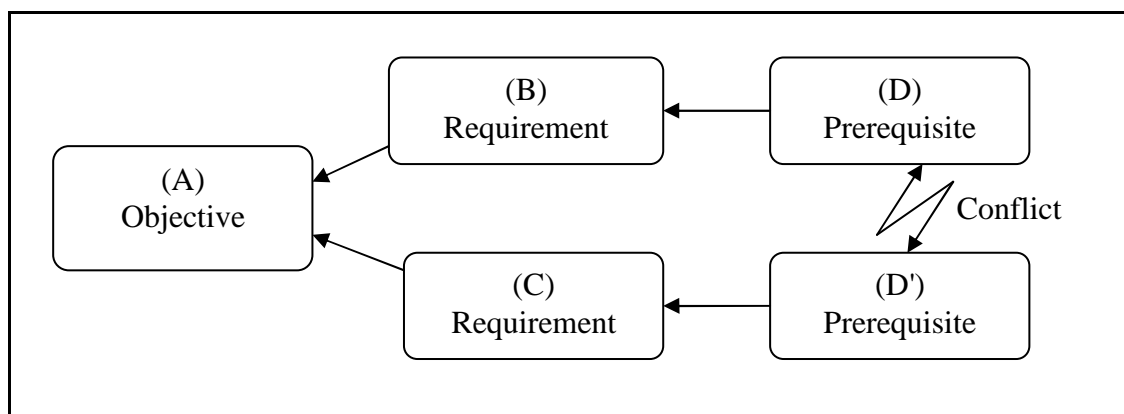


Figure 2.7 General format of an Evaporating Cloud (after Choe and Herman, 2004)

The next step involves determining requirements (B and C) and prerequisites (D and D'). Requirements and prerequisites are the necessary conditions to achieve the objective and the requirements, respectively. The “*in order to..., we must have...*,” logic is used to verify the necessary conditions. Thus the diagram is read as; in order to have requirements B and C, we must have prerequisites D and D', respectively. Since prerequisites D and D' are conflicting,

then, objective (A) may appear unattainable. Resolving the conflict would therefore require that the assumptions behind the necessary conditions be exposed, challenged and invalidated.

Literature provides many examples of the application of the EC (e.g. Jackson *et al.*, 1994; Garrison and Mitchell, 1997; Cooper and Loe, 1998; Sirias, 2002; Taylor and Sheffield, 2002; Simatupang *et al.*, 2004; Mabin *et al.*, 2006; Umble *et al.*, 2006). For example, Jackson *et al.* (1994) presented an actual case where the EC was successfully used to analyse and solve a logistical problem of forward buying (FB) in a packaged consumer goods company. Figure 2.8 is a conflict diagram of the FB problem before the deployment of the EC process. Referring to Figure 2.8, the objective of the company was to achieve higher long-term profits (A). To achieve the objective, both the annual sales volumes (B) and the profit margin (C) of their products had to be maximised. Using a buying allowances (BAs) system, annual sales volume would increase but profit margins would decline because of the free goods or price reductions offered to customers in return for volumes purchased under the system. Thus, BAs (D) and no BAs (D') were the conflicting elements in the system as the two cannot co-exist at the same time. It thus appeared to the company that it was impossible to achieve both high sales volume and a high a profit margin. Consequently, the company resorted to a compromise solution of offering some BAs to improve sales volume, but not so many as to reduce profit margins beyond a certain point *i.e.* a trade-off between high sales volume and high profit margins.

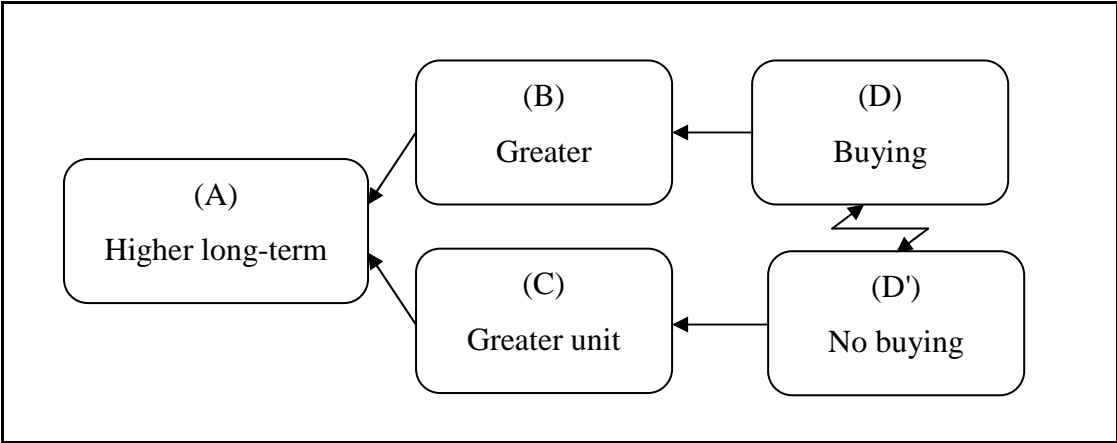


Figure 2.8 Logical diagram of the Forward Buying problem (after Jackson *et al.*, 1994)

An EC approach was later used to resolve the FB problem so that the company could achieve both high sales volume and high profit margins thereby eliminating the trade-off. The EC

process came up with an innovative solution to the problem that resulted in the company achieving production and distribution economies that ultimately improved its long-term profits.

The South African sugarcane supply chains are characterised by a large number of role players having different and often misaligned business objectives. As such, it is inevitable that conflicts would often arise among the chain members. In addition, it has already been mentioned that dilemma or conflicting situations often arise when trying to develop solutions to problems. Hence, improving the overall performance of the South African sugarcane supply chains would require the resolution of such conflicts and dilemmas. The Evaporating Cloud may provide the South African sugar industry with a valuable tool for resolving the conflicts and dilemma situations that may arise in its sugarcane supply chains.

Future Reality Tree

The FRT is a Theory of Constraints TP tool that is used after the EC. Like the EC, the FRT is also designed to identify a plausible solution to core problems identified using the CRT *i.e.* answers to the question “what to change to?”. The FRT is used to scrutinise and test the solution identified using the EC method to ensure that implementation of such a solution will really solve the problem but at the same time not create any negative future impact on the performance of a system (Mabin, 1999; Watson *et al.*, 2007). The FRT, according to Goldratt (Taylor and Churchwell, 2004), is a tool that assists people in developing a solution to a problem whose implementation will eliminate all the existing UDEs, replace them with desirable ones and not create devastating new UDES in the system.

The construction of a FRT is done as a group work and employs the natural human tendencies of criticism and negativity (Taylor and Churchwell, 2004). This ensures increased communication, understanding and acceptance by those involved with the problem (Kleine and DeBruine, 1995). In addition, Mabin (1999) stated that the building of FRT as a group greatly reduces the chances of overlooking significant potential problems that may arise from the implementation of the solution.

Mabin (1999) outlined some advantages of using the FRT as follows; (1) allows proposed solutions to be tested well before committing any resources to their implementation, (2)

reveals the actions that would be required to prevent any negative side effects from occurring as a result of implementing the proposed solution, (3) assesses the impacts that decisions made at subsystem level will have on the overall performance of the system, and (4) increases the chances of winning the support of top-level management in implementing a proposed solution.

Prerequisite Tree

Having answered the two questions “what to change?” and “what to change to?”, then the third question in the change management process becomes “how to cause the change?”. The answers to this question help managers to develop strategies and action plans for implementing proposed solutions otherwise known as injections. The PRT is used in answering the question “how to cause the change”. The PRT uses necessity logic to identify obstacles to the implementation of a proposed solution and comes up with ways to overcome such obstacles (Mabin, 1999; Rahman, 1999; Scoggin *et al.*, 2003; Davies *et al.* 2005; Watson *et al.*, 2007; Inman *et al.*, 2009).

The development of the PRT is usually done as teamwork. This ensures that obstacles to the implementation of a proposed solution that may emanate from social practices and power struggle are usually raised and addressed alongside the other obstacles (Davies *et al.*, 2005). Dettmer (1997) advised a compulsory application of the PRT in these two situations; (1) where the objective to be achieved is a complex condition, and (2) where it is not already known of how exactly to achieve an objective.

Transition Tree

The TT uses sufficiency logic in its construction (Mabin, 1999). Like the PRT, the TT is also used in answering the question “how to cause the change?”. However, unlike the PRT, the TT is used to identify the necessary and sufficient actions and tasks required to implement proposed solutions (Kleine and DeBruine, 1995; Davies *et al.*, 2005; Watson *et al.*, 2007; Inman *et al.*, 2009). It is stated, (Dettmer, 1997; Mabin, 1999; Scoggin *et al.*, 2003, Davies *et al.*, 2005) that the TT provides a way of developing a step-by-step tactical action plan for implementing a proposed solution. In addition, Dettmer (1997) and Scoggin *et al.* (2003) indicated that the other purpose of the TT is to communicate action rationales to others. It is

claimed (Davies *et al.*, 2005) that apart from providing a coherent step-by-step implementation plan, the TT also takes into account the prevailing beliefs, feelings and norms governing the problem situation under consideration and hence increasing the chances of success in implementing the solution.

Negative Branch Reservation

Kim *et al.* (2008) claimed that a step-by-step scrutiny of the FRT, as a group activity, will more likely result in participants expressing reservations about the negative side effects or other problems that might arise following the implementation of the proposed solutions in the FRT. Rather than brushing the participants' reservations aside or abandoning the proposed solution, the NBR process is used to find ways of adjusting the solution to prevent such negative side effects from occurring while still keeping the positive effects of the solution (Davies *et al.* 2005; Kim *et al.*, 2008). The NBR is an ancillary TP tool that is used to expose the potential UDEs that might emanate from implementing a solution proposed in the FRT (Scoggin *et al.*, 2003; Dettmer, 1997). The NBR is basically a sub-tree or off-shoot of the FRT (Kim *et al.*, 2008; Davies *et al.*, 2005). Davies *et al.* (2005) explained that the NBR can be used either as part of the Theory of Constraints TP suite of tools or as a stand alone tool to facilitate critical feedback and to further develop ideas. It is argued (Scoggin *et al.*, 2003) that NBR use can help in reducing managerial aggravation during change implementation process.

Scoggin *et al.* (2003) presented a case study in which the NBR was deployed in a manufacturing firm. The firm had limited capacity to simultaneously carry out design and production activities while at the same time meeting its customers' current product delivery schedule. Consequently, the firm used the majority of its production capacity to meet its customers' current product schedule despite the firm's desire to also satisfy their customers' future design requirements. Using the Theory of Constraints TP tools, one of the solutions that were proposed to solve the firm's problem was a change in labour policy. Deploying NBR to scrutinise the solution, an increase in the probability of union grievances or a strike were identified as the undesirable consequences of changing the labour policy if a well thought-out implementation plan was not put in place.

Categories of Legitimate Reservation

Strict logic rules called Categories of Legitimate Reservation (CLR) are used in the construction, interpretation and validation of the tree diagrams (Scoggin *et al.*, 2003). The CLR are used to scrutinise the tree diagrams used in the Theory of Constraints TPs (Balderstone, 1999; Kim *et al.*, 2008). The causal 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 TPs tree diagrams (Dettmer, 1997). The rules are; (1) clarity, (2) entity existence, (3) causality, (4) cause insufficiency, (5) additional cause, (6) cause-effect reversal, (7) predicted effect existence, and (8) tautology.

It is argued (Dettmer, 1997) that the use of CLR enhances the accuracy and validity of the Theory of Constraints' TP. Fredendall *et al.*, (2002) observed that the use of these rules ensure increased communication and understanding among those involved with the problem and hence create a consensus among them. Furthermore, Baldestone (1999) observed that the CLR can also be successfully used to validate similar cause-and-effect diagrams outside the Theory of Constraints domain and hence proposed their use in the validation of causal loop influence diagrams used in System Dynamics (SD) models.

2.2.3 The Theory of Constraints performance measurement system

Performance measurement systems play a critical role as far as the achievement of competitive success by organisations is concerned. Lockamy and Spencer (1998) argued that the success of an organisation may well depend on the degree of compatibility between the performance measurement systems used at subordinate unit levels and the global goals of the organisation. They also claimed that there is an increasing amount of research in operations management that aims at addressing the problem of incompatibility between the operation's performance measurement system and global goals of an organisation.

Theory of Constraints prescribes three operational measurements for assessing the performance of an organisation in achieving its goal (Goldratt and Fox, 1986). The three measurements are; (1) throughput, (2) inventory, and (3) operating expense. Gupta and Kline (2008) described throughput, inventory and operating expenses as terms representing money

coming into the system, money going out of the system and money stuck inside the system, respectively. It is claimed, (Goldratt, 1990) that these measures help managers to assess the effects that decisions made at subsystem level have on the overall performance of a system. Lockamy and Spencer (1998) and Draman *et al.* (2002) stated that the Theory of Constraints performance measurement system links together strategic objectives and operational capabilities of an organisation.

There is documented evidence regarding the use of the Theory of Constraints performance measurement system. Westra *et al.* (1996) reported on a manufacturing enterprise that attained significant reductions in inventory and labour costs and an increase in cash flow after adopting Theory of Constraints performance measurement system. Lockamy and Spencer (1998) reported on a study that examined the application of a Theory of Constraints performance measurement system in an actual manufacturing environment. One of the conclusions derived from the study was that the Theory of Constraints performance measurement system provides a means for monitoring operational performance in relation to the overall goals of an organisation and thus aligning operations performance measurement system with global goals. Gupta *et al.* (2002) demonstrated the effectiveness of using a Theory of Constraints-based global performance measurement system in making operational-decisions for strengthening the internal supply chain in a relatively complex manufacturing environment. They developed a simulation model to mimic the Theory of Constraints approach to manufacturing in a hypothetical job-shop type environment. The model was verified using analytical results. The model showed that the Theory of Constraints global performance system ensures that all management policies and decisions are innovative and focus on making money rather than saving money. Draman *et al.* (2002) reported on a Gedanken (thought) experiment that was carried out to evaluate the difference between strategy driven product-mix decisions based on Theory of Constraints accounting and traditional cost accounting. Four different strategies were used in the experiment *viz*; contraction, market share, product quality and cost leadership. Results of the experiment indicated that in all the four cases, strategic decisions based on Theory of Constraints accounting approach produced between 9 and 41 % improvements in financial performance of an organisation when compared to the decisions made based on traditional cost accounting approaches. Similarly, Mehra *et al.* (2005) used a computer-based simulation method, using actual data from a speciality chemical manufacturing firm, to compare performance measurement of a continuous process manufacturing operation under two accounting systems

– the traditional accounting system and the Theory of Constraints system. They found out that businesses using a Theory of Constraints-based system can gain a sustainable competitive position because they can improve their performance more accurately.

The South African sugarcane supply chains consist of multiple and independently owned business units. It is therefore likely that several performance measurement systems could be in use within the supply chains at any given time. Those performance measurement systems may not be compatible with each other. Additionally, the performance measurement systems may not be aligned with the overall goal of the supply chains. Consequently, the performance of the supply chains may be adversely affected. Literature in previous sections has shown that the use of the Theory of Constraints performance measurement system results in improved performance of systems. The South African sugar industry may therefore benefit if it adopts the performance measurement system for use in its sugarcane supply chains.

3. DISCUSSION AND CONCLUSIONS

The South African sugar industry needs to minimise its production costs if it is to favourably compete with world-leading low-cost sugar producing countries. An opportunity exists for the South African sugar industry to significantly reduce its production costs by improving the efficiency of its sugarcane supply chains, especially at the mill area level. However, the complexity of sugarcane supply chain systems requires that only those techniques capable of accommodating systems' complexity issues should be used for improving their efficiency, if at all any success can be achieved. Such techniques must possess the capability to (1) capture, study and analyse the complexity in the sugarcane supply chains, (2) identify core problem areas that need improvement, (3) develop solutions that address the core problems, and (4) develop management strategies for implementing the developed solutions. The Theory of Constraints, a Systems Thinking based management philosophy, has thus been extensively reviewed to assess its effectiveness for improving the performance of complex production systems and to investigate the possibility of applying some of its approaches for improving the performance of South African sugarcane supply chains.

This review indicates that the Theory of Constraints is effective in improving the performance of systems, regardless of their complexity. Theory of Constraints has a set of tools and strategies for identifying core problems in systems, developing win-win solutions, and managing the successful implementation of the solutions. Several examples of the successful application of the Theory of Constraints to both commercial and not-for-profit organisations and sectors attest to its effectiveness. Interestingly though, only one example of the Theory of Constraints application in an agriculture related area was found. However, the review has highlighted the various limitations of the Theory of Constraints approach to systems improvement, *viz*: (1) its inability to fully represent the dynamic complexity inherent in modern systems due to its often linear and relatively static representation of relationships between system components, (2) the considerable length of training time required to achieve mastery of the theory, (3) the considerable length of time required to complete the problem identification and solving process, (4) the need for the cooperation and enthusiasm of all the people (stakeholders) involved with the problem, and (5) its over reliance on group work.

It is nonetheless concluded that many of the fundamental approaches of the Theory of Constraints can successfully be used, albeit its limitations, for improving the performance of South Africa's sugarcane supply chains. However, the limitations need to be addressed in order for the Theory of Constraints to bring about the greatest positive impact on the performance of South Africa's sugarcane supply chains. Computerising the Theory of Constraints process and coupling it with system dynamics and cause-and-effect analysis techniques may significantly reduce the limitations.

4. PROJECT PROPOSAL

4.1 Proposed Title of Research Project

“Development of Network Analysis Diagnostics Approaches to Surface Opportunities in Integrated Sugarcane Production and Processing Systems”

4.2 Introduction

The South African sugar industry makes an important contribution to South Africa’s economy in terms of employment and foreign exchange earnings. The industry produces an estimated average of 2.3 million tonnes of sugar per season, which is sold on both the local and the international markets and generates an annual estimated average direct income of R7 billion (SASA, 2010). Though enjoying considerable production efficiencies, the South African sugar industry still needs to minimise its production costs if it is to continue competing favourably on the global market. Fortunately, there is a significant potential to minimise the production costs of South Africa’s sugar industry by improving the efficiency of its sugarcane supply chains, especially at the mill area level (*cf.* Higgins *et al.*, 2007; Le Gal *et al.*, 2008). However, South Africa’s sugarcane supply chains are complex, fragmented and continuously evolving systems involving 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). Furthermore, there is a multiplicity of factors that interact to affect the performance of the supply chains. These fundamental attributes of the sugarcane supply chains make it difficult and time-consuming to identify core problems of the supply chains using existing problem identification techniques. Hence, improving the efficiency of South Africa’s sugarcane supply chains remains a challenge.

In this study it is hypothesised that there is a potential to develop an innovative and quicker technique for identifying core problems in complex systems using Complex Systems Thinking tools. The technique will be developed by merging approaches from two Complex Systems Thinking tools *viz.* (1) the Theory of Constraints and (2) the cause-and-effect analysis.

The Theory of Constraints possesses a tool called the Current reality Tree that is used for identifying core problems in complex systems. Though applauded in literature as being effective, the Current Reality Tree has been criticised of being complicated to use and too time-consuming (Button, 2000; Cox *et al.*, 2003). The problem identification process, using the Current Reality Tree, is done manually as a group work, requires the participation of everyone involved with the problem and the facilitation of a Theory of Constraints expert. Furthermore, a new Current Reality Tree must be developed from scratch for each problem situation. The cause-and-effect analysis, albeit its limited problem identification capabilities especially when dealing with complex systems, can effectively eliminate most of the weaknesses of the Current Reality Tree.

The cause-and-effect analysis provides a fast way of mapping, describing, and analysing cause-and-effect dynamics in complex systems. A cause-and-effect network map for any system can be developed and analysed using appropriate computer packages such as the PAJEK Social Network Analysis software (de Nooy *et al.*, 2005). Once a cause-and-effect network map for a system has been developed, the development process of the Current Reality Tree can be computerised. This will make problem identification using the Current Reality Tree an easier, faster and less involving process. The need to develop a Current Reality Tree from scratch for every problem situation will be eliminated. In addition, the problem identification process will be done on an individual interview basis instead of a long workshop – this will save stakeholders time. Furthermore, the network maps will enable a wide range of systems diagnostics such as predicting the effects of factors on one another and on the overall performance of the system.

The coupling of the Current Reality Tree with the cause-and-effect analysis may hold a key towards the development of an effective, simple and fast technique for identifying core problems in South Africa's sugarcane supply chains and perhaps any supply chain for that matter. The proposed research project will combine the approaches of the Theory of Constraints and the cause-and-effect analysis to develop a cause-and-effect network analysis technique that can be used to establish the single most pertinent constraint in an integrated sugarcane production and processing system and to perform a wide range of diagnostics of the system. Such a technique would be valuable to the South African sugar industry in its efforts to improve the efficiency of its sugarcane supply chains.

4.3 Hypothesis

Innovative cause-and-effect network analysis techniques can be developed to establish the single most pertinent constraint in a complex sugarcane production system and to perform a wide range of diagnostics of the system.

4.4 Objectives

The objectives of the proposed research project are as follows:

- i. Provide a review of literature pertaining to the analyses of complex systems, such as the Theory of Constraints;
- ii. Refine the techniques of describing cause-and-effect dynamics in a sugarcane supply chain;
- iii. Develop cause-and-effect network maps for the South African sugarcane supply chains;
- iv. Develop a cause-and-effect network analysis technique for identifying problems and performing diagnostics in integrated sugarcane production and processing systems;
- v. Identify and/or derive mathematical, statistical and visual tools for establishing the single most pertinent constraint in South African sugarcane supply chains and for performing a wide range of valuable diagnostics like predicting the effects factors on one another and on the overall performance of the supply chains;
- vi. Apply the identified and/or derived tools in tandem with the cause-and-effect network analysis technique on four case studies in South Africa's sugar industry;
- vii. Identify the strengths, weaknesses and limitations of the cause-and-effect network analysis technique; and
- viii. Make recommendations on how to further improve problem identification and system diagnostics techniques in integrated sugarcane production and processing systems.

4.5 Methodology

This section contains a discussion of the procedures that will be followed in executing the proposed research project. Figure 4.1 is a roadmap depicting the sequence of events when executing the project.

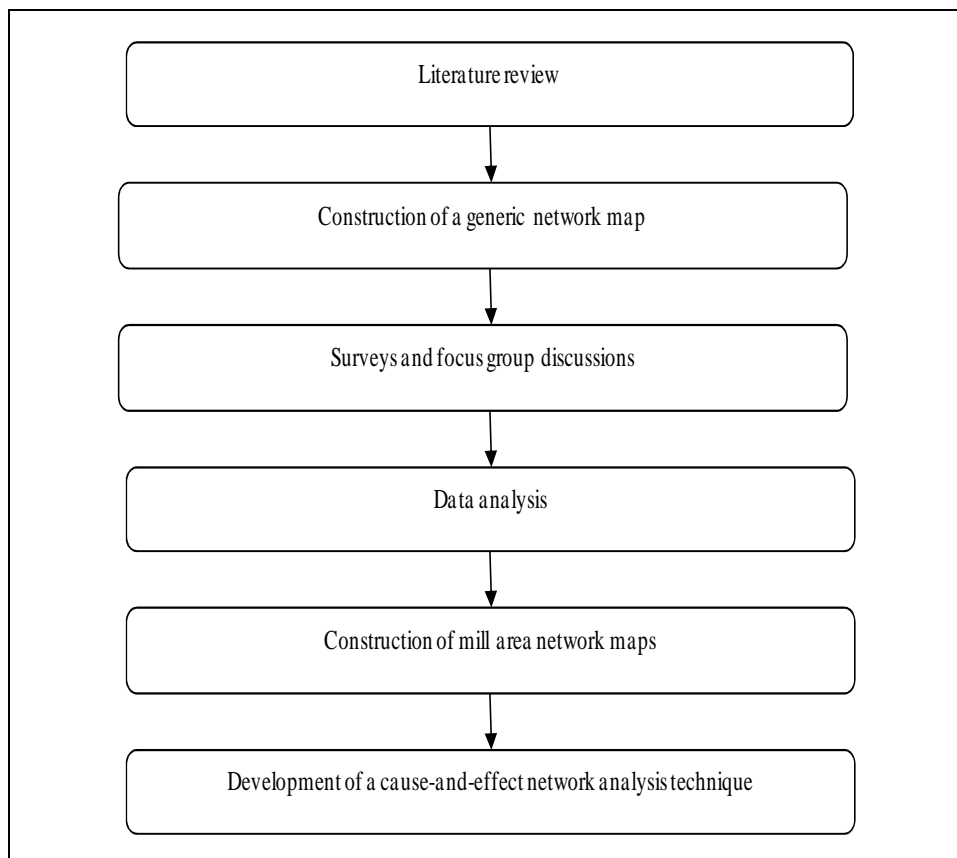


Figure 4.1 Road map for executing the project

A detailed literature review will be conducted on the Theory of Constraints and other cause-and-effect analysis techniques to establish their applicability and effectiveness for identifying core problems in complex systems and for performing systems diagnostics. The literature review will focus on the strengths, weaknesses and limitations of both the Theory of Constraints and the cause-and-effect analysis techniques, with respect to core problem identification and performing diagnostics in complex systems.

A generic network map depicting the cause-and-effect relationships among the factors that affect the performance of South Africa's sugarcane supply and processing chains at the mill area level will be developed using the PAJEK Social Network Analysis software. The network maps will be developed using available literature and the information that will be obtained from stakeholders and experts in South African sugar industry. The logic of the cause-and-effect relationships in the network map will be authenticated using the Theory of Constraints' Categories of Legitimate Reservations.

Using the generic network map as a blueprint, a series of surveys and focus group discussions will be executed during the years 2010 and 2011 in four South African sugarcane milling areas. During the surveys and focus group discussions, data will be collected on the problems the South African sugar industry faces and their respective causes. The data will be analysed to identify the major problems faced by each of the four sugarcane milling areas and their respective root causes. In addition, the data will be used to develop cause-and-effect network maps for the four sugarcane milling areas using the PAJEK Social Network Analysis software.

A cause-and-effect network analysis technique coupling some approaches from the Theory of Constraints and the cause-and-effect analysis will be developed for establishing the most pertinent constraint in an integrated sugarcane production and processing system and for performing diagnostics of the system. In addition, suitable mathematical, statistical and visual tools for isolating and quantifying problem areas and surfacing opportunities in complex systems will be identified and/or developed. The cause-and-effect network analysis technique, together with the identified and/or developed tools, will be tested on the cause-and-effect network maps of the four surveyed sugarcane milling areas. Results of the tests will be used to assess the strengths, weaknesses and limitations of the cause-and-effect network analysis technique with respect to its capability for identifying core problems in South Africa's sugarcane supply chains and performing systems diagnostics. Further development, testing and assessment of the cause-and-effect network analysis technique will be done up until satisfactory results are attained.

4.6 Significance of Research Project

It is generally accepted that a successful process of improving the performance of any system must start with identifying the right problem(s) to solve. However, identifying core systems problems remain a challenge for most modern organisations, because of the complexity of their systems. The South African sugar industry is one such complex system in which problem identification and systems diagnostics remain difficult tasks. This is particularly a problem in its sugarcane supply chains due to their inherent complexity. However, there is a growing need by the South African sugar industry to improve the efficiency of its sugarcane supply chains as one way of improving its competitiveness on the global market. It is

therefore important that the South African sugar industry must be equipped with a suitable problem identification and systems diagnostics technique. Techniques are available for identifying systems' problems, such as the Theory of Constraint's Current Reality Tree and the cause-and-effect analysis. However, a number of limitations adversely affect their usability as problem identification techniques. The problem identification process, using the Current Reality Tree, is complex and time consuming. The cause-and-effect analysis has very limited problem identification capability especially when working with complex systems. These limitations necessitate either the improvement of the techniques or the development of new techniques, altogether.

The proposed research project will result in the development of a cause-and-effect network analysis technique for establishing the single most pertinent constraint in any complex system, such as a sugarcane supply chain, and for performing a wide range of systems diagnostics. The project will develop a fast and easy-to-use technique for identifying problems and performing systems diagnostics in the South African sugarcane supply chains and perhaps any supply chain for that matter. The technique will be valuable to the South African sugar industry in its efforts to improve the efficiency of its sugarcane supply chains. In addition, the time, effort and the number of personnel involved in the process of identifying sugarcane supply chain problems will be reduced. Furthermore, the technique will allow for the analysis of systems dynamics and soft issues - something difficult to achieve using existing problem identification and systems diagnostics techniques. Also, once a supply chain has been mapped, it will be easier to update it and perform a wide range of diagnostics such as predicting the effects of factors on one another and on the overall performance of the chains. It must however be mentioned that the scope of this research project stops at the mill back-end, and as such, the rest of the chain all the way to the consumer will not be considered. Such is the case because the project focuses on assessing the biophysical drivers of the supply chains rather than the market drivers.

The proposed research project will also make a contribution to scientific knowledge. The project will generate valuable information about complex systems especially with regard to their behaviour, mapping, description, analysis and diagnosis. Such information may lead to a better understanding of complex systems. It is expected that the following scientific papers will be published from the results of the research project:

- i. Network analyses approaches for dealing with complexity in a supply chain;
- ii. Comparing the performance of cause-and-effect network analysis technique with traditional problem identification techniques;
- iii. Using a cause-and-effect network analysis technique for identifying core problems in integrated sugarcane supply and processing chains – four case studies; and
- iv. An overview of the statistical tools used when diagnosing complex systems using cause-and-effect network analysis technique.

4.7 Work Plan

Table 4.1 Work plan

Task - October 2009 – September 2010	Month of the year											
	O	N	D	J	F	M	A	M	J	J	A	S
Literature review and proposal writing												
Development of a technique for describing cause and effect dynamics of a complex system												
Development of a technique for quantifying and isolating problem areas in a complex system												
Acquisition of data sets												
Data entry, cleaning and manipulation												
Task - October 2010 – September 2011	Month of the year											
	O	N	D	J	F	M	A	M	J	J	A	S
Literature review update												
Development of a technique for quantifying and isolating problem areas in a complex system												
Application of developed techniques to case studies												
Assessment of the developed techniques												
Task - October 2011 – September 2012	Month of the year											
	O	N	D	J	F	M	A	M	J	J	A	S
Literature review update												
Assessment of the developed techniques												
Writing of journal articles and reports and attending conferences												
Thesis write-up												

4.8 Equipment and Resources

The equipment and resources that will be required for the proposed research project are outlined in Table 4.2 together with their respective uses.

Table 4.2 Equipment and resources for the project

Equipment /resource	Purpose
Office	Provide safe and conducive environment to carry out the research project.
Computer and disc storage space	Literature search, communication, data storage, data manipulation, data analysis, reports writing, and thesis writing.
Books and stationery	Reference, note taking, photocopying and printing.
Printer, photocopier, scanner	Printing, photocopying and scanning.
Telephone	Communication.
Data sets	Building cause and effect networks of sugarcane production systems Assessing performance of innovative problem identification techniques
Pajek software	Network analyses, network manipulation, and quantifying and isolating problem areas in systems.
Vehicles	Local travel.
Air tickets	International and some local travel.

4.9 Health and Safety Considerations

The proposed research project will largely be computer-based and hence there are no major health and safety concerns to be considered. However, depending on availability of funding, there will be some local and international travelling during the project period for the attendance of meetings and conferences. All health and safety rules regarding local and international travel will be adhered to during all trips to and from meetings and conferences venues.

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